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A paper presented at the 249th meeting of the American Institute of Electrical Engineers, New York, May 17, 1910.

METAL FILAMENT LAMPS

BY JOHN W. HOWELL

The first commerical metal-filament lamp was the osmium lamp, the filaments of which were made of osmium. They had a good commercial life at 1.5 watts per c-p., and were used in considerable quantity in Vienna and Berlin where they were made. They were not shipped to distant points, as the filaments were very fragile, and the metal osmium was so valuable that it was desirable to recover all the lamps after they had burned out.

The tantalum lamp appeared on the market in Germany in 1905 and in this country in 1906. The filament is drawn tantalum wire. This wire has a tensile strength greater than steel; it has a very high melting point, about 2800 deg. cent. according to Drs. Waidner and Burgess. It has radiating characteristics which make it an efficient light giving body. These qualities make it an excellent metal for use in filaments and these lamps have good commercial lives at 2 watts per c-p. The strength and flexibility of the filament prevents breakage in shipment and adapts the lamps for use wherever they are subject to handling or rough usage of any kind. This valuable quality has enabled the use of tantalum lamp to increase rapidly while in direct competition with the tungsten lamp which operates at a much higher efficiency. The physical structure of the tantalum wire changes with use; it loses its smooth uniform surface and becomes rough, offset and brittle. This change takes place more rapidly on alternating current than on direct current. The cause of it is not definitely known.

Tungsten lamps were first placed on the market in this country about the beginning of 1907. They were sold in Europe in September 1906. The development and production of these lamps since that time has been very rapid, and in 1909 about 10,000,000 lamps were sold in the United States. This great commercial success of the tungsten lamp and the very interesting physical characteristics of the tungsten filament are the reasons for the presentation of this paper.

Tungsten lamps when first introduced were rated at 1.25 watts per c-p. The announcement of this figure created an immediate interest in the lamp; lamp users anticipated a great reduction in their bills for current; current sellers feared this same reduction; lamp engineers and those with scientific interest in lamps were most keenly interested, for to them a lamp with normal life at 1.25 watts per c-p. meant a lamp over 200 times as good as the standard carbon lamp. This figure represented to them the relative quality value of the new lamp when compared with the old standard carbon lamp.

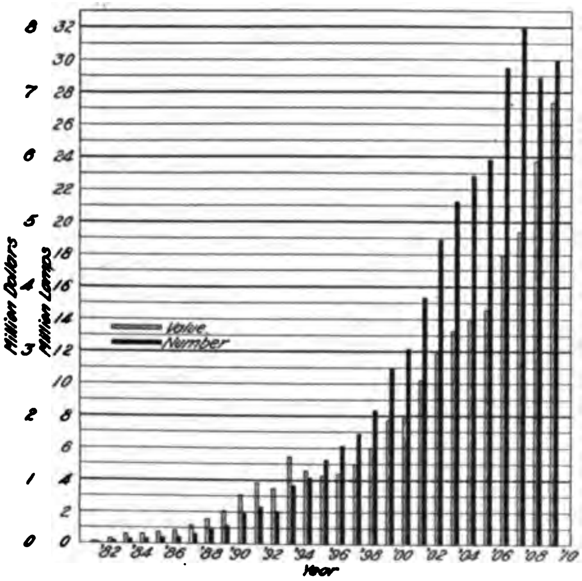

FIG. 1—Showing value and number of incandescent lamps produced annually by one manufacturer since 1881. The values for 1909 cover 11 months

Those who have used tungsten lamps with the object of reducing their bills have done so successfully, for if tungsten lamps are used to replace carbon lamps, candle for candle, a very material economy is effected and also much better lighting secured due to the much better color of the light and its much greater uniformity throughout the life of the lamp. Other users of the tungsten lamp have utilized the superior efficiency of the lamps to greatly increase the amount of light used while keeping the expense about what it was previously. Generally, however, a course between these two has been followed, the amount of light being materially increased and the cost of lighting also reduced; and experience has demonstrated that at current prices for electricity and lamps, the tunsten lamp will give much more light than will carbon lamps and at the same time reduce the cost of lighting.

The fears of current sellers that their income would be reduced by the introduction of tungsten lamps have not been realized, on the contrary, their income has been increased by the rapid extension of their business into new fields which were opened by the superiority of the new lamps, and by the availability of the larger sizes of lamps which, with carbon filaments, were not successful.

The first tungsten lamps sold in this country were high candle-power, thick filament lamps. There were two reasons for this: the filaments were more easily made than were thinner filaments, and the field of high candle-power lamps had been very imperfectly filled by carbon lamps. These early lamps consumed 100 watts and gave 80 candle-power; they gave us what we did no have before, good incandescent lamps of high candle-power, and they extended the use of incandescent lamps into an unoccupied field. Since that time both higher and lower candle-power lamps have been developed and the adaptability of tungsten to the making of all sizes of filaments has been fully demonstrated. Lamps are now on the market using currents as low as 0.15 ampere and as high as 10 amperes in a single filament.

Tungsten has been a boon to the pocket battery flash light business, in which lamps are now used consuming only 0.4 of a watt. Lamps using 500 watts and giving 400 c-p. are used in large numbers and some 1000-c-p. lamps have been made.

Lamps of the 220-volt class are also made. They require filaments twice the length of those required in 110 volt lamps, and they are therefore more liable to breakage, and are shorter lived at the same efficiency, than are the lamps of standard voltage.

Street series lamps taking from 3½ to 10 amperes and from

6 to 20 volts have short thick filaments and are very long-lived and satisfactory lamps.

Tungsten is one of the heaviest metals known, having a specific gravity of about 20. Its melting point is over 3000 deg. cent. according to Drs. Waidner and Burgess, which is higher than that of any other known metal. Its radiation characteristics are very favorable for its use as a light-giving source, for it possesses the quality called selective radiation, a relative term which implies that the proportion of its total radiations which are in the visible spectrum is greater than that of other substances which are considered normal.

The superior efficiency of tungsten lamps is due to these physical characteristics of the metal tungsten; namely, its ability to remain stable at a very high temperature, and its ability when at this high temperature to emit more than the normal proportion of its radiations in the visible spectrum.

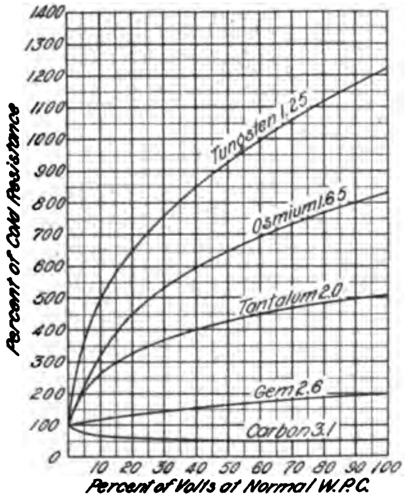

FIG. 2

Tungsten has other interesting characteristics; while its melting point is very high it oxidizes at a very low temperature—(about 300 deg. cent.). It also softens at a very low temperature, and filaments which are easily broken when cold can be bent permanently into any desired shape at a temperature below the oxidizing point. This characteristic is taken advantage of in making many filaments of special form, especially in making low voltage lamps; many filaments of spiral or helical form are made by winding straight pieces of filament on hot mandrels. Similar forms of filaments when made of carbon must be made in the desired form before carbonization.

The change of resistance with voltage in a tungsten filament is very interesting, especially when compared with a carbon filament. The specific resistance cold of carbon is 800 times that of tungsten and at normal working temperature it is 33 times that of tungsten.

The low specific resistance of tungsten is a disadvantage in making high voltage lamps, making it necessary to use very long thin filaments for these lamps. The length of filaments for 120-volt lamps ranges from 450 mm. for 20-watt lamps to 1400 mm. for 500-watt lamps. The disposal of such long filaments within the proper sizes of bulbs has necessitated a great advance in the art and science of lamp making. This advance has been made, and lamps of standard voltage are now made ranging from 20 watts and 16 c-p. to 500 watts and 400 c-p., all of which are well designed and of good quality.

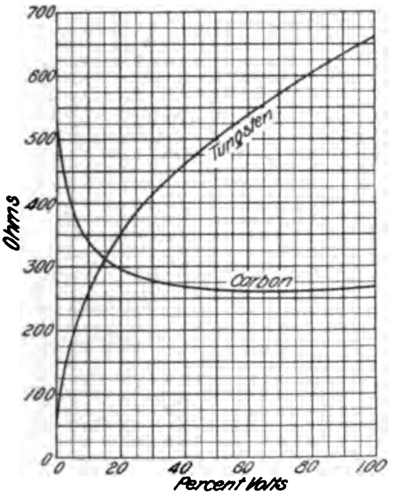

Fig. 3

For low-voltage lamps this low specific resistance is an advantage, giving more desirable dimensions of filaments for such lamps. This advantage has caused a considerable increase in the use of low-voltage lamps for many purposes in connection with storage batteries, and has led to the introduction of a residence lighting systems using 27 and 60 volt lamps, which are used with compensators or transformers on ordinary alternating-current circuits. These lamps have shorter and thicker filaments than lamps of standard voltage and the same candle-power. If filaments of the same diameter are used the filament will be one-quarter as long and give one-quarter the candle-power of the 100-volt lamps; thus, with the same filaments which are used in 20-watt, 100-volt lamps, lamps of 25 volts using 5 watts and giving 4 c-p. are made. These low candle-power lamps are very desirable in residence lighting in places requiring only a little light, and in chandeliers and clusters in which ornamentation is required as well as illumination.

If we compare lamps of equal candle-power, the 25-volt lamps will have filaments 0.4 as long and 2.5 times the diameter of those in 100-volt lamps, and the 25-volt lamps will be less easily broken by rough handling and will give longer life at the same efficiency. This longer life is due to the greater diameter and shorter length of the filament, for a thicker filament is less affected by minute imperfections, and a shorter filament has proportionately less chance of containing such imperfections.

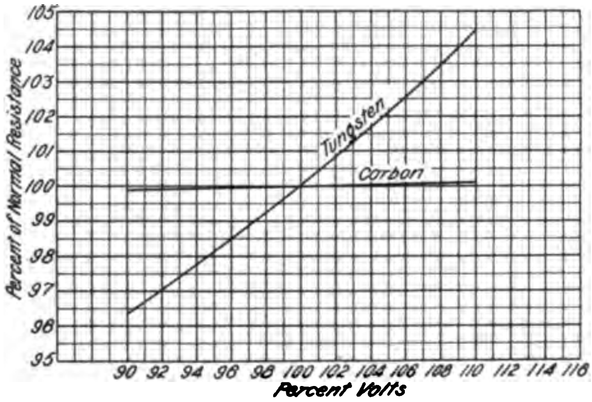

FIG. 4

Many lamps are now used in automobile headlights. These lamps have short thick filaments, which are not broken by the vibrations or jars to which they are subjected, and are very convenient sources of light. Ten-candle-power lamps in good parabolic reflectors give a very satisfactory light. These require 12 watts each, and ordinary storage batteries are well adapted for their use.

These resistance characteristics affect the rates of change of the candle-powers, efficiencies and lives of these lamps with changes of voltage, and curves are given showing the relative resistance changes of carbon and tungsten for a small range of voltage above and below the normal operating voltages of the lamps.

These curves show that in a tungsten filament an increase in voltage is met and partly counteracted by an increase in resistance, while in a carbon filament the resistance remains practically constant; consequently any increase in voltage produces less increase in watts, less increase in candle-power and less decrease in life in a tungsten filament than in a carbon filament.

It will be observed that an increase of 3.7 per cent in voltage will halve the life of a carbon lamp while it requires an increase of 5.2 per cent to halve the life of a tungsten lamp

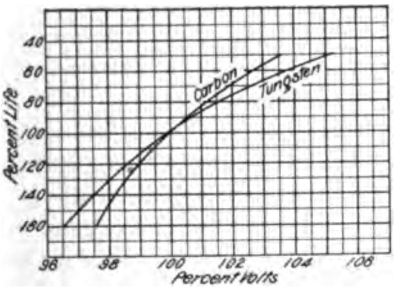

FIG. 5

The cold resistance of a tungsten filament is only one-twelfth the resistance at normal operating temperature, consequently when first connected to the circuit the current is for an instant much greater than the normal current. This excessive current is of sufficient duration to cause an instantaneous rise in candle-power, which is higher than the normal candle-power; this effect has been called overshooting.

Tungsten filaments as generally made today consist of an agglomeration of fine particles of metallic tungsten. These particles are sintered or welded together by raising the filaments to a very high temperature in a reducing atmosphere. This sintering is made as complete as the limitation of our knowledge of the art permits, and while great improvements have been made in this matter the best filaments are still more fragile than are carbon filaments. This fragility has been the greatest obstacle met with in the introduction of tungsten lamps, and in the beginning, when filaments were much more fragile than they are to-day, and when people had not learned the degree of care necessary in handling them, and when prices were very high, this weakness prevented many people from using the lamps. Now, filaments are much stronger, people have learned to handle the lamps carefully and prices are lower, so that the sales of tungsten lamps are increasing rapidly.

Flexible mountings for the interior structure of the lamps, which protect the filaments to a considerable degree, have been designed, and many lamps for railway car lighting and other special service are now being made, which have these flexible supports, to prevent breakage of the filaments in shipping and also in use.

The latest development which has been publicly announced is the drawn tungsten wire filament. This drawn wire has very great tensile strength, greater than steel, and can be drawn to any desired size. These filaments are very strong and are not injured by rough handling. In life and efficiency they are fully equal to pressed filaments.

Tungsten filaments when burning are quite soft and plastic and must be supported at points sufficiently near together to prevent the filaments sagging and touching each other or the glass. Spring supports are used in many lamps designed to prevent sagging and they do in fact keep the filaments nearly straight under all circumstances. These supports prevent the filaments being attracted over against the glass and being broken by static electricity which is a frequent cause of trouble with carbon lamps.

The variation of light from a filament due to the variation in current caused by the successive impulses of an alternating current depends upon the heat capacity of the filament, the heat radiating characteristic and the resistance characteristic. Tungsten has a specific gravity, about 10 times that of carbon and a specific heat one-fifth as great, so the heat capacity of a tungsten filament is about twice that of a carbon filament of the same dimensions. The heat radiating characteristic of tungsten is better than that of carbon because at a given temperature it radiates heat less rapidly than does carbon.

The resistance characteristic of tungsten is also more favorable than that of carbon for the retention of energy and heat as the current wave recedes. All these physical characteristics of tungsten are therefore better than those of carbon in respect to the retention of heat, and they all tend to make the flicker of tungsten lamps less than of carbon lamps of the same size filament.

The actual diameters of tungsten filaments, however, are much smaller than those of carbon filaments of the same candle-power lamps, and this more than offsets the advantages of the other characteristics, for the flickering of tungsten lamps is greater than that of carbon lamps of the same candle power, while it is much less for lamps with the same size filaments.

The flicker of a 25-watt tungsten lamp on a 60-cycle circuit may be observed by standing with your back to the lamp and moving a pencil rapidly back and forth, but I have been unable to observe this flicker by ordinary observation.

The flicker of a 40-watt tungsten lamp on a 60-cycle circuit is scarcely perceptible on a moving pencil.

LAMP TESTING

Lamp testing is an absolutely necessary adjunct to lamp making, and it is also a very necessary adjunct to proper lamp using. In order to determine the relative quality or value of different lamps, it is necessary to compare their lives at the same watts per candle-power or else to know the law of the relation of lives of lamps to their watts per candle-power, and I know of many cases in which inventors and investors have deceived themselves by judging the value of lamps when they did not know the rate of variation of life with efficiency, or the value of the time element in a test on a lamp.

From the results of experiments made over twenty years ago it was deduced that the lives of lamps at different candle-powers varied inversely as the 3.65 power of the candle-power. These experiments were made on lamps with untreated bamboo filaments. When treated carbon filaments came into use a great many experiments were made to determine whether or not this same exponent was true for them. The conclusion was that the same exponent should be used for both types.

Again when metal filament lamps became established the same question arose, and now comparisons have been made upon large numbers of lamps at different candle powers, each comparison being made between lamps of the same type, and the result of these comparisons indicates that the same exponent which is used for carbon filament lamps is also the proper one for lamps with metal filaments. In order to determine such a law it is necessary to make comparative tests upon a great many lamps, for it is impossible to get lamps so perfect that they each show the proper relative life to all the others. Averages must be used, and the law must be an empirical one. The exponent we have determined may simply indicate the relation between lamps of the usual degree of imperfection, but its persistence for so many years is remarkable, and we believe that it applies to all types and sizes of lamps which are well designed and well made.

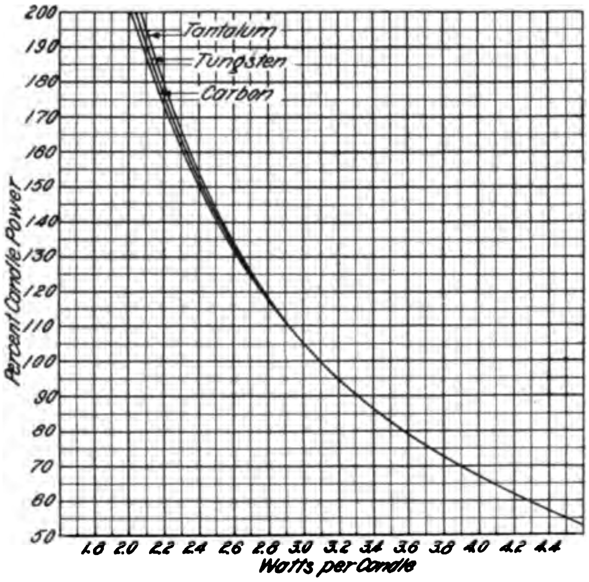

FIG. 6

From this relation between life and candle-power we can determine the relation between life and voltage, current, watts, or watts per candle-power. The relation between life and voltage or current depends upon the resistance characteristic of the filament and as different types of lamps have very different resistance characteristics, a different relation will be found for each type, and these relations are very little used.

The relation between life and watts or watts per candle-power is very nearly the same for all different types of lamps, because the relation of candle-power and watts per candle-power is nearly the same for all types. But as it is not quite the same it is customary to refer all life relations to the candle-power curve of the lamp for we consider this relation the same for all kinds of lamps.

LIFE FACTORS OR PER CENT LIFE OF TUNGSTEN LAMPS AT VARIOUS WATTS PER C. P.

Watts per c.p.	0	1	2	3	4	5	6	7	8	9
0.1	—	—	—	—	—	—	—	—	—	—
0.2	—	—	—	—	—	—	—	—	—	—
0.3	—	—	—	—	—	—	—	—	—	—
0.4	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.13	0.15
0.5	0.17	0.20	0.23	0.26	0.29	0.33	0.37	0.42	0.48	0.54
0.6	0.61	0.70	0.80	0.91	1.03	1.15	1.28	1.42	1.57	1.74
0.7	1.93	2.13	2.34	2.56	2.79	3.03	3.30	3.60	3.93	4.30
0.8	4.71	5.15	5.62	6.13	6.69	7.31	8.00	8.77	9.63	10.60
0.9	11.70	12.60	13.65	14.65	15.70	16.75	17.85	19.00	20.20	21.50
1.0	23.00	24.50	26.10	27.80	29.50	31.30	33.20	35.20	37.30	39.50
1.1	41.80	44.70	47.65	50.65	53.75	57.00	60.75	64.60	68.55	72.60
1.2	76.80	80.85	85.20	89.85	94.80	100.00	106.50	113.30	120.40	127.80
1.3	135.60	143.00	151.00	159.00	167.00	175.00	184.00	193.00	202.00	211.00
1.4	221.00	231.00	242.00	253.00	264.00	275.00	286.00	298.00	310.00	322.00
1.5	335.00	349.00	363.00	377.00	392.00	407.00	423.00	440.00	458.00	477.00
1.6	496.00	512.00	531.00	552.00	572.00	595.00	617.00	640.00	666.00	690.00
1.7	717.00	746.00	776.00	807.00	839.00	872.00	905.00	938.00	972.00	1007.0
1.8	1043.00	1081.00	1120.00	1160.00	1201.00	1243.00	1285.00	1327.00	1370.00	1413.00
1.9	1457.00	1510.00	1564.00	1619.00	1675.00	1734.00	1797.00	1864.00	1935.00	2010.00
2.0	2089.00	—	—	—	—	—	—	—	—	—

This table is made for use with metal filament lamps. It shows their lives between 0.4 and 2 watts per c-p. in percentage of their life at 1.25 watts per c-p. This table is very useful in interpreting life tests made at various watts per candle-power.

Metal-filament lamps last so long when tested at 1.25 watts per c-p. which is their normal rating, that it is customary to test them at higher efficiencies. Tests at one watt per c-p. are usually made; many tests at 0.75 watt per c-p. are made when quick results are desired, and daily factory tests, outside the life-test department, at double voltage, are very valuable when properly interpreted.

All tests comparing different types of lamps should be made on the basis of their spherical candle-powers, for the ratios between the spherical and horizontal candle-powers of lamps is sufficiently different to introduce very considerable errors if they are compared on the basis of their horizontal candle-powers, as is quite generally done.

Tungsten lamps of the ordinary 110-volt type have a spherical candle-power which is 0.785 of their horizontal candle-power, and when taking 1.25 watts per c-p. on the basis of their horizontal candle-power are taking 1.59 watts per c-p. on the basis of their spherical candle-power.

Many lamps for 63 volts are used for train lighting, and these lamps have a spherical candle-power which is 83 per cent of their horizontal candle-power. When taking 1.25 watts per c-p. on the usual horizontal rating they are taking 1.5 watts per c-p. on basis of their spherical candle-power. If life tested at 1.25 watts per c-p. horizontal, these lamps should have 335/477 or 0.7 as long life as a lamp of the 110-volt class having the same diameter filaments and also tested at 1.25 watts per c-p.

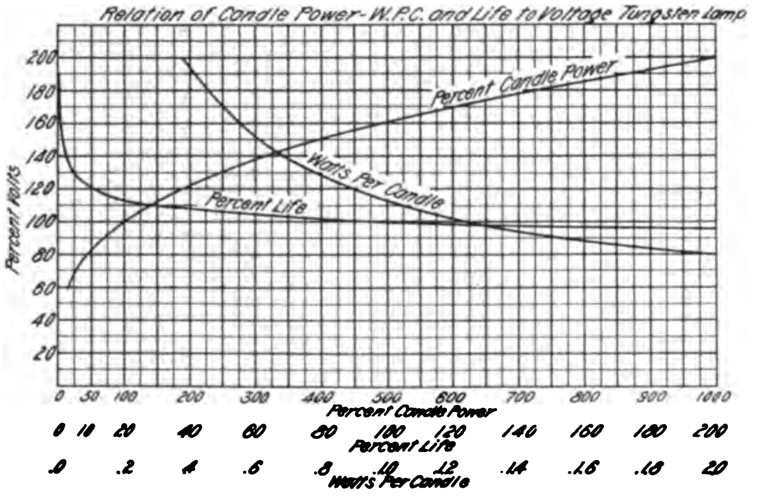

FIG. 7.

These lamps are tested at 1.25 watts per c-p. horizontal, and appear inferior to similar lamps of standard voltage, thereby suffering from an improper comparison.

The relation between horizontal and spherical candle-power depends upon the arrangement of the filaments in the bulb. As tungsten lamps generally have a number of simple loop filaments arranged in series, the relation will depend upon the height and spread of the filaments; the number of filaments in a bulb does not affect it.

DISCUSSION ON "METAL FILAMENT LAMPS", NEW YORK, MAY 17, 1910.

Clayton H. Sharp: I would refer for a moment to the importance of the tungsten lamp in street lighting. At the present time it would seem that our older illuminants for street lighting are on the decline. The arc lamp, as we have it, is being superseded by the more powerful arc lamps which have more recently been produced. The series incandescent lamp with the carbon filament, a lamp which never was very satisfactory for its purpose, has been most certainly pushed aside by the tungsten lamp. Not only this, but the advent of the tungsten lamp with its high efficiency and long life and favorable color has enabled the electrical engineer to go into fields of street lighting which previously have been practically closed to him, and which have been the exclusive domain of other less convenient and less satisfactory illuminants. I wish to point out further that there remains now the next stage, which is to provide means for utilizing more efficiently and satisfactorily the flux of light which the tungsten lamp produces in order to extend its usefulness in the range of street lighting still further. Such plans have been under consideration, and I recently had the pleasure of presenting to the Illuminating Engineering Society the details of a form of reflector by which the light which under ordinary circumstances is wasted by being thrown to the heavens, or thrown to the sides of the streets where it is not wanted, is directed into the dark portions of the street, midway between lamps, where such additional illumination is most desired. Along these lines I think the next step in progress is to be made.

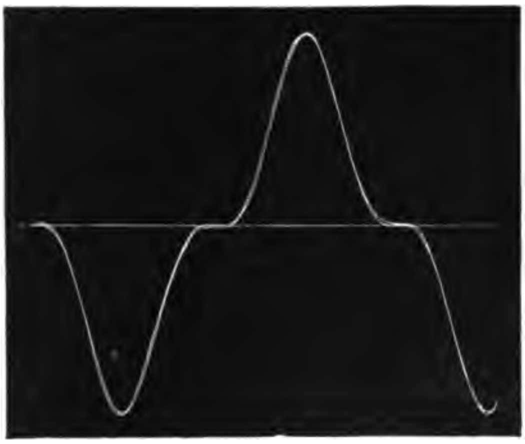

FIG. 1

I wish to refer also to another feature of the tungsten lamp which is intimately connected with the over-shooting of current at the moment the circuit is closed, due to the large positive temperature coefficient. Another thing results from this, which is perhaps of academic interest only and that is that the change in resistance of the filament during a cycle of alternating current necessarily lags somewhat behind the change in electromotive force, on account of the thermal capacity of the filament. Since the resistance of the filament lags behind the e.m.f., the current in it must lead the e.m.f. by a certain small amount and the lamp is not strictly non-inductive, but behaves as if it possessed a certain electrostatic capacity. In an attempt to demonstrate this effect, an e.m.f. having an extremely peaked wave was built up using the harmonic synthesis set of the Electrical Testing Laboratories. This wave form was selected so that the effect might be exaggerated as much as possible. Wavemeter curves were taken of the e.m.f. and of the current in a 25-watt 110-volt tungsten lamp with a frequency of 25 cycles per second. This frequency was chosen as being as likely as any to give a maximum effect. Too high a frequency would not permit the filament to cool enough during the zero portion of the wave, whereas, if the frequency were too low, the rate of change of e.m.f. on the lamp would be too slow to enable the effect to be seen. The curves of current and electromotive force are shown in Fig. 1, and the phase angle between them, though small, can be clearly appreciated. In order to make the difference more effective, the tungsten lamp and the carbon lamp were connected as the two arms of a Wheatstone bridge, while the wavemeter was used to determine the wave form of the electromotive force across the diagonal of the bridge. This gave a wave which is shown in Fig. 2.

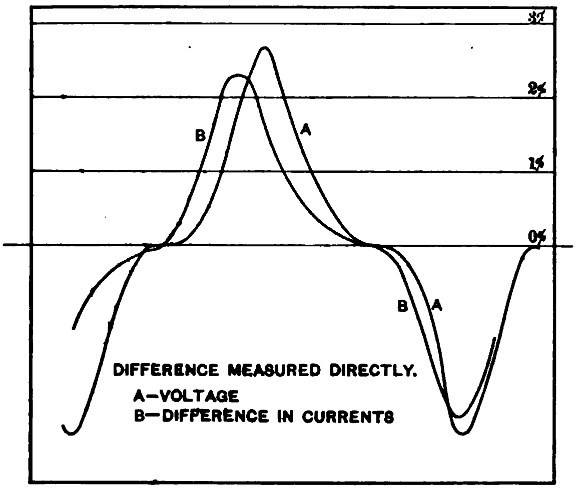

Fig. 2

The resistance variation of the tungsten lamp during the cycle was measured, and the minimum value of resistance was found to be about 10 per cent less than the maximum value. The power factor as roughly calculated was found to be 0.99975.

John B. Taylor: Dr. Sharp has just been enlarging on what he calls a feature of merely technical interest, and that is, a slight improvement in power factor due to the substitution of tungsten lamps for carbon lamps.

I think there is a much more practical point directly connected with this matter of positive temperature resistance coefficient, in the fact that the lamp cold takes a much larger current than when in normal service. Resistance curve, Fig. 3, of Mr. Howells paper, shows a cold resistance of 50 ohms, and a hot resistance of 650 ohms, or a little more than thirteen times greater. An oscillograph actually shows a peak value of current about eight times the normal. This difference is due partly to the fact that the lamp has risen slightly in temperature before maximum deflection of the oscillograph, but mainly to reactance and resistance in the circuit. In practice the initial current may be five to eight times the normal value. Usually this large rush of current is not important, but imagine the case of a general shut down on a large interconnected Edison system. Even with carbon lamps there is difficulty in getting under way again, for the reason that all the different substations cannot be connected at the same moment, and the ones that come in first get more load than they can carry. This difficulty with carbon lamps, will be more serious with tungsten lamps. In an isolated plant, if the main breaker opens and it is attempted to throw in the load again, at this one switch, instead of breaking up the system at feeder switches, the generator will be momentarily overloaded five to eight times, depending on line drop and other matters. This may not be a serious matter with some machines, but it cannot be dismissed without investigation. Fuses are not liable to blow on account of the short interval of time during which the current has the large value, but circuit breakers with less time lag may be tripped, and the excess load may cause mechanical troubles or flashing at the commutator. These points deserve consideration.

Another point I want to bring out is more academic. Mr. Howell says: " This excessive current is of sufficient duration to cause an instantaneous rise in candle-power, which is higher than the normal candle-power; this effect has been called " overshooting ." I believe I am responsible for the term " overshooting " having used it two years ago when describing the effect in one of the technical periodicals* with photographic records demonstrating that it is a real " effect " and not a mental impression. The point I want to make is that the positive temperature resistance coefficient and excess current will not explain " overshooting " unless it can be shown that there is a time

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**Electrical World*, April 25, 1908 and May 16, 1908.

lag between temperature of a body and its electrical resistance. The temperature is going up very rapidly, perhaps 100,000 degrees cent. per second, but that is no reason why, merely because it is rising so fast, it should continue rising beyond the ultimate temperature determined when balance is reached between energy radiated and conducted away and energy supplied. The only thing I suggested, when I showed the photographic evidence of overshooting was that it might be some secondary action, possibly connected with gases absorbed by the filament, which before begin driven out might modify the resistance for a very brief time. I think the present tungsten lamps do not show the "overshooting" to the extent that the early ones did.

Farley Osgood: I think I may be pardoned if I bring up a point which is purely financial or commercial. The discussion so far has been confined entirely to the physical side of the lamp, and the various problems, theoretical and practical, pertaining to its improvement in efficiency, but there is another point which to my mind is equally important, especially to the users of the lamp, who are quite as much to be considered as the makers of the lamp. Of course, the manufacturers advocate the use of the highest efficiency lamps of the metalized filament type, but my experience is that it is still an open question as to whether or not the metalized filament lamp is an economical proposition for an operating company using a million lamps or more per year. The product of metalized filament lamps of the not most perfect type, namely, all lamps except tungsten, is still so uncertain that the economical average life of such lamps does not from a saving standpoint warrant their introduction on a free renewal basis by operating companies. Most of the operating companies in the country have free renewals of the older type of carbon lamps among all consumers of electric current, and although the total average of metal filament lamps show such a life as to be equal to the carbon lamp, our investigation seems to show that such a result is brought about by the unusually long life of some of the lamps put under test. A few lamps will give extraordinarily long life, and a large proportion of lamps will give not so long a life in the life test, so that although the advocates of the use of this lamp, namely, the manufacturers, are able to show that these conditions are equal between carbon lamps and metalized filament lamps, the operating men are unable to realize it from a financial standpoint. If a greater portion of the lamps show shorter life, and the equal average life is occasioned by the abnormal continuance in service of a few lamps, the expense, from an operating company's standpoint, will increase greatly rather than remain the same. I think it is an open question whether the metalized filament multiple lamp should be used on a free renewal basis, unless the operating companies decide that it is desirable to spend a considerable additional sum for incandescent lamps for the sake of the various benefits which accrue to the consumer by the use of the metalized filament lamp.

In the street lighting service, the condition is almost entirely changed. The tungsten filament lamp can be safely said to average a life of 1500 hours, so that its use is equal to, or better than, the carbon series filament lamp; the renewals are less frequent per year, and the financial results, particularly on account of the lower current consumption, are beneficial to the operating company using tungsten lamps for series street lighting purposes. But I do not think these facts should be lost sight of in the consideration of a more modern or metalized filament type of lamp, and I do not think it amiss to bring out at this time some of the uncomfortable features of the metalized filament lamp as many of the consulting engineers of this Institute have before them for decision such problems for the companies which they represent.

William L. Nodell: I wish to add to the information which Mr. Howell gives concerning tungsten automobile headlight lamps. These are now made in candle-powers ranging from 10 to 25 and operate satisfactorily at the excellent efficiency of 0.8 to 1.0 watts per c.p. They are recommended to be used at 6 volts (3 cells of storage battery) though lamps suitable for other voltages are furnished.

Mr. Howell's paper may give the impression that the normal commercial rating of tungsten lamps is still 1.25 watts per c.p. This is no longer the case, the efficiency being better in lamps of 60 watts and higher, as may be seen from the table given herewith, showing the watts per candle-power and life obtained since the 3 voltage method of rating tungsten lamps has been established:

TUNGSTEN REGULAR MULTIPLE LAMPS FOR 100–125 VOLTS

Designation total watts	At top voltage			At middle voltage			At bottom voltage			
	Watts per c.p.	Nominal mean horizontal candle-power	Hours useful and total life	Watts per c.p.	Nominal mean horizontal candle-power	Hours useful and total life	Watts per c.p.	Nominal mean horizontal candle-power	Hours useful and total life	Horizontal c.p. multiplied by this reduction factor = spherical candle-power
25-watt	1.33	18.8	1000	1.39	17.4	1300	1.45	16.1	1700	0.78
40-watt small bulb	1.25	32.0	1000	1.30	29.9	1300	1.35	28.0	1700	0.77
40-watt large bulb	1.25	32.0	1000	1.30	29.9	1300	1.35	28.0	1700	0.77
60-watt	1.20	50.0	1000	1.25	46.5	1300	1.30	43.5	1700	0.78
100-watt	1.15	87.0	800	1.20	80.8	1000	1.25	75.2	1300	0.78
150-watt	1.15	130.3	800	1.20	121.1	1000	1.25	112.8	1300	0.78
250-watt	1.10	227.3	800	1.15	210.0	1000	1.20	195.0	1300	0.77

Figures furnished by the N. E. L. A.

The philosophy of the three voltage plan is that formerly applied only to gem lamps. Since May 1, 1910 this method of rating is applied to all incandescent lamps, tungsten, tantalum, gem and carbon. A lamp is no longer identified by candle-power and watts-per-candle power but is designated by watts; the efficiency at which it is to burn being determined by the selection of top, middle or bottom voltage. Exceptions to this general rule are miniature lamps and the 4 watt per c.p., series-burning railway lamp, which will be known, as heretofore, by their candle-power.

Referring again to Mr. Howell's paper regarding spring supports to prevent sagging of tungsten filaments; though molybdenum supports are being used for this purpose by some manufacturers, the alleged benefit to be derived is not sustained by the general experience of the majority of manufacturers who have, after exhaustive tests with every known method of support, finally adopted the copper hook at the tip end of the lamp as giving the greatest satisfaction, particularly in the 25-watt, 40-watt and 60-watt sizes. In the larger sizes with heavier filaments the spring support is still less necessary and in the 250-watt lamp practically all manufacturers employ a rigid support. For a time a center anchor was used in one make of 25-watt lamp but this is not now recommended, as the advantages expected are not borne out by experience.

I wish to call attention to a paper on " Tests of Tungsten Lamps ", by T. H. Amrine and A. Guell, giving the results of observations on three types of lamps, two of German manufacture, the third American. The results in comparison with the two foreign lamps are very much in favor of the home product.

John W. Howell: There is one characteristic of the tungsten and carbon lamps which I have omitted to mention in this paper, and that is their relative candle-powers per unit of surface. We are all familiar with the intense brightness of the tungsten lamp, as compared with the old carbon filament, and we know that it is necessary to shade the direct light of the filament from our eyes, either by shades or frosted bulbs. As a matter of figures, the tungsten filament at its normal efficiency is giving twice as much light per unit of surface as the carbon filament at its normal efficiency. If the two lamps are placed at the same efficiency, the conditions reverse; the carbon filament is then giving twice as much light per unit of surface as the tungsten filament. This is an indication of one of the reasons of the efficiency of the tungsten lamp, because when you see a carbon lamp giving twice as much light per unit of surface as the tungsten lamp, there is a strong physical indication that the temperature of the carbon lamp is much higher than the temperature of the tungsten lamp, and it is a fact, at the same efficiency, a carbon lamp is much hotter than a tungsten lamp. When you examine the same characteristic for a tantalum lamp it is interesting, because the normal efficiency of a tantalum lamp is two watts per candle, and at that efficiency the light per unit of surface is the same as the carbon lamp, at 3.1. This marked difference between tantalum and tungsten indicates one reason for the poorer efficiency of the tantalum lamp.

G. S. Merrill, M. D. Cooper, H. D. Blake (by letter): It is well known that tungsten filaments, due to their positive temperature coefficient take more current at the instant of starting than after they become heated. The engineering department of the National Electric Lamp Association recently conducted a series of experiments to determine whether this initial current rush has the effect of decreasing the life of the lamps. Three lots of tungsten sign lamps, 6 lamps in each lot, were placed on test—the first lot was burned continuously, the second lot was flashed 3 times per minute and the third lot was flashed 30 times per minute. It was found that there was a slight decrease in life with the lamps that were flashed, but that this decrease was so slight as to be practically negligible. The curve of Fig. 1, plotted between frequency of flashing and the per cent of normal total life, shows a decrease of about 6 per cent in life up to 35 flashes per minute. For higher frequencies the life rises toward normal value. This test, due to the small number of lamps used, is not, of course, absolute proof that the initial current rush may not have a greater effect in decreasing the life, but it indicates that the effect is not as great as might be supposed.

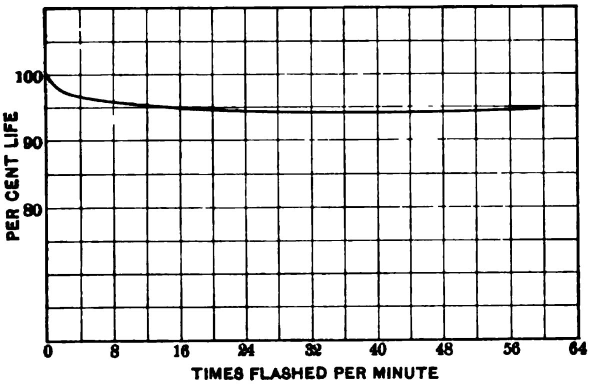


FIG. 1

That the above should be the effect becomes evident on consideration of the "cooling curves" given in Fig. 2. These curves show the per cent of cold resistance of tungsten lamps at various time intervals after the lamp has been turned off. If the lamp is allowed to cool completely before being again lighted, the initial current rush will be as severe as at the first lighting. If, however, it is turned on when the resistance is still considerably above cold value, the current will not rise to as high an initial value. For instance, if a sign lamp is flashed six times per minute (5 seconds on, 5 seconds off), it will be relighted when the resistance is still 2½ times the cold value, and as the hot resistance is about ten times the cold value, we would expect only about one-fourth as great a rush of current as when the lamp had fully cooled.

Flashing at very high frequencies would correspond to operation on alternating current, which would give the same life as when burned without interruptions.

Mr. Howell's mention of spring supports brings up the question of the adaptability of tungsten lamps to burning in a horizontal position. The complaint is sometimes made that tungsten lamps do not prove satisfactory when burned horizontally because the filaments sag.

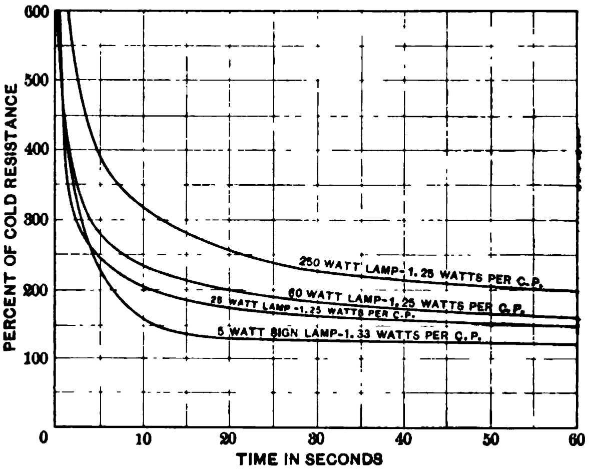


FIG. 2

The sagging filament in a horizontally burning lamp will conform closely to the catenary curve, for the filament is comparatively heavy and after continued heating will respond to the force of gravity nearly as well as a perfectly flexible string or chain.

The accompanying curves were derived on the assumption of this catenary curve. The equation of the catenary is:

$$y = \cosh x$$

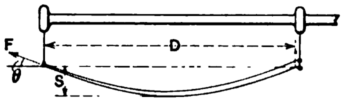


FIG. 3

and in this form the y intercept is 1. For a given distance, D, between supports, the sag will be

$$s = \cosh \frac{D}{2} - 1$$

or the per cent sag $= \frac{100}{D} S = \frac{100\,(\cosh \frac{D}{2} - 1)}{D}$ (2)

Fig. 3 shows in an exaggerated manner, the way in which a filament will droop and as there shown, D is only the distance between the ends of the freely sagging portion of the filament. Due to the rigid weld at the base, the whole filament will not sag freely, hence D will not be the whole of the distance between supports.

The slope of the curve will be

$$\frac{d\,y}{d\,x} = \sinh x$$

The angle θ, which the filament makes with the horizontal through the end of the freely sagging portion will be given by the equation,

$$\tan \theta = \frac{d\,y}{d\,x} = \sinh \frac{D}{2}$$

If the weight of the filament is W, the supporting force F will be given by

$$F = \frac{W}{\sin \theta}$$

from which

$$\frac{F}{W} = \frac{1}{\sin \tan^{-1} \cosh \frac{D}{2}} \qquad (3)$$

Using the parametric equations (2) and (3), curve A of Fig. 4 was plotted, showing the "stress ratio", F/W, for any given sag.

When a lamp hangs vertically, the maximum force is equal to the weight of the filament, hence the above ratio is the same as the ratio between the filament stress when the lamp burns horizontally and that when it burns vertically.

To investigate the effect of contraction on cooling, it is necessary to get some relation between length of filament and corresponding sag.

The total length L is given by the equation

$$L = 2\int_{0}^{\frac{D}{2}} \sqrt{1+\frac{d\,y^2}{d\,x}}\;d\,x$$

$$= 2\int_{0}^{\frac{D}{2}} \sqrt{1+\sinh^2 x}\quad d\,x$$

$$L = 2\sinh\frac{D}{2} \tag{4}$$

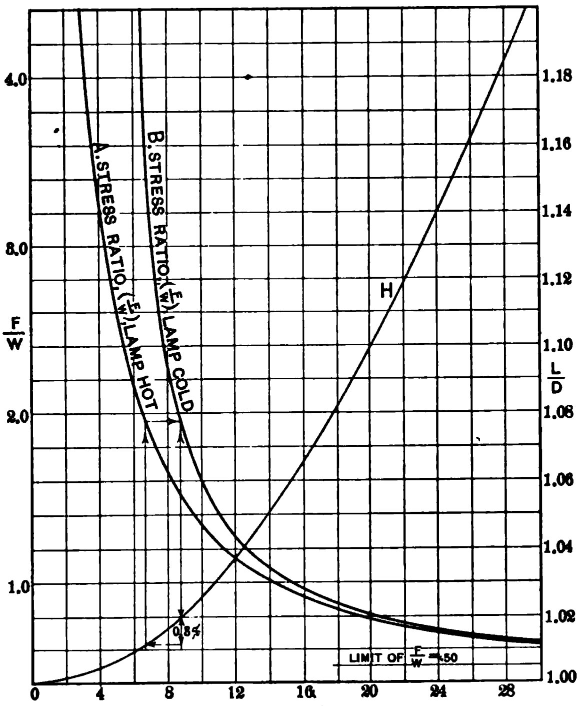


FIG. 4

Using this equation in connection with (2), curve H was plotted showing the per cent sag for a given value of L, expressed as a percentage of D.

A point on curve A shows the stress in a horizontally burning filament for a given sag when the lamp is burning. At the same point, the ordinate or curve B shows to what extent this stress is increased by the shrinkage of the filament on turning off the lamp. In deriving this second curve a shrinkage of 0.8 per cent was used, as determined by experiment. Curve B was derived from A as follows: For example, at 8.8 per cent, sag L is 102 per cent of D. On turning off the lamp, L decreases 0.8 per cent, hence the sag will be reduced to 6.8 per cent, corresponding to a stress ratio of 1.90, which is plotted over the " hot sag " of 8.8 per cent.

The curves show that a certain amount of sag is necessary if excessive filament stresses are to be avoided. If a lamp were so designed that when burning horizontally the filament would sag but 7 per cent, the stress would be 1.85 times as great as when burning vertically, and when turned off, the stress ratio would rise to 3.0.

The effect of burning a lamp is to cause the filament to disintegrate gradually. This disintegration, moreover, is not absolutely uniform, but is liable to localize at any weak points on the filament, if such there are. As the lamp continues to burn, the weak spots disintegrate more and more rapidly, till they can no longer withstand the imposed mechanical stress and a burnout results. It is therefore apparent that, although the filament as a whole could withstand a stress many times greater than its weight, yet, due to its non-uniform disintegration, an early burnout will be the inevitable result of insufficient sag and consequent high stress ratio.

A number of lamps, of the 25, 40 and 60-watt sizes and of the most recent design, showed from 10 to 15 per cent sag after they had burned for some time. The curves show that for this range of sag, the filament stress ratio, even when cold, will not rise above 1.60.

The curves cannot be rigorously applied to lamps larger than the 100 watt, for in these the filaments are larger and stiffer and do not sag freely.

The investigation of the flickering of incandescent lamps on alternating current can be separated into two divisions; first, the determination of the effect on the cyclic variation in candle-power produced by varying the size, length and material of the filament; and second, the determination of the relations between cyclic variation in candle-power, intensity of illumination, and " critical frequency " (or the frequency at which the sensation of flicker just disappears).

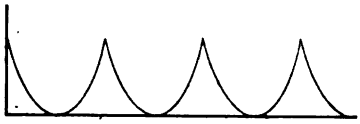
We have recently conducted some experimental work on the second division of the subject—the relation between cyclic candle power variation, illumination intensity and critical frequency. We found that for a cyclic variation M, equal to $\frac{\text{variation in c.p.}}{\text{max. c.p.}}$, and an illumination I, in foot candles, the critical flicker frequency f, in cycles per second (twice the current frequency) is given by the relation

$$f = 43\,(I\,M)^{0.13}$$

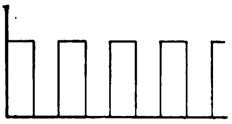
The constants in this equation were derived from five sets of data taken by two different observers, and the average deviation from the mean is about 7.8 per cent for each constant.

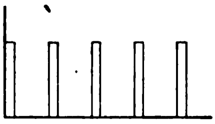
The cyclic variation in illumination was produced by a vane rotating at variable speed in a beam of light. In front of the vane was an opaque screen with a hole in it, the hole being covered with a ground glass diffusing plate. By using vanes of different sizes, we obtained different ratios of variable to maximum illumination. The flicker was viewed on the test plate of an illuminometer placed eight inches from the ground glass. Simultaneous readings were taken of the illumination and of the speed of the rotating vane at which the flicker sensation disappeared.

The rotating vane gives a cyclic variation in illumination about like the following curves:



Experiments show that the cyclic variation in candle-power of a lamp on alternating current very closely approximates a sine wave raised up above the axis. Dr. Kennelly conducted some experimental work on flicker using cyclic light waves of the following shapes, and his results tend to show that the critical frequency is a function only of the maximum and minimum illumination, and is not affected by wave shape. His equations when put in the form expressed above, agree closely with ours. His results were published in the 1907 Proceedings of the National Electric Light Association.





The question of flicker comes up most often in connection with the operation of metal filament lamps on 25 cycle current. Letting f in the above equation be 50 (the flicker frequency corresponding to a current frequency of 25 cycles) there results

$$IM = 3.18$$

The table below is computed from this equation and shows the maximum permissible cyclic variation in candle-power allowable with various intensities of illumination. If in any case the variation is greater than that given in the table, a flicker will be perceptible. With an illumination of less than about 3 foot candles, flicker will not be discernible, no matter how great the cyclic variation.

Intentisy of illumination I	Maximum allowable cyclic variation on 25-cycle current M
10	31.8%
8	49.8
6	53.0
5	63.6
4	79.5
3.18	100.0

We thoroughly agree with Mr. Howell in his statement that lamp testing is absolutely necessary to lamp making and also a very necessary adjunct to proper lamp using, but one should not understand from Mr. Howell's remarks that the necessity of testing in any case extends beyond the manufacturers or other thoroughly equipped lamp testing bureaus. Unless lamps are tested under the most rigid conditions the results are worse than useless and this applies with particular force to tests run at higher than normal efficiencies in order to shorten the time of testing. In such " forced " testing the effects of errors in test voltage are multiplied many times in reducing the results to normal performance and if the forcing is carried to an excessive point the extremely high temperature produced may create abnormal conditions which tend to make the lamps appear better or worse than tests at actual rated efficiencies would have indicated. Do not understand for a moment that we wish to undervalue the importance of forced testing, for when conducted under proper conditions and with proper knowledge of the limitations and errors to which it is subject, the forced test forms a very valuable means of rapidly attaining comparative results and has proved of inestimable service to the manufacturers. The Engineering Department of the National Electric Lamp Association has been devoting a great deal of study to the forced testing of metallic filament lamps, principally because the extremely long life attained at normal efficiencies served to severely tax the testing capacity and because urgent demand was being continually made by the factories for quicker test results. In spite of the fact that this problem has been before the engineers of the department for some time, no correction figures have yet been decided upon which can be regarded as final. Since Mr. Howell has brought the subject before you and as some may endeavor to proceed with forced tests upon the figures he has given, he will give some data in connection with this matter.

The earlier attempts to secure a correction figure for forced tests were based upon the average life of numerous lamps, run at various efficiencies. Tests conducted on such lines were not fruitful of results of the accuracy it was desired to attain. A study of the results of such tests, and previous experience with performance of the older and better known carbon filaments led to the following conclusions.

Steinmetz* has stated that "tungsten filaments do not ordinarily fail by evaporation as is the case with carbon, but by melting at some weak spot;" and also that "blackening of tungsten lamps is not gradual, as with carbon, but occurs simultaneously with impaired vacuum and appears rapidly." Our experience would indicate that there is a certain slight amount of normal blackening of tungsten lamps. The fact that this blackening deposit is found to consist largely of tungsten, and that the current after the initial rise tends to decrease gradually leads us to believe that the filament actually is vaporized to a limited extent.

A perfect filament would have a perfectly uniform temperature throughout practically its entire length. Near the supporting wires, the cooling effect due to these supports, would demand consideration. This filament could be conceived to be disintegrating at a uniform rate throughout its entire length except near the supports, with an ultimate result somewhat as shown in Fig. 5, which represents in an exaggerated way a short length of filament.

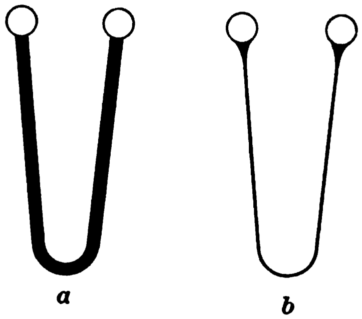


FIG. 5

The candle-power of such a filament when burned at a constant normal voltage would probably show a slight initial rise due to changes in the physical characteristics of the filament material and to changes in the condition of the residual gases in the bulb (which of course are at extremely low pressure). After an initial rise the candle-power would drop gradually at a diminishing rate, until the radiation within the limits of the visible spectrum had become incapable of producing the sensation of light. During this period the value of the current flowing through the filament would have changed in a somewhat similar manner to the luminous radiation, but even after the filament had ceased to emit visible radiation the current would still flow and the filament would never burn out.

The decrease in candle-power would be due essentially to two things:

1. The temperature would decrease as the filament material evaporated and the diameter decreased. Neglecting possible changes in physical characteristics after the initial changes already noted, the energy expended in the filament would decrease as the square of the diameter of cross section. Obviously the surface of the filament would decrease directly as the diameter, so that as the filament evaporated the energy expended

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* "Radiation, Light and Illumination" pp. 80, 81.

therein would decrease more rapidly than the radiating surface and the temperature would decrease.

2. The total radiating surface would be decreased. As a third, though secondary effect blackening of the bulb by condensation of evaporated filament material upon the interior surface would cause a decrease in candle-power of the lamp as a whole.

Such would be the performance of a filament without defect. In actual filaments defects exist and the magnitude of the defects is a variable quantity which follows to some extent the laws of probability for a given lot of lamps. For example, out of a large number of lamps started on life test under the same conditions, a few would probably fail rather early in life due to large defects or imperfections in the filament itself. As the burning continues the " mortality " rate would increase as the average size defects would begin to cause failures. Then with the number of lamps burning considerably reduced, the rate of failure would decrease, for there would then be left only lamps having defects of less than average size. Finally there would be left only a few lamps which would give a very abnormal life, because they might happen to be particularly free from imperfections in structure. During this period the candle-power would have been undergoing the general changes previously noted which may be illustrated by the actual performance curve obtained from a test of 115, 16-c.p., 3.5-watts per c.p. carbon lamps as shown in Fig. 6. The average total life to burnout of the lamps represented on this test was several times the so-called " useful life ", to 80 per cent of initial candle-power. The average candle-power corresponding to the average life gives us a means of judging the magnitude of physical imperfections which exist in the filament. On this basis it appears that at the present the carbon filament is more highly developed than

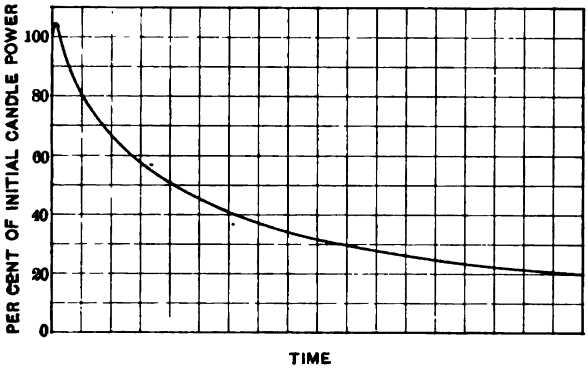

FIG. 6

the tungsten filament, inasmuch as the carbon lamps reach a relatively lower candle-power value before failure than the tungsten lamps. This shows that there is still room for enormous improvement in the tungsten filament and that there are possibilities for obtaining still higher efficiencies than those at present attainable.

From the above considerations, it was decided that the correction figure to be applied to the life of metal filament lamps burning at other than normal efficiency could be determined more accurately from the time required by lamps operating at various efficiencies to reach the same percentages of initial candle-power or of initial current than from the actual time to failure or burnout. This should be true whether the changes in candle-power and current are due entirely to disintegration of the filament or whether they result from some other physical change which takes place during life.

It is manifestly impossible to obtain results on a single individual lamp at more than one efficiency, consequently for the purpose of arriving at the proper figure a special lot of lamps were made.

The following condensed report of the test on these lamps will be of interest in indicating what precautions have been taken in order to arrive at a proper correction factor for tungsten filament lamps.

Fifty 40-watt, 109-volt lamps were formed and assembled with the greatest possible care, in order to produce a lot of lamps which should be similar in all characteristic qualities. The work was started with over 1000 filaments from which 200 of the most perfect were selected after several rigid and careful inspections. Upon measuring the lamps made from these carefully prepared and selected filaments at 1.25 watts per c.p. the voltage with two exceptions was found to fall between 108.8 and 109.2 volts inclusive, a range of but 0.4 volts.* Aside from indicating a close selection, this uniform rating simplified to a large extent some of the work of testing, and has, we believe, eliminated the possible source of several small errors.

The test was divided into five sets of ten lamps, which were burned on 60-cycle alternating current at efficiencies of 1.25, 0.97, 0.85, 0.75 and 0.67 watts per mean horizontal candle

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* If lamps can be made by commercial processes and in an ordinary factory which come within 0.2 of one per cent of the rating for which they were designed, it might be possible, by using more refined methods of manufacture, to produce a primary standard of light with tungsten filament.

An ordinary commercial lamp would not, of course, serve the purpose. It might, however, be possible to make a single loop lamp under rigid specifications as to size, length, and processes of manufacture of filament, dimensions of leading in wires, size and shape of bulb, etc., that could be exactly reproduced at any time. Such a lamp could be not only a primary standard, but an absolute standard as well, for it is well within the range of possibility to compute as well as measure the luminous intensity of such a source.

power respectively. According to the best correction figures available at the time the test was started each set was measured at approximately equivalent intervals. Readings were made with a contrast Lummer-Brodhun screen at rated voltage and

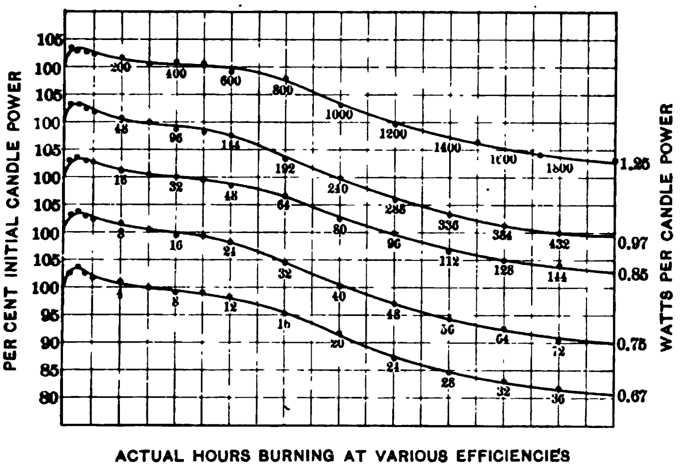

FIG. 7

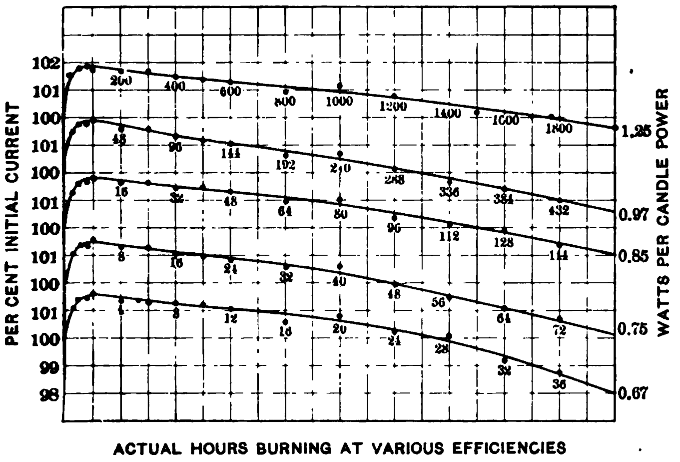

FIG. 8

all currents were checked in each instance with accurately calibrated standard laboratory meters.

Average candle-power curves for the various efficiencies, together with the actual hours burning, are plotted in Fig. 7, and average current curves for the same lamps are plotted in Fig. 8. We are able to show these only out to 2000 equivalent hours, at 1.25 watts per c.p., because the test is still in progress with over 80 per cent of the lamps still burning.

We wish to call attention to the peculiar shape of the candle power curves of Fig. 7. Their peculiarity is the unexpected maintenance of candle-power during the interval corresponding to 300 to 700 hours on the 1.25 watts per c.p. curve.

We are at a loss for an explanation of this peculiar curve form but the accuracy of the timing and the photometry of the test leads us to believe that the results are correct.

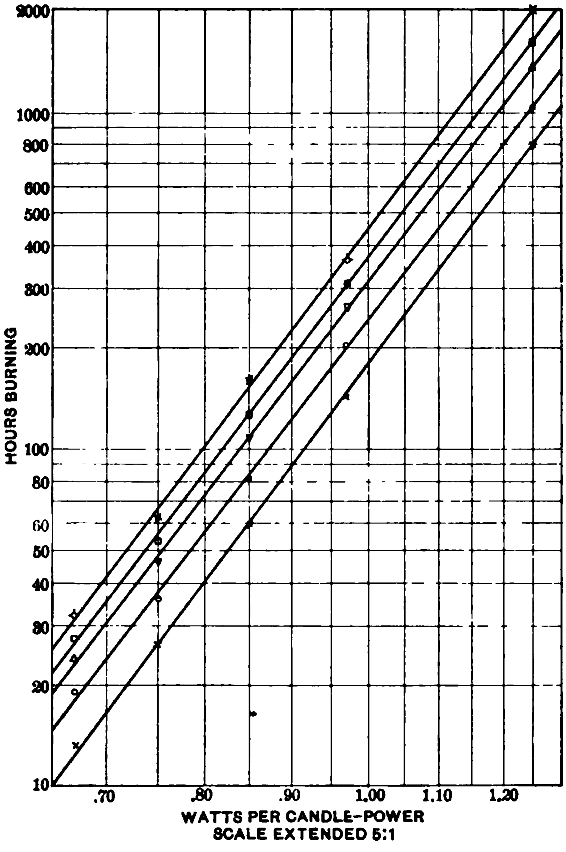

FIG. 9

From previous experience we assumed that the equation between life and efficiency is of parabolic form:

$$\frac{\text{Life}_1}{\text{Life}_2} = \left(\frac{\text{Watts per c.p.}_1}{\text{Watts per c.p.}_2}\right)^b$$

the object of this test being to determine the exponent b. In Fig. 9 and Fig. 10, we have shown several logarithmic graphs between watts per c.p. and hours life obtained by comparing the interval of time required to reach various percentages of the initial values of candle-power and current. The results show that the life equations for tungsten lamps conform very rigidly to a pure parabolic law over the range investigated. The candle-power curves and the current curves appear to give slightly different values of exponent *b*. We believe that the exponent derived from the candle-power curves is the more accurate, where total life values are to be determined. In Fig. 11 we have shown curves between the watt per candle-power life exponent, *b*, and hours burning at normal efficiency (1.25 watts per c.p.).

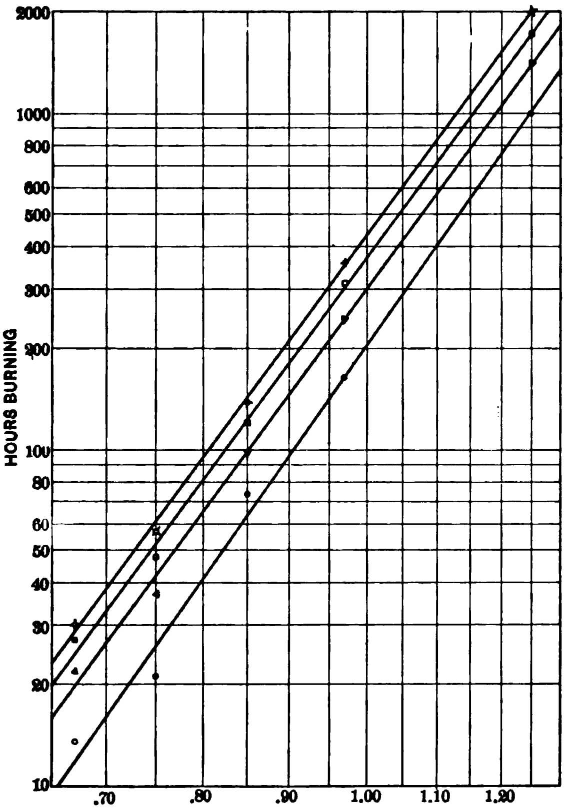

FIG. 10

The correction figure for tungsten filament lamps is still in some doubt, which may be evident from the results of the test previously described, and also from the fact that in his paper Mr. Howell seems to have used two different values for the exponent of the life-efficiency equation. Mr. Howell states that the life was found to vary universally as the — 3.65 power of the candle-power. This exponent was derived from experiments on lamps with untreated bamboo filaments, but he says it was later found to hold for treated carbon and metal filament lamps. If the candle-power is taken to vary as the 1.75 power of the efficiency, as careful work would indicate, the exponent connecting the life and efficiency would be 6.4. From the life factors in the table given by Mr. Howell the value of the exponent through the normal working range is found to vary from 6.7 to 6.8.

In connection with the work we have done on forced testing of tungsten filament lamps, we might mention that a similar line of work is now being carried out on the tantalum filament lamps on both alternating current and direct current for a similar purpose. Here interesting developments are expected on the alternating current, as from previous tests there is much to indicate that below a certain temperature the life is not affected greatly by the efficiency, being, we believe, more dependent upon the effect of frequency. However that may be, we will undoubtedly be in a position to throw considerable light upon the matter in the near future.

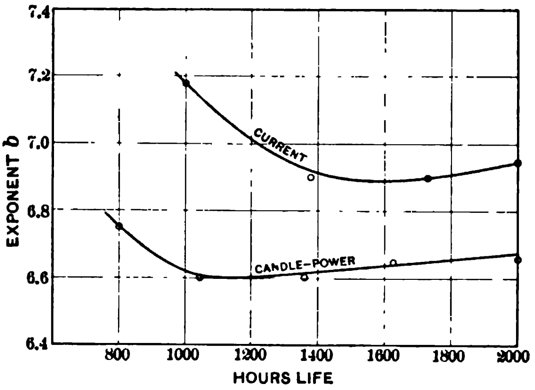

FIG. 11

As to the relation between life and watts or watts per candle power being very nearly the same for all different lamps we cannot agree. The exponent by which we express the relation between life and efficiency varies from 6.65 for the tungsten filament lamps to about 5.43 for untreated carbon. The first mentioned figure may be changed somewhat in view of later developments, but we find that the treated carbon, gem, and tantalum exponents, in so far as we have been able to determine them, are scattered between these limits.

In the table below are given our determinations of the exponents of the following equations, in which L = hours life, C = candle-power, W = total watts, e = watts per candle, V = voltage, I = current and R = resistance.

$$\frac{L_1}{L_2} = \left(\frac{C_2}{C_1}\right)^a = \left(\frac{e_1}{e_2}\right)^b \qquad \frac{C_1}{C_2} = \left(\frac{e_2}{e_1}\right)^h = \left(\frac{V_1}{V_2}\right)^k$$

$$\frac{W_1}{W_2} = \left(\frac{V_1}{V_2}\right)^n \quad \frac{V_1}{V_2} = \left(\frac{I_1}{I_2}\right)^x \quad \frac{R_1}{R_2} = \left(\frac{V_1}{V_2}\right)^q$$

Exponent	a	b	h	k	n	x	q
Tungsten	3.80	6.65	1.75	3.68	1.59	1.718	0.418
Tantalum	†*3.73	†*6.30	1.69	4.20	1.72	1.382	0.276
Gem	*3.7	*5.8	1.6	4.9	1.8	1.25	0.20
Treated carbon	3.65	5.83	1.59	5.55	2.07	0.930	-0.075
Untreated carbon	*3.62	*5.43	1.50	6.89	2.31	0.763	-0.310

(*) Computed from the dotted curve of Fig. 12.
(†) Direct current.

The values given for h, k, n, x, and q are correct within the limits of accuracy of photometers and electrical instruments, therefore are correct within 1 per cent. The values of a and b, however are subject to much greater error, probably at least 5 per cent.

In applying correction figures to forced tests, we have found the exponent b to be the most convenient one to use, hence we call this the *fundamental* life exponent. The exponents k and x are also *fundamental* exponents, k being determined from photometric relations, and x from electrical relations. Given these three fundamental exponents, it is possible to determine the relation between *any* two of the variables, life, candle-power, watts, watts per candle, volts, current and resistance.

A curve plotted between x and k brings out some interesting considerations. As shown in Fig. 12, the points for all the lamps, except the gem fall on a very smooth curve. This is rather surprising, in view of the fact that the metal filaments exhibit more selective radiation than those made from carbon. The point shown in Fig. 12 for " old treated carbon " was obtained from performance curves of some treated carbon lamps which had burned for several thousand hours. The effect of this burning was to evaporate part of the graphitic layer deposited on the filaments in the treating process, or to partially " untreat " them. As could be anticipated, the point representing these lamps falls between those for treated and untreated lamps.

By using the curve of Fig. 12 it is possible to determine the relation between any two of the variables, but the life (excepting for lamps of the gem class) when either of the fundamental exponents, k and x, is known. The exponent x of the voltage-current equation is obviously the easier of these two to determine, as it can be obtained from voltage and current measurements of a lamp.

It is within the range of possibilities that future experiments may give a smooth curve between x and one of the life exponents.

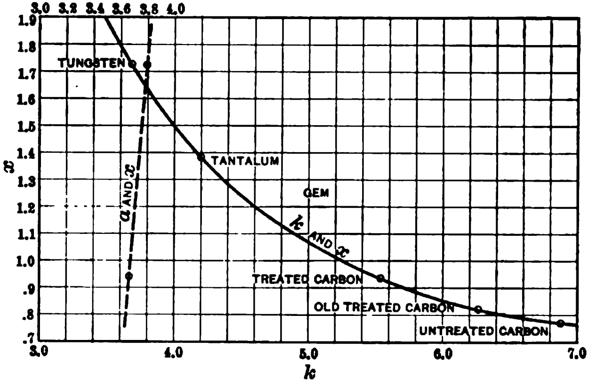

Fig. 12

If such proves to be the case, it will be possible to predetermine the *entire* performance of a lamp from its volt-ampere curve. The dotted curve of Fig. 12 is plotted between a and x. As only two points on this curve are known, it is drawn in as a straight line. Future developments may show that it has a slight curvature, but in the meantime it will serve as a good basis for calculations.

A paper presented at the 249th meeting of the American Institute of Electrical Engineers, New York, May 17, 1910.

DUCTILE TUNGSTEN

BY W. D. COOLIDGE

When work was first started on the problem of producing a ductile form of tungsten, the metal looked very uncompromising. It was so hard that it could not be filed without detriment to the file, and was, at ordinary temperatures, very brittle.

It was of course known from the start that, at the operating temperature of a tungsten lamp, the metal was soft; but this fact seemed unavailing, for there was no tool that could be used for working the metal at such temperatures, and materials from which such tools could be made were lacking.

To a man ignorant of our success, the problem would certainly look more hopeless to-day than it did then. For since that time millions of tungsten filaments have been produced from all available tungsten ores, by widely differing methods, and by different groups of men. And each manufacturer has been fully alive to the fact that he must strive for the highest attainable purity. Yet all of the filaments made have been brittle. They are elastic and flexible as spun glass, but, like the latter, are incapable of taking the slightest permanent set.

Not only was there nothing in the past history of tungsten to encourage us, but, in the natural periodic system of the elements, the metal belonged to a family no member of which had been brought into a ductile state. The other members of the family are chromium, molybdenum, and uranium, elements which had always been characterized by hardness and brittleness. A study of the periodic system shows that, in a general way, elements of the same family do resemble one another in point of ductility, as well as in their other physical and chemical properties. For example, copper, silver, and gold are all in one family and are all very ductile.

Little encouragement could be drawn from the achievement of Dr. Von Bolton with tantalum, because of the fact that this element is in a different family. And the two families differ markedly in both physical and chemical characteristics.

The only arguments on which we could base the hope that tungsten could be produced in a ductile state, were founded on the effect of mechanical working and of chemical purity on the ductility of some of the other unrelated elements. But even this hope seemed of doubtful fulfilment, owing to the apparently insuperable difficulties of mechanically working this particular material.

Mechanical working increases the ductility of some metals. Cast zinc, for example, undergoes a marked increase in ductility when subjected to ordinary wire drawing processes. Some special steels, also, which, as cast, are coarsely crystalline, have to be handled very carefully until they have undergone a certain amount of mechanical reduction, while from this point on they are very ductile.

Chemical purity also, is, in general, conducive to ductility and in some instances, slight amounts of impurity produce a marked effect. Some striking examples of this are the following:

Copper is very sensitive to the presence of bismuth, even 0.02 per cent of the latter rendering it brittle when hot, and 0.05 per cent brittle when cold. Sulphur is also a harmful impurity, and copper containing 0.25 per cent of it is only moderately malleable.

Gold is rendered brittle by 0.05 per cent of lead, bismuth, or tin, and is no longer malleable when it contains as little as 0.0003 per cent of antimony.

Nickel is rendered unsuitable for rolling by the presence of 0.1 per cent of either arsenic or sulphur.

Platinum is made hard and brittle by 0.03 per cent of silicon. Its ductility is also considerably lessened by the presence of small quantities of the other platinum metals.

Tin is brittle when cast at a temperature either too high or too low.

The analogy with iron is in some ways more interesting than the above, for both tungsten and iron take up carbon, and may be greatly hardened thereby. And iron is extremely sensitive to traces of sulphur, phosphorus, and arsenic.

Our early experiments in mechanically working tungsten led to work on tungsten alloys, and on suspensions of tungsten powder in metals in which there was little or no alloying. One of the most interesting suspending media proved to be an alloy of cadmium, bismuth, and mercury. This amalgam is very pliable. For our purpose it has several other important characteristics. Upon heating to about 140 deg. cent., it becomes soft and plastic, and from this point it retains its plasticity over a considerable temperature interval. While the amalgam is in this state, it is possible to incorporate with it considerable quantities of many foreign substances, such as tungsten, in powdered form. (Such a mixture, containing about 30 per cent by weight of tungsten was exhibited at the meeting.) At room temperature, it is about as hard as lead, but, at a temperature of about 110 deg. cent., it can be readily pressed through a diamond die, and comes out as a silvery looking strong pliable wire. If this wire could be freed from everything but tungsten and still preserve its present strength and ductility, it would solve the tungsten filament problem. But such is not the case. Upon heating it by the passage of current, in a non-oxidizing atmosphere, the mercury first distils out then the cadmium and then the bismuth. Some shrinkage takes place as the foreign metals leave the filament, and the remainder is brought about by raising the temperature to white heat. Most of the ductility of the wire leaves with the mercury, and the remainder goes with the cadmium. This finished filament has been used in thousands of lamps, but these all lack ductility.

The above experience was duplicated when we tried copper as a binding agent for the tungsten, and again when nickel was used for this purpose. In each case there was a ductile stage in which the filament could be bent and otherwise manipulated, but not a trace of this ductility remained after the removal of the foreign element.

The above experiments gave us several new and valuable methods for producing tungsten filaments of the usual quality. But in so far as our ultimate goal, a ductile tungsten filament, was concerned, they were not promising. They were, however, in one respect, instructive, for in the case of all of the above and with many other foreign additions, we got a complete removal of the foreign elements, at least so far as our analytical tests showed, with the final high temperature treatment of the filament. This seemed to indicate that we either did not need to worry about contamination from such elements, or else that brittleness was due to traces of impurity so minute as to escape detection by our analytical methods.

To return now to the mechanical working of pure tungsten. This work received a great impetus by our discovery that an ordinary, dense, well sintered, tungsten filament can be easily bent and put into various forms, and otherwise manipulated at temperatures well below redness, and even below the temperature at which appreciable oxidation takes place. This helped us in two ways. First, it reduced the temperature at which mechanical working operations could be carried on, and, second, it gave a means of recognizing which of the mechanical and chemical processes involved in our experiments were bringing us nearer to the goal. Anything which reduced the temperature at which the metal could be permanently bent was, clearly, helping us.

We found that steps tending to the elimination of the last traces of certain impurities did greatly improve the resulting product. While it may be true that certain impurities present in small amount are harmless or even helpful, we know that certain other impurities are detrimental. We also found that a certain micrographic structure in the tungsten rod with which we start, was conducive to mechanical working and to ductility in the resulting product. Once arrived at the point where mechanical working was easy and where there was a certain amount of ductility in the product even when cold, the development became more rapid. It was aided by the construction of more refined apparatus, in the design of which care was taken to guard against the taking up of impurities during mechanical reduction processes, both from the atmosphere in which the work is carried on and from the surfaces of the tools.

Hand in hand with this improvement on the mechanical side has gone the work on greater chemical purity of the metal with which we start. One of the difficulties in purifying tungsten has been due to the fact, which has been pointed out by Smith and Exner and others, that tungstic acid is very prone to form difficultly separable complexes. Because of this tendency, especial care must be taken with regard to the purity of the reagents used, as otherwise recrystallization beyond a certain point does not result in corresponding purification.

The knowledge obtained from our various lines of research now makes it possible for us to prepare tungsten which can be mechanically worked without more difficulty than would naturally attend the manipulation of very fine wire.

The product which we now have is a perfectly pliable ductile wire, which has the strength of steel. (Specimens of ductile tungsten wire of various sizes were exhibited at the meeting.) It gives a lamp which is strong and whose filament retains its ductility throughout the life of the lamp.

The following data on the drawn wire, obtained from measurements made in the laboratory by Dr. Colin G. Fink, may be of interest:

Diameter (in inches)	Tensile strength (lb. per sq. in)	Specific gravity
0.150	——	19.30
0.005	490,000	——
0.0028	530,000	——
0.0015	600,000	20.19

The electrical resistivity at 25 deg. cent., expressed in microhms per centimeter cube, is, for the hard drawn wire, 6.2, and for the same annealed, 5.0.

The temperature coefficient of electrical resistivity between 0 deg. and 170 deg. cent is 0.0051 per degree centigrade.

The above values, with the possible exception of the temperature coefficient, are of course somewhat dependent on the early history of the wire from which they were determined.

The work which has been outlined above is the result of the close coöperation of about 20 trained research chemists, with a large body of assistants, in the research laboratory. These men were of course given, from the factory organization, all of the mechanical and electrical assistance they could use, and were assisted in no small measure by the staff of the incandescent lamp factory.

A paper presented at the 250th meeting of the American Institute of Electrical Engineers, New York, May 27, 1910.

THE APPLICATION OF PORCELAIN TO STRAIN INSULATORS

BY W. H. KEMPTON

Porcelain possesses some qualities which make it a very good material for line insulators and especially strain insulators. It can be moulded and worked into almost any desired form or size; when made of proper materials and properly burned it has practically no depreciation when exposed to the weather, acid fumes or gases, which sometimes create so much havoc on electric lines. It is hard and dense and has high dielectric strength. It is practically non-absorbent and so is not affected by frost.

The great difficulty in the use of porcelain is its lack of elasticity. It is practically inelastic and has low bending and tensile strength. It has fair shearing strength and good crushing strength. It is these last two properties that make it available for strain insulators.

In order to have definite working data, tests were made to determine the strength of what is known as high voltage stock, in compression, shear and tension. After a number of trials, a pony insulator of the dimensions shown in Fig. 1, and a transposition insulator, Fig. 2, were selected for the compression test. These samples were placed in a Riehle tension and compression machine having a piece of ⅛-in. fibre above and below the samples to take up irregularities in the porcelain. In the case of the pony insulator, Fig. 1, the break always occurred at the upper groove, and at the middle groove of the transposition insulator, Fig. 2. The average breaking stress for the insulator shown in Fig. 1 was 16,370 lb. per sq. in.; high 21,400 lb., and low 12,200 lb. For the one shown in Fig. 2 the average breaking strength was 12,690 lb. per sq. in.; high 17,400 lb., and low 8,200 lb. In each case the results are from 10 samples. The shape and proportions of the insulators doubtless account for the different results in the two cases.

For the shearing test, ten pieces like that shown in Fig. 3 were tested in the manner described above. The fracture in each case showed almost pure shear on the line indicated in the sketch. The average shearing stress was 2400 lb. per sq. in.; high, 2,880 lb., low 1,770 lb.

For determining the tensile strength of porcelain, a number of porcelains from insulators like the one shown in Fig. 9 were selected. They were supported by a free but close fitting ring about the projecting head, and load was applied by means of a steel pin resting against the bottom of the pin hole. Only figures from samples showing a pure tensile break were used in the calculation. The average of nine samples was 654 lb. per sq. in.; high 897 lb., low 539 lb.

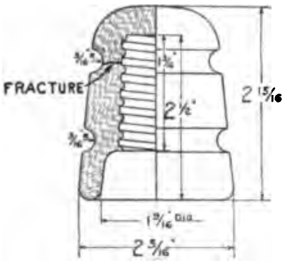

Fig. 1

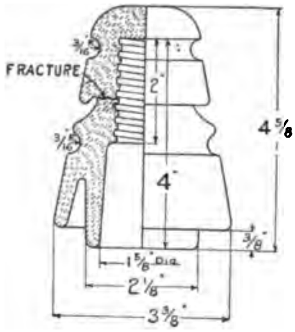

Fig. 2

In presenting these figures to the Institute it is realized that if carefully prepared test blocks were used under perfect conditions, much higher results would be obtained, showing the porcelain to better advantage. If the object were an investigation of the porcelain stock such results would be preferable. However, the object of these tests was to secure data for use in insulator design. Inasmuch as perfect conditions cannot be obtained in the practical manufacture of insulators, it was thought that tests from stock insulators under conditions including the imperfections met with in design and manufacture would be more reliable than absolute data obtained from perfect test blocks under ideal conditions.

SOME FEATURES IN THE DESIGN OF PORCELAIN STRAIN INSULATORS

As porcelain is strongest in compression, the preferable form of a strain insulator from the standpoint of mechanical strength would be one in which only compression strains existed, and in which sufficient stock was placed under the load to give a proper factor of safety. In practical design this condition is difficult to realize, and the load on most types of insulators gives a combination of compression and shearing stresses.

There are three types of porcelain strain insulators, suitable for high voltage railway work, now on the market and in successful service. The spool type, the loop type, and the compression or barrel type.

The spool and the loop types are the simplest and oldest but both are limited in mechanical strength owing to the fact that the load is applied between a cable and pin at right angles, and two cables at right angles, respectively. This throws a comparatively small volume of porcelain in direct compression, the larger part of the load producing bending stresses.

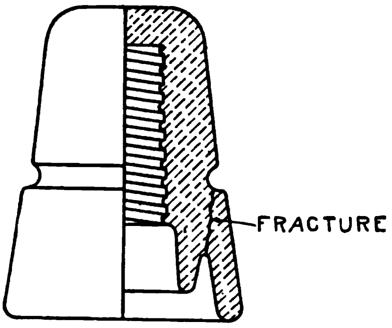

FIG. 3

The spool type insulator is further limited mechanically by the possible bending strength of the pin, and electrically, by the amount of surface insulation possible. On account of the inelasticity of the porcelain, if the pin fits the hole in the insulator snugly and the hole is of uniform diameter, the least bending of the pin will throw a bending stress on the insulator and break it. If a metal sleeve be cemented in the pin hole to distribute the load along its length, the expansion of the metal with heat may burst the porcelain. Practical design has settled down to a form of pin hole smallest in diameter under the wire groove and enlarging toward each end. This allows the pin to bend without pressing on the ends of the pin hole. The problem then becomes one of designing a pin of such length as to allow the desired insulation, and of such diameter as to give the desired bending strength. Of course the walls of the porcelain must be made sufficiently thick to also stand the load.

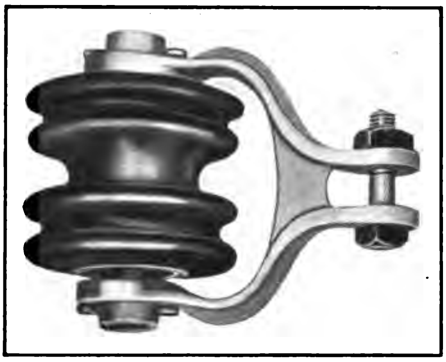

FIG. 4

Fig. 4 shows one form of spool strain insulator for 1200-volt service. Fig. 5 shows another form of spool strain insulator with a shorter pin for 6600-volt service. Fig. 6 shows a form of spool strain insulator for higher voltages. These forms of spool strain insulators have an ultimate strength of from 9,000 to 12,000 lb.

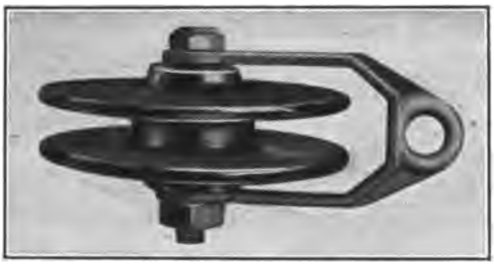

FIG. 5

The ideal porcelain strain insulator would have the load-bearing portion of the porcelain made with two exactly parallel surfaces held between two exactly parallel and absolutely rigid plates. Fig. 7 shows a form of compression insulator which approaches this condition. It consists of a porcelain bushing with an undercut head portion so that two approximately parallel bearing surfaces are obtained. The head of the bolt passing through the bushing rests on a steel washer bearing on its inner end, and the shoulder of the bushing rests against an inner end of a split cylindrical case, riveted or bolted together over the porcelain head. The irregularities incident to the practical manufacture of porcelain are taken care of by placing a lead washer under the steel washer and embedding the portion of the insulator inside the case in neat Portland cement. The bolt head is insulated from the case by means of a porcelain cap cemented over the head of the bolt and the insulator, with a good insulating cement.

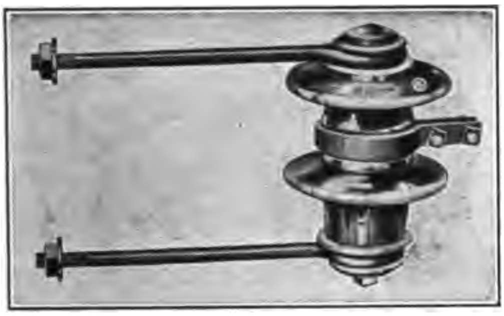

FIG. 6

The chief requirement in the design of this form of insulator is to make the case of such form, and to reinforce it with ribs, so as to prevent the end bearing surfaces from sagging. If these surfaces sag it throws the load on the outer rim of the porcelain head causing the sides to split off. One sample with a 4-in. diameter head stood a test of 34,000 lb., at which point the bolt broke. On tearing down the insulator a crack in the porcelain was discovered with difficulty. Insulators of about half the

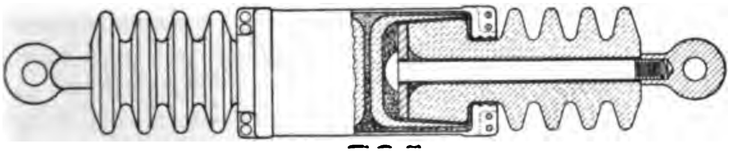

FIG. 7

above size, with 2½-in. diameter heads, will stand mechanical tests of from 18,000 to 20,000 lb.

The size mentioned as standing a 34,000-lb. stress—5½-in. diameter of corrugations by 24 in. long—has stood break-down

Fig. 8

electrical tests of 80,000 volts, and receives a regular shop test of 50,000 volts for one minute.

It was thought that high mechanical stresses weakened the porcelain stock electrically. To determine this point the following tests were made. Twenty-six insulators like that shown in Fig. 9 were connected in series for simultaneous mechanical and electrical tests. The load was increased by small steps, 70,000 volts being placed on each insulator for 15 seconds at

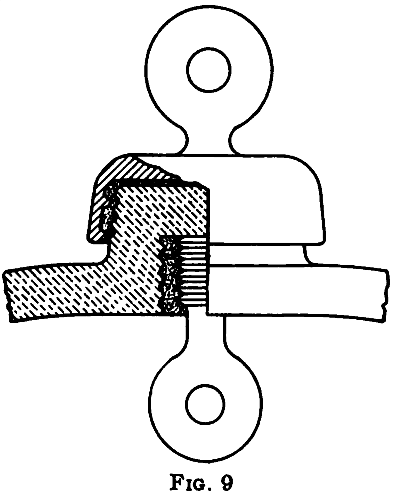

Fig. 9

each step. The test was carried on until three insulators had broken, the broken insulators being replaced each time, and in no case did the porcelain puncture before mechanical breakdown. The failure always resulted in breaking the porcelain off at the lower edge of the cap, so that each porcelain was tested at 70,000 volts at practically its ultimate mechanical strength.

A second test consisted of connecting ten loop strain insulators in series and applying the same test as before. In this case three of the insulators punctured before any of them broke. Inasmuch as this happened at the normal breaking load of the samples and as seven of the ten did not puncture it was thought probable that the high stress in the section of porcelain under the load opened up slight flaws in the stock rather than causing the sound porcelain to puncture below its unstrained puncture voltage.

It will be noted that the above discussion on design is all on high-voltage insulators. For low-voltage work what is known as the " goose egg " strain insulator, Fig. 8, has been used for several years and has proved to be quite strong and reliable.

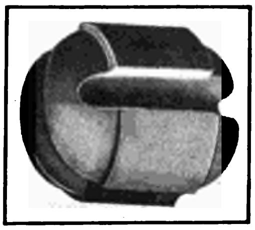

FIG. 10

It consists merely of an oval mass of porcelain about 5 in. long by 3 in. thick with wire grooves in opposite ends and at right angles to each other. Practically all of the porcelain helps carry the load directly or indirectly, and a very strong insulator results. Its proportions also make it quite sturdy and proof against rough handling. The ultimate mechanical strength is from 12,000 to 14,500 lb. A smaller size 3¼ in. long, shown in Fig. 10, stands from 9000 to 12000 lb. stress.

These results are from tests made with ½-in. high-grade seven-strand steel cable. If a more flexible cable had been used, higher results would have been obtained, as the hard strands of the cable used tended to cut into the insulator, and being so stiff, did not conform closely to the grooves.

On account of the rough usage they are apt to receive in low-voltage work, however, the moulded form of strain insulator has been more popular. The load being carried directly by metal parts with hard and tough insulation, usually sheet mica, interposed between and surrounded by tough moulded protecting covering, makes a very reliable insulator mechanically, and one that, on low-voltage work, is reliable electrically.

For high-voltage work moulded strain insulators are not so well suited. To stand the higher electrical test the metal parts must be further apart. On account of the resulting greater leverage, to maintain the same mechanical strength, the metal parts must be made much heavier. When large iron parts are embedded in the moulded insulation the expansion and contraction of the metal with heat is apt to crack the covering and admit moisture.

As compared to porcelain all forms of moulded strain insulators whether for high- or low-voltage work possess the element of depreciation due to exposure to the weather that porcelain does not have.

Wood strain insulators for both low- and high-voltage work have become quite popular, chiefly for the reason that long service tests have proved them to be reliable. Owing to the general unreliability of wood, the manufacturer must exercise much care in purchasing and inspecting his stock to maintain its quality. Equal care must be exercised in inspecting the metal caps before and after swaging them to the sticks. Even then, defects are apt to escape the inspector, and it is desirable to test every wood strain insulator mechanically before shipment, to make sure of results.

It will be noted that, although the porcelain strain insulator has certain inherent weaknesses, so has every other kind, and a perfect material for this purpose remains to be discovered.

A paper presented at the 250th meeting of the American Institute of Electrical Engineers, New York, May 27, 1910.

ELECTRIC RAILWAY CATENARY TROLLEY CONSTRUCTION

BY W. N. SMITH

During the past twenty years overhead trolley construction for electric railways has become such a familiar type of engineering construction, and apparently so settled in practically all its detail, that it is apt to be regarded as commonplace compared with many other features of electric railway equipment engineering. As long as the electric energy for train propulsion was everywhere standardized at 500 to 600 volts direct current, trolley construction practice followed a comparatively well settled and practically uniform line of standards; but since 1904 wide departures have been made from the original forms of railway motors, both as to current and voltage. This advance, made entirely in the interest of economy in transmission, has been accompanied by radical changes in trolley construction which have required the closest engineering attention and have lifted it above the level of the commonplace into which it had generally come to be relegated.

This paper is intended to be a review of current practice in electric railway catenary construction, its purpose being to bring some details of the present state of the art before the Institute in a practical way, to call particular attention to such features of it as may seem to be open for discussion, and to invite expressions of opinion about them; and it is hoped that each interested member will contribute something from his own practical experience so that an interchange of ideas will result which will be helpful to all concerned.

It may be well to state at the outset one cardinal point about overhead trolley construction, which is often overlooked by those who have given their time chiefly to the fascinating study of electric railway equipment predetermination and especial peculiarities of electric railway motors. I refer to the one thing which makes the electric railway differ from all other forms of electric power transmission and distribution, and that is the fact that the motor derives its power from a moving contact, maintained essentially parallel with the line of travel followed by the motor. The moving element of this contact is carried on the car or moving load, but the fixed element must be as long as the railway line itself, and every inch of it must at all times be in alignment and effectively insulated in order to make the entire railway system effectively useful. No matter how efficient the power station or the motors may be, neither is fully effective unless the contact wire through which they are joined is at practically 100 per cent efficiency. This efficiency must be continuously maintained over long distances and under all conditions of weather and of accidental or intentional interference; and the impossibility of relaying it without interrupting service makes the contact wire the most difficult and uncertain part of the entire system to maintain.

As interurban railways grew in importance, and in the size and speed of their equipment, not only did the necessity for economy in power transmission grow increasingly important, but the problem of collecting trolley current at high speed became more and more serious. The figure 8 and grooved types of trolley wire afforded some relief, but as supports were still 100 ft. or more apart the points of suspension caused slight changes in elevation of the wire, sharp enough to make trouble at high speed. It was not until 1904 that a new step was taken, namely, the elimination of the sag by means of more frequent points of support of the wire, resulting in the development of the so-called catenary type of suspension. This consists simply in suspending the trolley wire practically without sag by hangers of varying length placed every 10 ft., (sometimes 15 ft. or more) the same being supported by a messenger wire hanging in its natural catenary curve directly over the trolley wire. The messenger wire alone is supported on insulators. This type of construction was first successfully carried out on the Indianapolis & Cincinnati Railway, in 1904 from the designs of Mr. B. J. Jones.

This principle of construction has since been adopted in a number of other installations, with some modification, and has come to be accepted as a practical solution for high speed trolley operation. The original installation was made for 2,200 volts, and installations are now in service with this type of construction using voltages all the way from 600 to 11,000.

The principal features combined in this construction are the flat and smooth alignment of the trolley wire for high speed, the prevention of a trolley wire falling to the ground when broken, which is imperative with high potentials, and the use of a pneumatically-operated sliding bow for making contact, which dispenses with the trolley rope, avoids the necessity of frogs at switches and will stay on the wire at any speed regardless of the swaying of the car.

Although the above mentioned advantages of the sliding bow would seem to be conclusive for high tension trolley operation, it has the drawback of responding more sluggishly to unevenness of the trolley wire than the wheel and pole type of trolley, and this has resulted in a number of cases in the retention of the wheel trolley even in 3,300- and 6,600-volt lines. The writer's observation leads him to believe that the objections to the bow trolley have developed particularly where the catenary construction is defective, due to lack of appreciation of essential difficulties in construction and maintenance, and lack of skill in meeting them. It is easy to allow an amount of slack to go into a catenary trolley wire that will cause sufficient sag in the 10-ft. sections to make kinks at the hanger points, and under such circumstances high-speed operation with a sliding bow trolley is extremely unsatisfactory on account of the resulting sparking and flashing, while with a wheel trolley whose rate of vibration is about double that of the pantagraph, such a condition is not so prejudicial to smooth operation.

Types of Construction. Catenary construction is divided into three types as follows:

1. The original and most common is the plain single catenary, with the trolley wire hung directly from the messenger wire.

2. The compound or three-wire single catenary, in which the trolley wire is suspended by clips of uniform length from a tight secondary wire just above it, this secondary wire being supported by hanger rods of varying length from a slack messenger wire above it. There are several variations of this type and it permits the use of devices which maintain a uniform tension on the trolley wire through any range of temperature.

3. Double catenary construction, consisting of two messenger wires and one trolley, the latter below and between the other two, the three wires being at the corners of an equilateral triangle and rigidly connected by triangular pipe spreaders varying from 6 in. to 6 ft. on a side according to the sag of the messenger wire. The excessive rigidity of this type has been found to be undesirable in practical operation, and it has been successfully modified on the New Haven railroad by stringing a second trolley wire and fastening it a few inches below the first by clips at points halfway between the original trolley wire hangers. This construction was fully described and illustrated by Mr. W. S. Murray in his Institute paper of December, 1908.

The second of these general types has been extensively developed in Europe, particularly that feature which enables the maintenance of uniform tension on the trolley wire. Conspicuous examples of this type are the single phase lines of the Blankenese-Altona-Hamburg-Ohlsdorf line in Germany, and the Rotterdam-Haag-Scheveningen line in Holland.

Poles and Bridges. No paper on overhead construction can be regarded as complete without giving due consideration to the materials and construction of the poles or towers on which it is carried. In working up this division of the subject, however, there has been accumulated sufficient material of interest to warrant treating it in a separate paper, which the writer hopes to be able to do in the near future.

Where wooden poles are used they should invariably be treated with some preservative, preferably of the creosote type, before being set. The treatment may be either by the vacuum process which involves an expensive plant but thoroughly impregnates the wood; or it may be by the so-called " open-tank " process, in which about eight feet of the butts are treated with hot creosote or similar oil; or, cheapest of all, and yet quite effective, the " brush method " may be used, which simply means painting the pole with hot creosote or similar oil for a distance of about two feet above and two feet below the ground line, applying a second coat after the first coat has had time to soak in. Any engineer can prove to his own and to his client's satisfaction that either of the last two named methods of treatment will pay dividends, as the life of any pole so treated will be lengthened anywhere from 30 to 75 and possibly 100 per cent, according to the treatment used.

Steel poles can be had in three types. The familiar two- or three-section tubular pole, in either standard or extra heavy pipe; the "tripartite" pole, built up of re-rolled Bessemer steel U-sections with malleable iron collars and spreaders, the steel having an ultimate tensile strength of 100,000 lb. per sq. in.; and the "diamond" pole which consists of two sheet steel V-shaped troughs tapered and flanged over the edges, one being driven lengthwise within the other to form, when assembled, a box shaped pole, the extra strength lying in the extra thickness of the overlapping flanges.

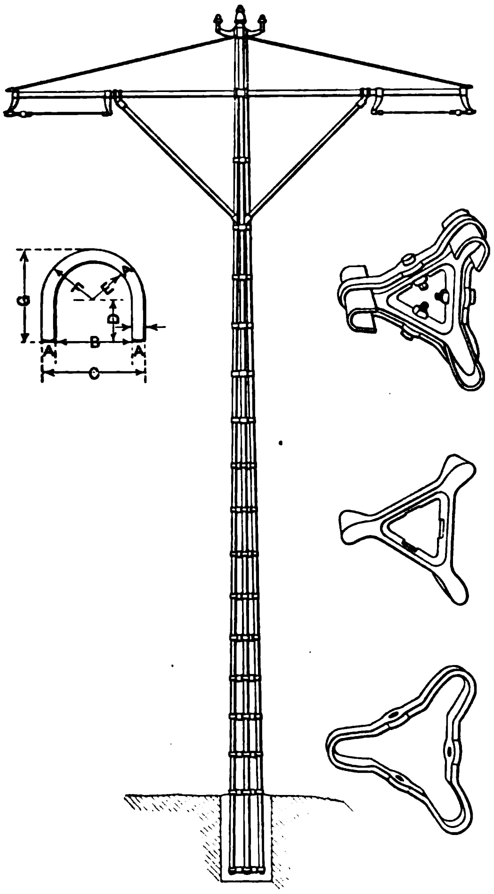

Fig. 1

Fig. 2

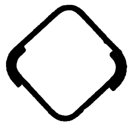

Fig. 3

"Tripartite" and "Diamond" steel poles

The relative merits of these three types of steel poles may be briefly summed up by saying that the tubular type is the least economical of weight for a given strength; and that while the diamond pole is superior to the tripartite in the matter of weight economy, the tripartite has a great advantage in that the Bessemer steel composing it is almost rust-proof and that every inch of metal surface upon it can be reached with a paint-brush. Its taper can also be easily varied to suit local conditions.

Reinforced concrete poles have come into use during the past few years, for railway trolley construction. Under favorable conditions they can compete with cedar or chestnut poles as to first cost; they are, roughly speaking, about twice as stiff as a cedar pole and of 30 per cent to 50 per cent greater ultimate strength. Most important of all, they are practically indestructible. A considerable number of them are in use on the lines of the Fort Wayne & Wabash Valley Traction Company.

On account of the load being from two to three times that carried on a single bracket pole in standard direct suspension, it is necessary to use heavier poles for catenary work. If of wood, they should average 25 in. in circumference at the top and should invariably be seasoned and treated with creosote, at least at the butts. The standard setting should be 6 ft. for a 30-ft. pole and 6½ ft. for a 35-ft. pole where the wire is at a high elevation. Over highways, 19 ft. is usually high enough, but in the steam railroad electrification carried out in this country the standard height of trolley wire, except under low bridges, is 22 ft. above the rail. Bracket poles should be set with 14 or 15 in. rake, as they will pull up to about one foot rake after the load has been applied. On steam railroads particular care must be paid to side clearances. Eight feet from center of track to the face of the pole is a minimum, and some roads require more. With an 8-ft. clearance, a bracket 10 ft. in length is sufficient.

Early practice in setting poles on curves, allowed greater offsets than experience has shown to be desirable. One manufacturer's catalogue gives pole spacing based on a maximum variation of 17 inches in the position of the trolley wire with reference to the center of the track. Another one gives seven inches, and a third is somewhere between. It is much safer to prescribe small offsets, and the Denver & Interurban catenary line was laid out not to exceed 3½-in. offsets, as follows:

TABLE OF POLE SPACING ON CURVES

Degree of curvature	Pole spacing feet	Max. offset of trolley wire from center of track, inches
Tangent	120	0
1	120	1.87
2	110	3.37
3	90	3.06
4	80	3.37
5	70	3.06
6	60	2.87
7	50	2.34
8	50	2.64
9	50	2.94
10	50	3.24

On curves, brackets must be so inclined from the horizontal as to be nearly parallel to the position taken by the pantagraph bow, the outer end of which will tilt up considerably, due to the elevation of the outer rail.

For attaching bracket truss rods to pole tops, the three-part pole-collar (Fig. 8) is preferable to any other means, as a single pattern forging is sufficient not only for the truss rod but for constraining the body of the bracket. This method was devised by the writer for the bracket construction of the Denver & Interurban R.R. in 1907. Insulator pins should be tightly adjustable on the brackets and should be made with a two-part clamp base, which the writer believes preferable to one with a J-bolt base as the J-bolt base will open out when screwed up tightly and has a very limited area of contact on the inside. Insulator pins should be of malleable iron.

Porcelain insulators of the petticoat type, are now universally used, and even over steam railroad tracks they have given no special trouble from gathering soot. The types used on the Erie and the Denver & Interurban lines have been uniformly successful, for three years on the former and two years on the latter railroad. The general form of this insulator is shown in Fig. 4.

Brackets ought also to be stronger than are usually made in direct suspension, particularly if over steam railroads. In the equipment designed by the writer for catenary construction on the Erie Railroad, two truss rods were used per bracket.

Some forms of bracket are made with two horizontal members, one on each side of the pole. To guard against accidents and minimize breakage in case of accident, the writer believes that it is desirable to design the pole attachments to the bracket so that if the trolley and messenger wire break, the bracket and truss rods may be swung around the pole as on a hinge, rather than be broken off or twisted out of shape. This is effected by using pole collars at the butt of the bracket and at the point of attachment of the truss rod, offering the additional advantage of obviating the boring of holes through the pole. Figs. 5 to 10 show several types of brackets used experimentally by the Connecticut Company. For high voltages, the brackets must be grounded to the rail to prevent a broken insulator from causing the pole to be set on fire.

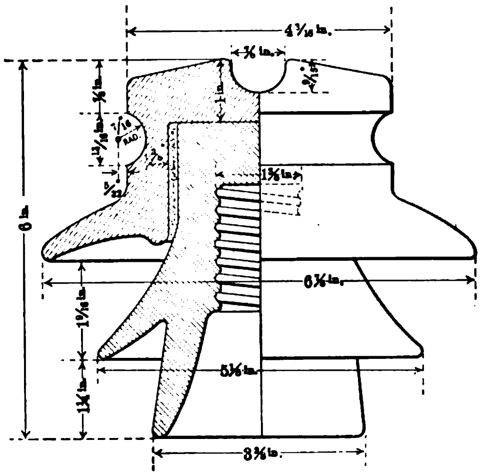

Fig. 4—Porcelain insulator

Catenary Spans and Bridges. The expense of steel bridges for supporting catenary trolley wires over more than two or three adjacent tracks can be greatly reduced by using span wire construction. A number of spans constructed under the writer's supervision at the Rochester terminal of the Erie railroad are illustrated herewith in Fig. 11. In this design the span wires and all supporting fittings are grounded. The trolley wire is supported by suspending from the span wire a stirrup of the same size of tee iron as is used for the bracket. The same type of pin as well as insulator is used for the span as for the bracket construction on the remainder of the line. The voltage on this installation is 11,000. For lower voltages heavy wooden strain insulators are sometimes cut into the spans without any insulation between the span and the messenger wire at the point of attachment, but the advantage of entirely grounded span wires should commend itself so obviously that it does not seem worth while to go to the extra trouble of working various styles of insulators into them.

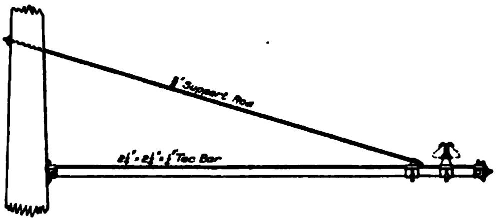

Fig. 5

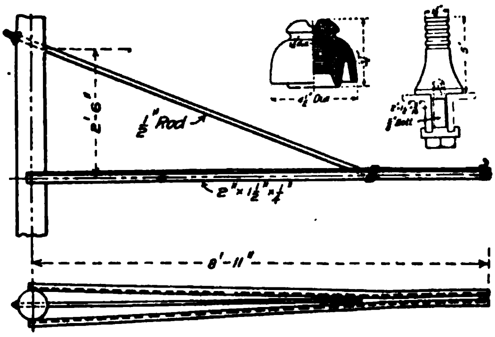

Fig. 6

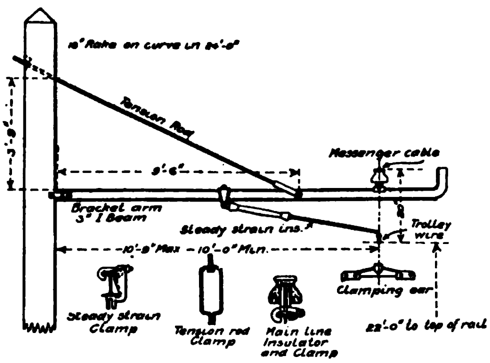

Fig. 7

This form of span is practically in duplicate, though it is intended that the upper should carry the load and the lower act to steady the stirrup sideways. It is hardly necessary to add that steel poles are necessary for catenary span construction of this character, unless there is ample room to substantially guy wooden poles. For this purpose the tripartite pole has been found very satisfactory. The illustration shows seven tracks spanned, being a distance of 96½ ft. across the tracks between poles, and four tracks of the seven electrified.

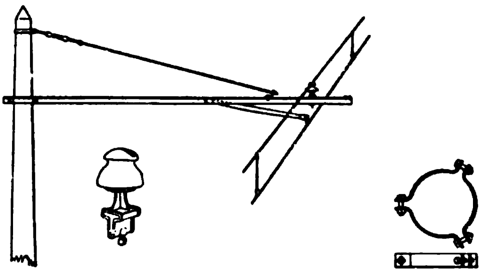

FIG. 8

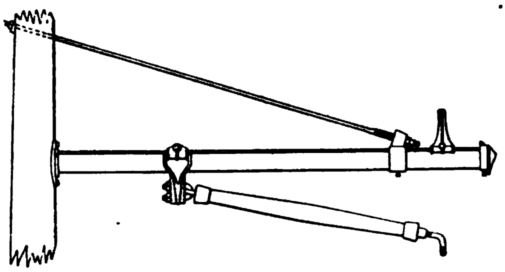

FIG. 9

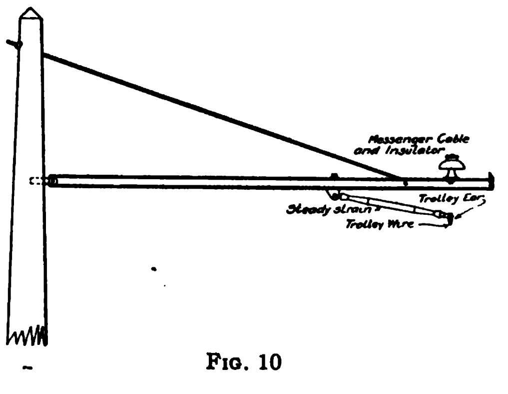

FIG. 10

Some of the latest catenary construction for double track has been supported by a light bridge construction, the most recent example being that of the Rochester, Syracuse & Eastern Railway, recently completed, and illustrated in Fig. 12. This is for 600-volt direct-current construction with bridges 300 ft. apart. It is of the plain single catenary type, without any special adjustment or tension devices. The sag of the cables in a 300 ft. span is about 62 in., the maximum length of hanger being about 67½ in. and the minimum 5½ in. in length. The form of bridge and foundation is stable and permanent. The side frames of the bridge are 28 ft. between the centers and the spread of each base is 4 ft. The insulators on top of these bridges are of porcelain moulded in a special saddle shape and set on treated timber. There is said to be comparatively little side swaying between bridges. On this particular line the messenger cables are of copper, constituting the feeders and are of 500,000 cir.

FIG. 11—Overhead construction at Rochester terminal of the Erie railroad

mils. The feeder was necessary for power distribution and the cost of the steel messenger wire was saved by this combination.

In the *Electric Railway Journal* for May 22, 1909, were published some figures showing the relative cost of this type of construction compared with the ordinary wooden pole and span wire construction for double track. The fact that the messenger wires were eliminated and the feeders made to do double duty enabled quite a saving to be made, and the cost of the supporting structures, exclusive of copper conductors, is reported for this particular line as being only $100 per mile of double track more than with wooden pole construction. It is hardly necessary to comment on the greater permanency of steel construction.

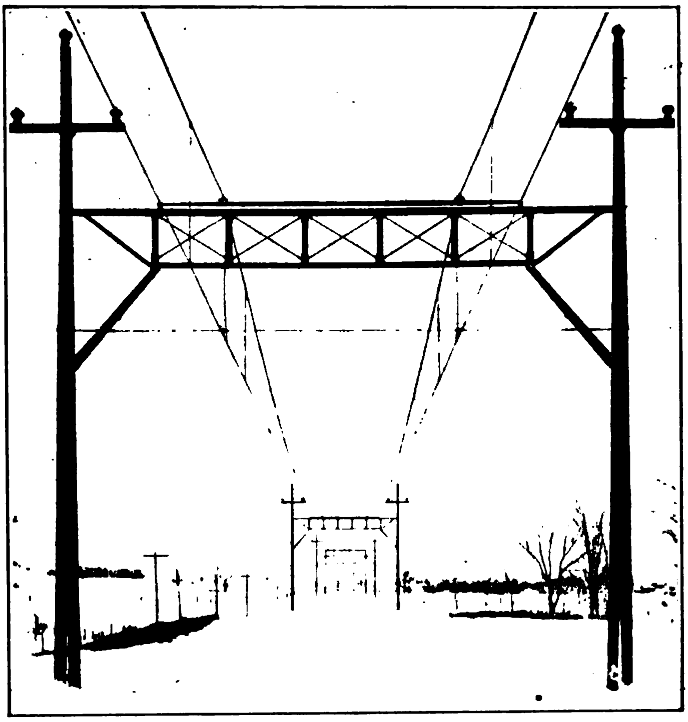

FIG. 12—Light bridge construction on Rochester, Syracuse & Eastern railway

The varying costs of steel bridges, poles and wires render it necessary to make very careful estimates for comparison before the engineer commits himself to the adoption of a radically new type of construction, but there will doubtless be many instances where this type of bridge for a double-track line would prove economical.

The original bridge construction of the New Haven Railroad has been so frequently described and illustrated that it is only necessary to refer to it by name. The newer type of construction now being used by the New Haven Railroad will be referred to later. The writer believes it to be a great improvement over the original.

Messenger and Trolley Wires. By reason of their somewhat intimate relationship, it is desirable to consider messenger and trolley wires together. The original and simplest form of catenary construction utilized a galvanized 7-strand steel cable of high strength steel, with hard-drawn grooved copper trolley wire. The messenger wire has varying sags but a common sag was 10 to 12 in. for a 120-ft. span. The trolley wire which is generally of 3/0 or 4/0 B. & S. gauge, is meant to be perfectly level at average temperature, but owing to the different coefficients of expansion of steel and copper, the trolley wire is relatively tighter at low and slacker at high temperatures than the messenger wire. With the plain type of catenary construction where no take-up devices are employed, the result is that in warm weather the 10-ft. sections between hanger points become slack enough to cause the sliding bows to pound kinks into the wires at the hanger points, and, at any considerable speed, mechanical pounding and electrical flashing are both injurious. The only remedy for this situation aside from providing overlapping breaks, is to pull the wire so tight that its strain at maximum temperature will not be less for a 4/0 copper wire, than 2,000 lb. If the minimum tension at 100 deg. fahr. is to be 2,000 lb., at zero deg. fahr. it will run up to about 5,000 lb., and the elastic limit of the wire is reached at 5,817 lb. As 5,000 lb. is so close to the elastic limit it is to be expected that copper trolley wire pulled tight enough to be effective at maximum temperatures will be likely to get pulled beyond the elastic limit in the course of a season or two, particularly after the outer skin is somewhat worn down by the passage of the moving contact. These considerations may explain much of the trouble that has been experienced with plain catenary construction using hard drawn copper trolley wire. It sometimes happens that when a road is quite crooked, the elasticity of the poles will do something towards maintaining the tension of the trolley wire at varying temperatures by giving sideways at the curves, but usually the only remedy is to pull out the slack as often as required.

This warm-weather slackness can be obviated where a wire can be pulled sufficiently tight to be at a minimum of 2,000 lb. at a high temperature and 5,000 lb. at low temperature. This can be done with "phono-electric," with steel wire, or copper-clad steel wire. The principal objection to the use of wire other than copper is the decreased conductivity. Phono-electric wire costs more than copper, while steel wire, of course, costs very much less. Both of these wires are so much stiffer than hard drawn copper that there is a marked tendency to resist kinking. At 11,000 volts the conductivity does not greatly matter when dealing with the usual interurban train weights and distances of transmission.

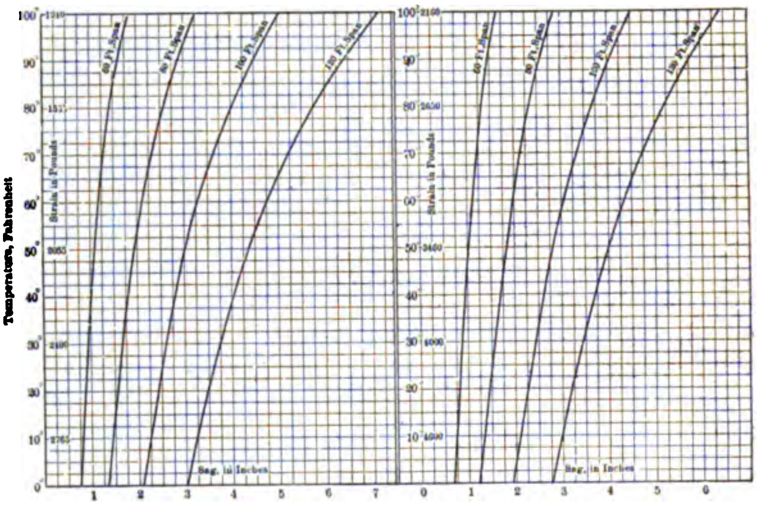

FIG. 13—Curves of messenger and trolley sag

On the Denver & Interurban Ry. in 1908, phono-electric trolley wire was strung on 45 miles of plain catenary construction, using a dynamometer to register the tension, which was so adjusted that at 100 deg. fahr. there was not to be less than 2000 lb. tension, rising to nearly 5000 lb. at zero deg. fahr. The curves of messenger and trolley sags are shown in Fig. 13*. The

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* From a paper on "Catenary Trolley Construction" read before the Am. Soc. C. E., October, 1908, by O. S. Lyford, Jr.

road has been in constant operation for two years and it has not been necessary to pull any slack out of the trolley wire in that time, thus demonstrating the correctness of both the design and the selection of materials.

The use of tension devices for trolley wire as thus far developed, which is chiefly in Europe, does not seem to contemplate tensions of more than 1000 to 1500 lb., and furthermore the clips which hang the trolley wire from the secondary wire directly over it are of a type that will yield vertically, so that the trolley can, as it were, carry a wave along with it as it travels underneath the wire. It is the writer's belief that without the upwardly yielding hangers, it is necessary to maintain a minimum tension of at least 2000 pounds; and that it is permissible to maintain a lower tension only when the trolley wire can yield upwardly at the hangers. Such hangers have not yet been generally adopted for use in this country and the only experiments with them under American conditions of which the writer has knowledge, have not been particularly conclusive. On the New Haven road good results have been effected by a maximum tension of about 5000 lb. on the trolley wire, and without the use of automatic devices for producing uniform tension under all temperatures.

A table is presented herewith showing the characteristics of the four kinds of wire now available for catenary construction, those characteristics being for one size only, No. 4/0 B. & S. gauge, which is that most largely used in catenary construction

PROPERTIES OF TROLLEY WIRE, NO. 4/0 B. & S. GAUGE

	H. D. copper	Phono-electric	Copper clad	Steel
Tensile strength, lb..........	8,310	11,330	9,470	12,000
Elastic limit, lb..............	5,817	9,640	8,523	9,000
Res. per mile, ohms..........	0.259	0.575	0.634	2.21
Weight per mile, lb...........	3,382	3,382	3,140	2,940
Modulus of elasticity.........	16,000,000	18,500,000	——	30,000,000
Coeff. of expansion, deg. fahr..	0.00000950	0.00000932	——	0.00000640

An excellent feature of the modified type of compound catenary construction used by the New Haven R.R. is the upward yielding made possible by suspending the contact wire from the old trolley wire at points halfway between the original hanger points. There is thus available a limited amount of upward yielding, depending somewhat on the temperature. The combination of this yielding effect with the high tension in the contact wire has proved so generally satisfactory that in future extensions of the New Haven system the contact wire is to be similarly suspended. The clips by which the working conductor is attached to the lower or secondary messenger are fast to both the wires and allow no vertical play other than that due to the yielding of the secondary wire.

The European compound catenary however has these hanger clips so designed as to permit the trolley wire to yield vertically and as all new European work seems to be designed along these lines the principle under European conditions seems to be successful.

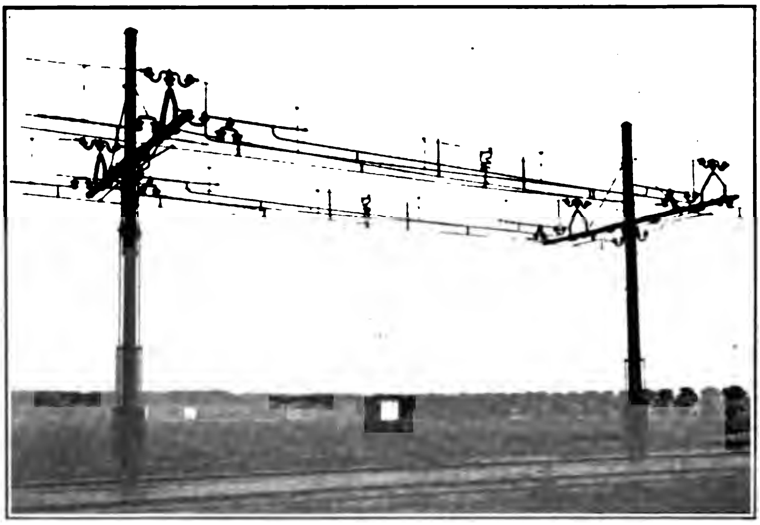

Fig. 14—Catenary construction with strain insulator at each bracket

The other principal feature of the compound catenary is the tension device placed at intervals to take up the expansion in the trolley wire due to temperature. This consists of a system of weights operating by chains over pulleys, pulling against the free end of the trolley wire at the end of each section, the consecutive sections overlapping so that the contact bow slides readily to one before leaving the other, there being, however, no electrical connection between the trolley wires of the overlapping sections except during the passage of the bow.

These sections are from 3,000 to 4,000 ft. long and the arrangement serves naturally as a section insulator around which a jumper can be placed if desired. On the line at Rotterdam the builders have cut the messenger wire at every bracket, inserting a strain insulator resting upon the bracket and composed of three insulators so that there are ordinarily two in series. This construction is shown in Fig. 14. Previous practice, as at Hamburg, (see Fig. 15) and Lancaster, England, adhered to the continuous messenger, but presumably the change was made in the interest of diminishing the effect of changes in temperature of the continuous messenger.

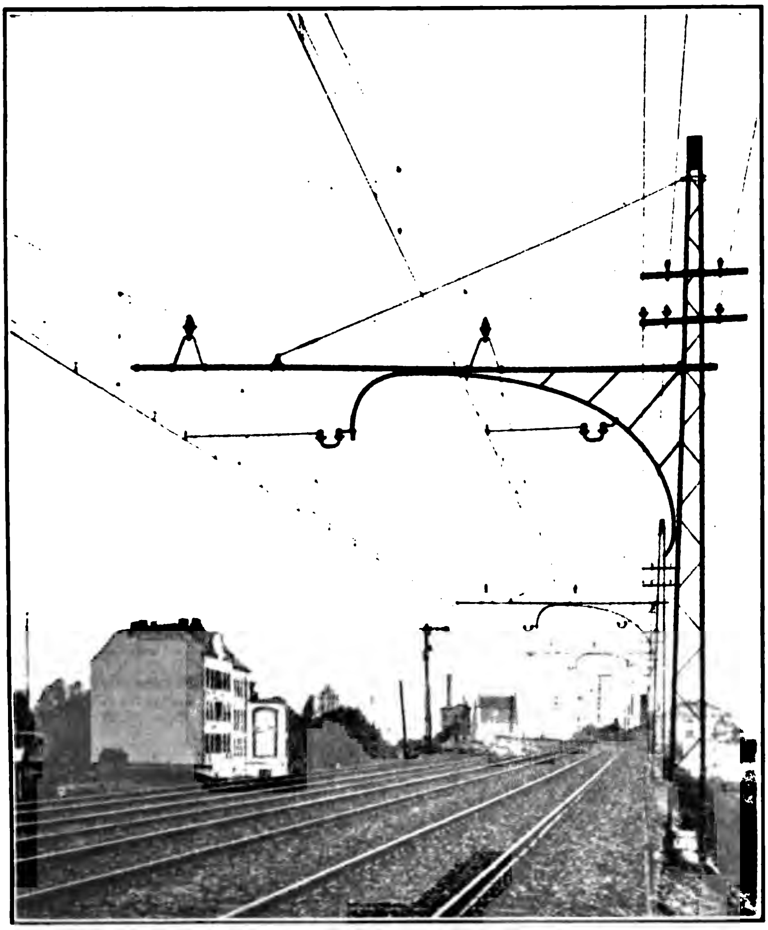

Fig. 15—Catenary construction at Hamburg

The latest improvement introduced in Europe for eliminating unevenness of operation due to temperature changes is a new design in which there is included an equalizer wire, so-called, which runs above the catenary between brackets without any intermediate hangers, as shown in Fig. 16. Being somewhat shorter and with less slack than the messenger wire proper it tends to lift the catenary at points where it is anchored thereto a short distance away from the brackets, and thereby raises a short bight in the catenary directly under the bracket where the trolley is attached to it, thus lifting the trolley wire at the bracket when temperature is lowered, which would not be the case in the ordinary type of plain catenary construction. In this type of catenary the trolley wire is of hard drawn copper, while the catenary and the equalizer are of silicon bronze, so that all three have similar coefficients of expansion. In several instances a copper messenger wire has been used instead of steel, this having been done on lines where low-tension direct current was used, requiring feeder copper. It has the advantage of saving the cost of a steel messenger. The fact that both the trolley and messenger are of the same material will greatly lessen the troubles that have been experienced with a steel messenger and a copper trolley wire.

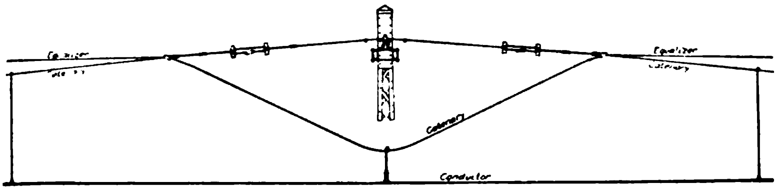

FIG. 16—Catenary construction with equalizer wire

The excellent service being rendered by steel trolley wire on the New Haven R.R. has suggested to the writer that it might be worth while to propose using a combination of a copper messenger and a steel trolley wire. In this arrangement the trolley wire would expand and contract less than the messenger and it would seem as though it should therefore be more easily kept at required tension. There has not been time to work up the idea in detail but it is submitted for the criticism of those who are interested. It will probably be more suitable for the higher than lower voltages, but as it is no more difficult to insulate catenary trolley construction for 11,000 volts than for 2,200 volts, the extra cost of insulation due to carrying the higher voltage is insignificant.

Catenary Hangers. There are so many types of catenary hangers that a description of all would be tiresome. Six different companies are each offering several different types of hangers,

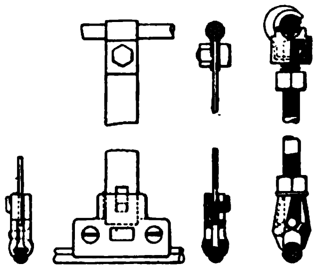

Fig. 17

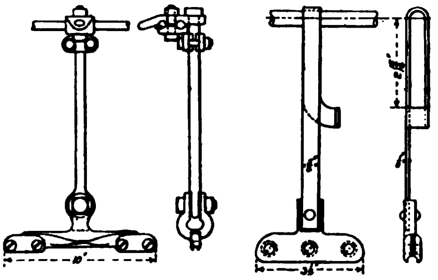

Fig. 18

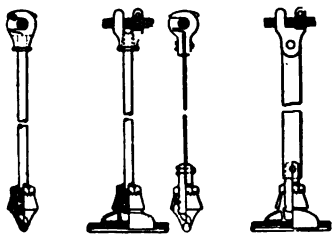

Fig. 19

including both the messenger and the trolley clamps and the rod connecting them. For the plain type of construction there now seems to be a preference for a hanger that has an easy or flexible grip on the messenger wire and a powerful positive grip on the trolley wire, with a joint between clamp and rod, either at the top or bottom, or sometimes both, to increase the general flexibility. In the earlier work, four or five years ago, messenger and trolley clips were rigidly connected together and even in spite of the lack of experience in design and erection they operated very well in many cases, provided the trolley wire was pulled sufficiently tight.

The Connecticut Company recently constructed several miles of catenary construction on a line between Middletown and Hartford, Conn. About two miles of track were given up to trial sections of construction designed and erected by six manufacturing and supply companies, each one having a chance to erect that which it considered its best practice. Some of the designs of hangers are reproduced in Figs. 17 to 23.

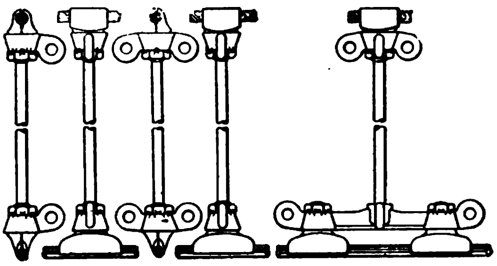

Fig. 20

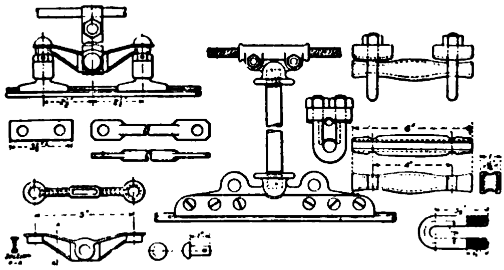

Fig. 21

It is safe to say that almost every engineer who has built a catenary line has tried his hand at devising a new catenary hanger that would combine simplicity, flexibility, certainty of grip, speed of application and adjustment, and cheapness. Fewness of parts is essential to cheapness and speed of adjustment. A hanger of five or six parts, including bolts and nuts, is preferable to one of ten or twelve parts. The grip on the trolley wire should be powerful and easily applied. One nut only should be allowed, to tighten or loosen the trolley clamp. The hanger shown in Fig. 24 seems to answer most of these requirements.

The writer's preference is for a nut screwing down on the lower end of the hanger rod as in Fig. 24, as it can then never work off. It is desirable to have at least one pivot joint in the rod, either at the messenger or at the trolley ear. The loop type of connection to the messenger wire where the top of the rod is practically looped over the messenger wire or forms a slot for the entire hanger to work up and down on the wire as in Fig. 25, has only one drawback and that is the possibility of wearing away the galvanizing of the steel messenger cable. If the messenger be of copper the wear would probably injure the cable mechanically. This type also has the advantage of permitting the endways movement of the contact wire which will allow its tension to be well equalized on different sections of the line.

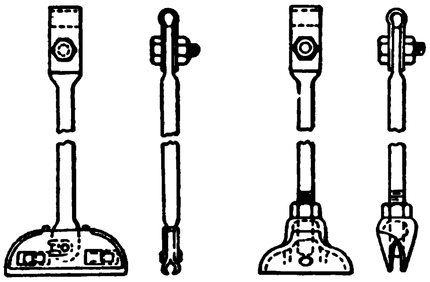

FIG. 22

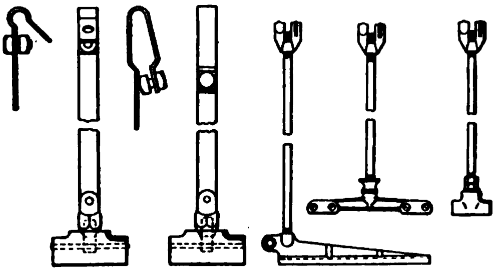

FIG. 23

In our hunt for the best imaginable solution it must not be forgotten that some existing solutions are operating very satisfactorily, and we may sometimes do well to call a halt and ask ourselves whether all these adjustment features are really worth while, particularly if they are costly.

There is one feature of catenary design that always deserves careful attention and that is the number of different lengths of hanger rods in a span. The average railway will have more or less curvature, and spans of different lengths on the same, in which the number of inches sag of the messenger will vary considerably, though the spacing interval of the hanger rods is ordinarily uniform no matter what the distance between poles or bridges. On the Erie R.R. electrification there was little curvature and the number of different lengths of span was limited, and only six different lengths of hanger rod were needed, with 10-ft. spacing. On the Denver & Interurban there was considerable curvature; the spans varied from 120 ft. down to 60 ft. in length, spacing 10 ft., and yet there were only six lengths of hanger rod required. Three of the manufacturing companies issue catalogues or instruction books dealing quite fully with catenary construction and from the three together one can pick out most of the mechanical details necessary for equipping a line, and much

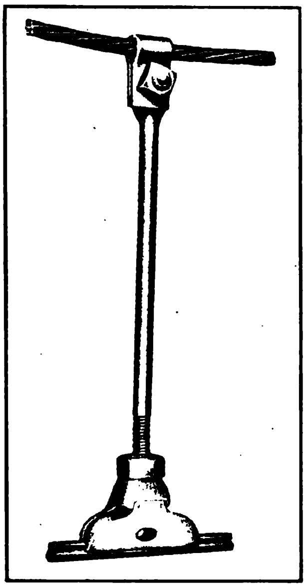

FIG. 24

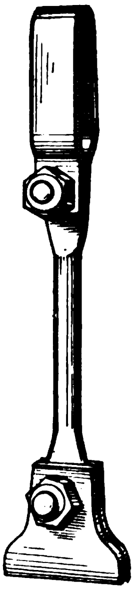

FIG. 25

valuable information is given that will aid an engineer greatly in laying out the work. But with respect to this matter of lengths of hanger rod, shown in these catalogues, it is found that for spans from 150 ft. down to about 70 ft. one firm shows 18 different lengths of hanger rods necessary to carry in stock, while another firm illustrating spans from 150 down to 55 ft., proposes only 11 different standard sizes. A third manufacturing company shows about the same range with 14 sizes. The Rochester, Syracuse & Eastern construction requires 11 sizes. There is thus always room for the exercise of judgment in reducing the number of parts.

The vertical distance between the messenger and trolley wire at the brackets is from 20 to 23 in. on 150-ft. spans and 17 or 18 in. on 120-ft. spans. The minimum distance in the center of long spans is about 4 in. for 150 ft. and 6 in. for 120-ft. span and as much as 20 in. in a 60-ft. span when the interval between hangers is 15 ft. It is noticeable that there is a tendency toward increasing the distance between hanger points in catenary spans. It originally started at about 10 ft. One company, during the early development advocated three-point suspension on tangents for spans as long as 150 ft. At the present time however the three-point suspension is only recommended for wheel trolley operation and 11-point suspension is recommended for sliding bow operation. This brings the hangers approximately 14 ft. apart. Another company shows spans varying between 10 ft. and 13 ft. 7½ in. which is 12 points of suspension for 120-ft. span, and 11 points for 150-ft. span, as desired. A third company gives in its catalogue fittings designed for 10-ft. and 15-ft. spacing, on spans from 60 ft. to 150 ft.

The American Street & Interurban Ry. Association's Committee on Power Distribution prepared a report on catenary construction in 1908 and its conclusions were rather in favor of hanger spacing of 20 ft. to 30 ft. because the sag between hangers, though very slight, would still be sufficient to help take up the expansion of a copper trolley wire in warm weather. It was quite evident that the committee hesitated to recommend the complication of the compound catenary type of construction if any means could be adopted that would accomplish reasonably smooth operation with plain catenary construction. It also reported very favorably on making spans 300 ft. in length; that the hangers should be as light and flexible as possible and that the messenger cable should be of plow steel, strung to a small sag.

Much is said from time to time about the necessity of staggering the trolley wire from side to side when constructing for sliding bow operation. The writer has noted enough successful operation without staggering, to confirm his belief that it is not absolutely necessary under interurban conditions with average track, and motor cars of the usual interurban style. With these conditions the car is generally so sure to sway from side to side as to equalize the wear fairly well on the sliding bow. It is only where there are very heavy locomotives and extremely solid track and roadbed that the writer would entertain seriously the necessity of staggering the wire, but though these conditions are present on the New Haven Road, the contact wires have not been staggered. Unless great pains are taken to prevent it a staggered wire always tends to pull straight and consequently to induce some sag that is not desired.

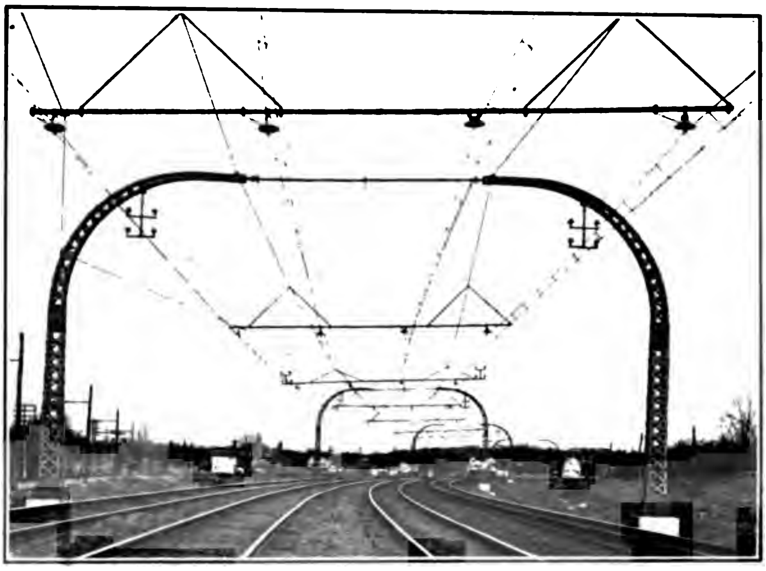

FIG. 26—New catenary construction of the N. Y., N. H. & H. R. R.

The new design of heavy catenary construction developed last year by the New Haven road is a remarkable advance in several respects, and is illustrated in Fig. 26. The chief points of interest are the following:

1. The supporting bents are much more sightly and more economical of material than the original bridges.

2. The main suspension cables of 1¼-in. stranded steel wire which carry the insulators and the messenger wires proper are uninsulated and grounded, which will facilitate maintenance, painting, etc., and will obviate much of the danger to men on the signal bridges.

3. Insulators, if broken, can be replaced by removing only three bolts, the two by which the insulator is suspended from the crossbent and the one which suspends the messenger wire from the insulator.

4. The feature of a steel working trolley wire below a copper conductor, using the spring in the upper wire to permit the contact wire to yield in an upward direction, is here developed, showing it to be regarded as a successful means of securing smooth and reasonably flexible contact.

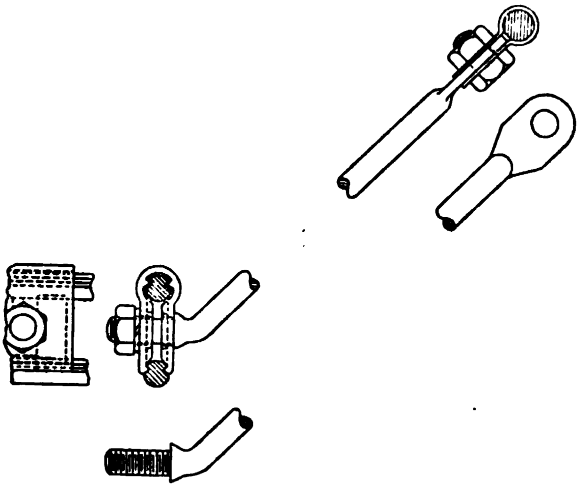

Fig. 27—Bent inclined hanger rods

5. The necessity for steady-strain insulators and pull-offs of the previously accepted types on curves is entirely done away with because the hanger rods are so dimensioned that, by inclining them at such an angle that the trolley wire follows the alignment of the curve exactly, the tendency is for the lower wire to pull to a curve of shorter radius than the messenger wire. By adjusting the lengths of the hanger rods with some care the curve of the center line of the track can be closely approximated by the lower ends of the hanger rods when thus inclined

and rightly adjusted for length. By bending these inclined hanger rods so that their bottom ends are horizontal, then passing the horizontal end through the middle of the clip that fastens the contact wire to the secondary messenger, the two latter are held rigidly in a vertical position and the working trolley is maintained as exactly under the secondary messenger as though it were on a straight line. See Fig. 27.

The criticism is sometimes made of steady-strain insulators for catenary curve construction that the tension under which they do their work makes the curve rigid and unyielding. In this case the heavy steady-strain insulators are dispensed with altogether, being replaced by the light iron hanger rods which for the time being are acting as steady strain insulators. Their greater frequency must minimize the pull of each individual rod and tend to make the whole structure less rigid than where steady strain insulators or pull-offs are applied at intervals of 30 ft. to 60 ft.

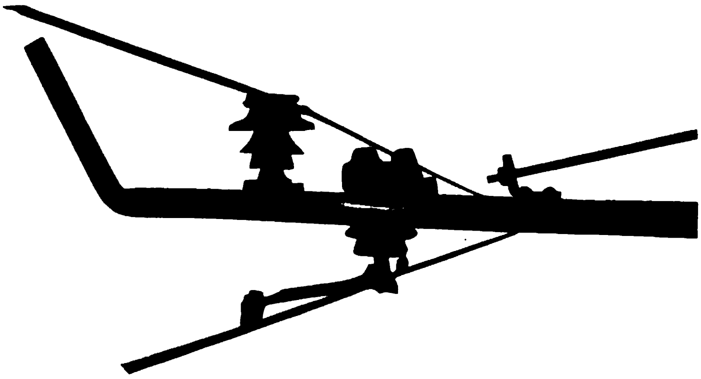

Fig. 28—Steady strain insulator, Denver & Interurban Railway

6. The adjustments for height in this construction are extremely simple, being accomplished by slipping the suspending members of the cross bents nearer to or further from each other along the bent, thus raising or lowering it.

The features here mentioned can all be easily noted in the illustrations and should appeal as only a first-class mechanical job can, to every engineer who has had to deal with overhead construction in general and catenary in particular.

Steady Strain Insulators. Steady strain insulators usually consist of a stick of treated wood shaped like a long strain insulator, terminating at the outer end in a hook-shaped fitting that is attached to the trolley car, being pivoted at the inner end to an insulator on the bracket. When in this form they must be inclined upward away from the trolley wire so as to clear the sliding bow. While originally intended for curve construction only, it is often found desirable to install them at intervals along tangents say from 5 to 10 poles apart, as their presence helps to prevent swaying of a suspended trolley wire in a very high wind.

The form of steady strain insulator used on the Denver & Interurban Ry., is shown in Fig. 28. This has the merit of employing the same kind of 11,000-volt insulator that is used on the standard straight line catenary support, the head of which is cemented into a socket on the end of a malleable iron bolted to the bracket. The brace proper is a short link of malleable iron loosely hooked into an eye-bolt projecting from the bottom of the insulator. It will thus swing through an arc permitting some longitudinal movement of the trolley wire. In case the insulator breaks it will fall to the ground from the outer end of the hook, and the hook is light enough so that the stiffness of the trolley wire will make it stand out straight after the insulator has fallen and it will not hang down and foul the sliding bow.*

Between poles, various schemes for pull-offs are used, but the commonest method is to run a bridle from the upper and lower ends of the hanger spacing rods, joining the bridle wires at some distance away from the trolley and insulating the pull-off by a strain insulator. Sometimes a wood strain insulator may be put into each of the bridle wires, but care must be taken not to weight them down so that they would be in danger of fouling a bow trolley. Probably the best way to insulate a pull-off for high voltages is to use the disk type of strain insulator, which was first brought out by E. M. Hewlett in 1907. This is the handiest form of light-weight porcelain insulator and fits nicely into almost any pull-off situation. A porcelain spool has also been used as a pull-off insulator, to slip over a hanger rod. This adds weight to the trolley wire and may make a hard spot, which is undesirable for bow trolley operation if located at a point where high speed is to be made, but it is not especially objectionable on a siding or in a yard and it insulates every inch of the pull-off wire and is probably the cheapest form of pull-off for high voltages. The pull-off wire is attached directly to the middle of the spool.

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* This device has been patented.

Strain Insulators. The writer's experience with catenary construction having been with high voltages, it has been necessary to be particular about strain insulators.

After some unfortunate experiences with strain insulators built up of metal and moulded insulating material of one form or another, it was found that porcelain, if it could be kept in carefully equalized compression, was the most reliable insulation, and as in the case of the straight-line insulators, a single insulator (of the heavy porcelain spool type), properly mounted, can always be depended upon. The easiest way to mount such insulators is to cement them upon a piece of pipe large enough to carry a ⅞- or 1-in. bolt. If the bore of the spool is fairly large it may be necessary to use 1½-in. pipe. It is more necessary to have the pipe nearly as large as the insulator than it is to have the bolt nearly fit the pipe.

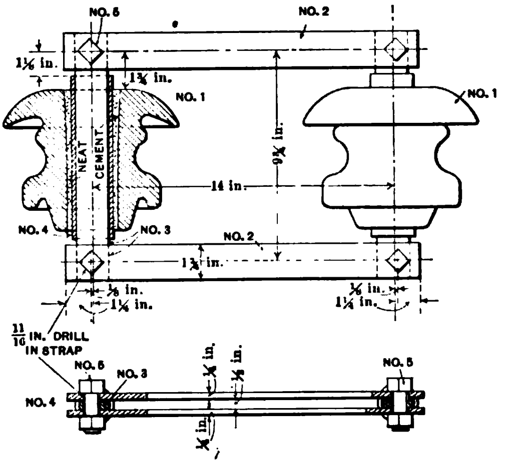


Fig. 29—Double spool strain insulator

The disk type of insulator is very ingenious, light and attractive but the body of the porcelain under compression is not sufficient to resist a crushing strain of more than 5,000 or 6,000 lb., or it was not when certain tests were made under the writer's supervision between two and three years ago. The 6½-in. diameter disk insulators are now advertised to carry a safe working load of 2,500 lb. and the 10-in. insulator 4,500 lb. With the trolley tension sometimes reaching 5,000 pounds at low temperature, a strain insulator for dead ending must have a working capacity of at least 7,500 to 10,000 lb., and it ought to be as high as 12,000 to 15,000 lb. This puts the disk type out of the running. The writer designed for the Denver & Interurban a double spool insulator comprising a porcelain spool cemented on 1½-in. pipe with 1½ by ½-in. flat iron driven through the pipe and standing edgeways to the strain, there being a hole in each end of the flat iron for linking to the other porcelain similarly fitted. This insulator, under test, carried 50,000 volts and 14,000 lb. strain simultaneously, without failure. It is shown in Fig. 29.

It is the writer's belief that, even more than in the case of direct suspension, strain insulators for catenary construction should be specified to be tested mechanically and electrically at the same time, up to their maximum mechanical and electrical capacities. It is only in this way that actual conditions of service can be duplicated in a test.

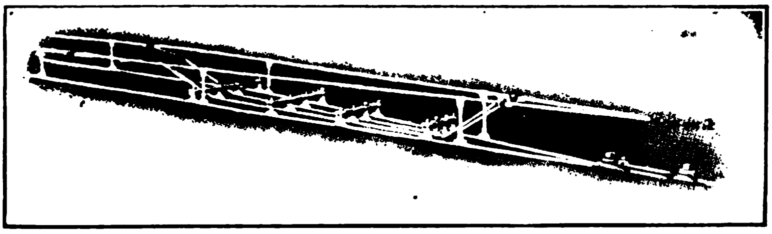


Fig. 30—Deflector

An excellent point about the disk type of insulator when used within its capacity is that there is a mechanical linkage of the guy cables on opposite sides of it which prevents their falling apart if the porcelain burns. This is not true of a wood strain insulator, which under high voltages is much more likely to get burned in two than at low tension, and for this reason the writer does not believe in using wood strain insulators for heavy strains where there is any possibility of a full voltage being applied to opposite ends of the insulator.

Deflectors and Frogs. The deflector is illustrated in Fig. 30. This contrivance has sometimes been found necessary to prevent the horns of the pantagraph bow trolley from getting tangled in the wrong wire where two trolley wires intersect on a switch or crossing. If the bow has no horns or if the horns are prolonged downwards there is no danger of a bow catching and no necessity for the deflector. In fact deflectors are about the worst nuisance one has to contend with in maintaining a catenary line, and even where they have been carefully installed they are very apt to give trouble. It is very difficult to stretch the intermediate wires perfectly tight, and to keep them tight, even after they are adjusted.

The use of frogs on catenary construction for a sliding bow is unnecessary and when so installed they have usually been taken out afterwards.

Deflectors are heavy enough to require considerable care in setting them up, and on account of their weight, it is desirable to have them under a bracket or as near as possible to one. If not kept in good trim a bow trolley rapidly traveling underneath one will cause more or less flashing, which sometimes spreads up to the bracket, grounding the line and throwing the current off for the time being.

Section Insulators. With wheel trolleys, wood section insulators are a necessity, as in the case of direct suspension, but by far the best form of section insulator for bow trolley operation is the overlapping break without any wood or any other insulated under-run. They are also cheaper to install than the wooden insulator, there is far less weight to support, and there is no danger of warping or of destruction by fire. Section insulators make good feeding-in points and should always be fitted with a jumper which includes a knife switch, usually kept closed. When it is desired to open a section of high voltage trolley a hooked stick with a grounding chain attached above the handle is used to pull the switch, being kept hung permanently in the switch box which should be well up on a pole out of reach of all but employees. It is desirable to have such switch boxes located at railroad stations or signal towers.

On two important installations of 11,000 volts, with multiple unit car operation, no feeder wire has been found necessary and section insulators have been introduced mainly for subdividing for the purpose of more readily locating trouble. The best information for computing trolley drop in a single phase railway, and calculating feeders, is to be found in Mr. A. W. Copley's discussion of Professor Whitehead's paper on "From Steam to Electricity on a Single-Track Road," in the A.I.E.E. PROCEEDINGS for 1908.

Lightning Protection and Ground Rod. It is absolutely necessary at high voltages to ground all the brackets and spans of a catenary line. This is most effectively done by steel or iron bars about $\frac{5}{16}$ or $\frac{3}{8}$ by $1\frac{1}{4}$ in. with the top end bolted to the butt end of the bracket and the bottom end run over to the track through the ground from the butt of the pole. The best kind of a connection to make with the track is through a cross bond, as this is more flexible than to connect a rod directly to one of the rails. The ground rods, brackets and truss rods together form a pretty fair lightning protector for the trolley construction, but to make it more effective, on the Denver & Interurban Ry. a $\frac{7}{16}$-in. steel ground cable was run on the tops of all the poles and connected to every bracket and at every fifth pole a ground rod was run down the pole and attached to a cross bond and also to a pipe or a plate ground, the latter being used when there was any moist earth near at hand. This general scheme is the cheapest method of combining the grounding of brackets and lightning protection and it has an additional advantage of stiffening the pole line considerably.

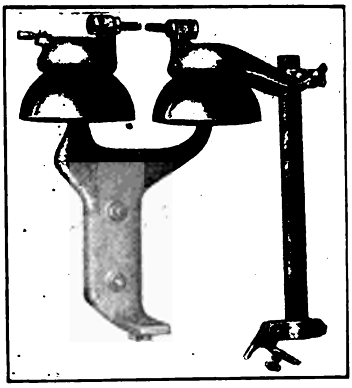
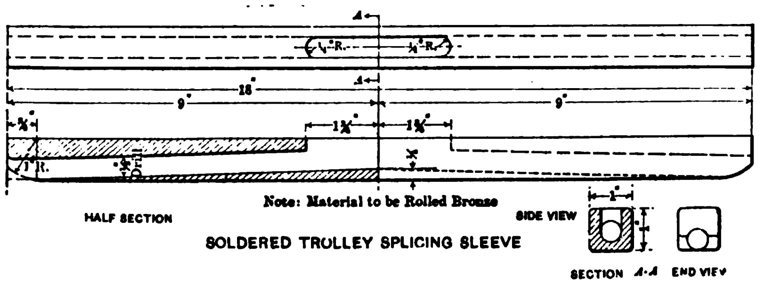


FIG. 31—Fuse type lightning arrester

If circumstances make the use of line lightning arresters desirable, the swinging fuse type shown in Fig. 31 may be installed at intervals of a half mile. This arrester has given good service for three years on the Erie railroad, at 11,000 volts.

Splices. For a trolley wire at ordinary tension, the old forms of splicing sleeve did fairly well, but where the tension is great and the wire very stiff, as with phono-electric or steel wire, the old form of sleeve, with the necessity of curving the wire slightly in order to get it through, is inconvenient, especially for quick emergency work. A sleeve with both holes bored perfectly straight and inclined slightly upwards toward the center will allow the trolley to enter and pass through without binding. To insure sufficient strength. this type of sleeve is made out of rolled bronze about 1 in. square with rounded edges, as shown in Fig. 32. Experiments showed that it was not safe to depend upon a mechanical splice that involved bending trolley wire beyond the elastic limit, although such a splice would be very quick and easy to make. For splicing messenger wire, use is made of cable splicing sockets shown in Fig. 33. To absolutely prevent the messenger wire from pulling out, the ends of the strands were doubled back on themselves, the cable end pulled back hard into the socket, and babbitt poured in.

Moving Contact. It is the writer's impression that the high voltage catenary construction now in use is in nearly all cases operating under conditions favorable to the sliding bow. The



SOLDERED TROLLEY SPLICING SLEEVE

Fig. 32

conditions on the New Haven road are doubtless more severe than any other as they involve high speeds, many low bridges, and the heaviest currents yet demanded in alternating-current railway work. On nearly every other single-phase alternating-current railway the traffic is in single-car trains, or with much lighter locomotives, and at lower speeds. More skill and judgment are needed to erect and maintain catenary than direct suspension, and experience shows that the fundamental difficulties preventing smooth operation arise primarily from the expansion and contraction due to changes in temperature, which must be overcome by following some of the methods herein suggested.

Barring the tendency of the old fashioned trolley wheel to jump at high speed, even on fairly well aligned wire, it has proved a reliable contact maker up to the limit of its capacity, and has shown itself readily adaptable to all conditions of sag in long spans. The gradually increasing use of the catenary construction with the wheel trolley, a combination which seems to be well thought of by railway operators, encourages the writer to believe that in the heavy railway work of the future on trunk lines or over long distances, where high voltage alternating current is the obvious solution, the rolling contact will tend to reassert its superiority over the sliding bow. The manufacturing companies, to whom engineers generally look for progress in such matters, cannot be said to have made much progress in this direction during the last few years. Although the writer has not been in a position to conduct any experiments with the roller type of trolley, nevertheless, in the absence of convincing proof to the contrary he is disposed to believe that it may yet be so developed as to constitute a distinct improvement over the present sliding bow, in the rough and ready service which the trunk line work of the future is sure to require.

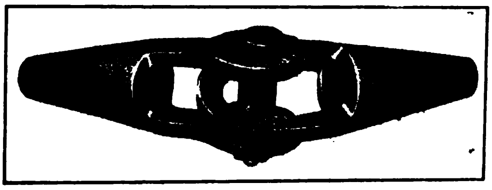


FIG. 33—Cable splicing socket

As has been the case before in some practical electrical matters, progress in this respect has (in the U. S.) had its start on the Pacific Coast. On the interurban cars of the San Francisco, Oakland & San Jose R.R. there are now in use pantograph roller trolleys of the type shown in Fig. 34. " The roller for these trolleys, which is held against the wire by a spring connected with the pantograph, is a brass cylinder 5 in. outside diameter and $\frac{1}{8}$ in. thick. The pantagraph has a vertical movement suitable to accommodate the rise and fall of trolley wire 14 to 22 ft. above rails. This type of trolley requires little attention and the brass cylinders show an average life of about nine months on cars making 250 miles a day."* These cars are working on 600-volt direct current and have four 125 h.p. motors, so that the roller trolley

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* Quoted from the *Electric Railway Journal*, Oct. 2, 1909.

evidently carries quite a respectable current, It is to be hoped that the heavy alternating current locomotive work of the future as well as the multiple unit car operation can be made even more successful than now, and the wear and tear on trolleys and line construction diminished, if the development of the roller contact trolley can only be given the attention to which it seems entitled.

The life of 67,500 miles for pantagraph roller trolleys, computed from the above quotation, seems incredible, and in the absence of detailed records may be somewhat discounted; but it is quite evident that the device is worthy of consideration. The life of pantagraph shoes is variously reported as all the way from 8,000 to 15,000 miles on single-car interurban lines, and very much lower than this on the New Haven road, where the conditions of high speed, heavy currents, more rigid trolley construction and low bridges, all combine to wear them out rapidly.

FIG. 34—Brown pantagraph roller trolley

Double Trolley Construction. The writer has paid no attention in this paper to double trolley construction as distinct from standard types, because it is used so little in the United States, either in direct current or alternating current systems, that it is not at present a matter of very great interest. Where used, it is generally erected with the same types of overhead material as are used in single trolley construction.

The Europeans have worked it out for three phase alternating railway equipment with all the care and neatness that characterizes their construction. They seem to be willing to put up with more complications in the accomplishment of results than does the average American engineer, and the principle of adherence to form rather than simplicity in attaining a result seems to prevail both in the personal side of railway administration and in the development of mechanical and electrical ideas. This temperamental difference is further manifested in the much greater respect shown by Europeans than by Americans for law, rules, and formulæ of every kind. While the American character would doubtless profit by stricter discipline in the matter of legal observance, there are some aspects of close adherence to theoretical rules and precedents which are essentially in conflict with the necessities of American railroading, and it is very doubtful whether any American railroad man will ever become reconciled to erecting two trolley wires of opposite polarity over any railroad track, if he can possibly get along with one.

It is the writer's opinion that this one condition more than any other, will retard three-phase railway development in this country. The discussion of Dr. Hutchinson's recent interesting paper on the three-phase electrification of the Cascade Tunnel indicates that while the three-phase motor was very well adapted for slow speed locomotive duty, the only really unsatisfactory element in the equipment was the overhead construction, though this was partly due to certain conditions imposed upon the engineers by the railroad authorities. Single trolley operation over steam railroad tracks has now been carried on for so many years as to be practically commonplace even among railroad men; and an object lesson of a more universal type than the Cascade Tunnel will have to be presented in working order, before the present convictions of American steam and electric railway operators, with respect to the double trolley, can be changed.

In considering the development of heavy electric traction on trunk line railways, therefore, we are brought back to our starting point by the controlling influence of the working conductor:—namely, that it is the trolley system rather than the motor which is the characteristic feature of a railroad, and that that type or system of motors will ultimately prevail which can utilize the cheapest and most easily maintained working conductor for the required conditions of operation.

At the conclusion of this paper six lantern slides of European catenary construction from illustrations kindly furnished through the courtesy of the *Electric Journal* and Mr. R. A. Hellmund illustrating the latest work in three-phase electrification on several sections of Italian railways. These views are published in the *Electric Journal* of May and June, 1910.

There were also shown four other views of American catenary construction on the Erie R. R. and elsewhere, including the original overhead Z-bar construction of the Baltimore & Ohio tunnel installation, which was built on the catenary principle in 1895.

For much valuable information and many of the illustrations given in this paper, the writer must acknowledge his indebtedness to Mr. J. J. Brennan of the Ft. Wayne & Wabash Valley Ry.; to Mr. T. H. Mather of the Rochester Syracuse & Eastern Ry.; to Mr. R. C. Thurston of the Erie R. R.; to Mr. H. W. Cowan of the Denver & Interurban R. R.; to representatives of the General Electric, Westinghouse, Ohio Brass, and Electric Service Supplies companies, to the *Electric Railway Journal* and to Westinghouse, Church Kerr & Co.

DISCUSSION ON "THE APPLICATION OF PORCELAIN TO STRAIN INSULATORS" AND "ELECTRIC RAILWAY CATENARY CONSTRUCTION", NEW YORK, MAY 27, 1910.

Percy H. Thomas: Mr. Kempton's paper gives us some actual tests on porcelain. We have had almost no data hitherto on the mechanical qualities of porcelain, quantitatively speaking. The manufacture of porcelain has been a secret, a mystery, and engineers have taken what was offered by the makers, taking the catalogues and selecting the best design for their purpose among those offered.

We here have a beginning of figures on the compressive, tension and other strength of porcelain as a material, some of the same sort of data as we have on steel and wood.

The compression strength of high grade porcelain is relatively very great, 16,000 lb. or thereabout. The average shearing stress here is given as 2400 lb. per sq. in., and the tensile strength as 650 lb.

This relationship between the various sorts of strength in this material dominates the form of design. We are very familiar with the shapes of insulators shown in the paper. There is one example among those of an important type of insulator in which is used the weakest quality of porcelain, and that is the suspension type of insulator, similar to Fig. 9 of the paper. This is a matter of which we should think pretty carefully.

I want to make a suggestion in connection with Fig. 9. That insulator shows porcelain in tension, as this design is made, and as the failure under test is described this insulator had better be made in some different proportion.

As shown in the paper we have a fracture at the bottom of the cap, that is across from the top of the inside pin to the bottom of the outside cap. The result is then only the tensile strength of the porcelain is utilized. If on the other hand, the insulator had been shaped differently, the pin being carried well up inside, with a deep metal cap taking hold well down on the insulator, since the pin cannot pull out without crushing the porcelain.

These tests, while they give some numerical figures are faulty in one particular. Mr. Kempton has apparently taken some insulators which he had at hand for making tests, and these show numerical results for those particular forms; but in no case are the tests such as to give us a clear knowledge of the materials as materials. Some of the insulators broke at the edge. In Fig. 3, the shearing test, there must be some tendency to split the insulator as shown; perhaps not much, but enough to render this data uncertain.

I remember some tests on one of these suspension types of strain insulators, such as No. 9, which gave a tension strain, roughly two or three times as great as Mr. Kempton has given. Possibly Mr. Kempton can say something on this subject at the end of the discussion.

There is another point which should be determined further by tests before any final conclusion is reached, and that is whether materials made by different manufacturers and materials of different compositions and treatment, will show the same unit of strength?

This would be an admirable thesis for some post-graduate work at a university or college. It is difficult for engineers in general practice to make a careful general study.

We seem in the matter of insulators to be arriving at the condition which finally comes in all new classes of work. At first designs are on the hit or miss principle but finally after sufficient investigation, reliance in made on a few of the old simple, practical, fundamental laws. For example, it is an old principle to take account of unequal expansion. The cementing in of metal pins in the strain insulator, may lead to trouble where expansion is serious. Again, if you do not allow for differences of flexibility in different materials, there is a strain on the porcelain. These matters are easily overlooked, but they are the simple principles that should have been borne in mind from the beginning.

It is often suggested that the way to get reliability in insulation, is to increase the margin of safety. This can be done quite easily in overhead railroad work where the trolley voltages are low; by choosing a factor of safety of five instead of perhaps three. This, however, is not very possible at 100,000 volts or even at 60,000 volts. Where feasible is thus possible to gain superiority and reliability at only small additional expense.

I ask Mr. Kempton a question: It is well established that a high tension porcelain insulator, 60,000-volt petticoat type, can be *shattered* by a lightning stroke without the puncture of the material, and without any arc following from the generator. This seems to be caused by something in the nature of a mechanical shock. The result is often the dropping off of the outer petticoat, it being broken close to the stem of the insulator.

I also ask Mr. Kempton if he has any suggestion to meet this condition. The phenomenon is reported at the Taylor's Falls system, and on the Ontario Power system. These are two thoroughly authentic instances. How can this strain be resisted?

Considering Mr. Smith's valuable paper, I would like to have his opinion as to the practicability of obtaining sparkless action in pantagraph trolleys by having a relatively light piece on the top of the pantagraph which shall have the least possible inertia. The heavy arms would then not be required to follow every slight movement of the sliding contact.

C. J. Hixson: It has been most interesting to have Mr. Smith trace the development of the catenary construction and listen to his comments and descriptions of the various devices used in connection with the same.

It has been stated that catenary construction was first brought out in 1904. In 1903 while connected with the Allgemeine Elektricitats Gesellschaft, of Berlin I remember discussing and inspecting with visiting Westinghouse engineers, the catenary line installed by the Union Elektricitats Gesellschaft upon a branch of the State Railway known as the Nieder Schonweide-Spindlersfeld line. In October of the same year, the *Street Railway Journal* published an illustrated article describing the installation. I have no doubt Mr. Smith meant, that it was first used in this country at that time.

In Mr. Smith's comments regarding catenary developments abroad, and the improvements upon the New Haven System, as well as the experimental line of the Connecticut Company, he states there is a general feeling of satisfaction with these constructions. It is significant that all of these have a more or less flexible trolley wire.

This vertical flexibility of the trolley wire is, it seems to me, the keynote to the successful collection of current from a trolley wire.

The general conditions of stability and of sidewise anchorage, limit the vertical flexibility to a few inches, and it is necessary to assist this flexibility by frequent supports or hangers

The height of the wave in the trolley wire as the collector passes along should be such as to take up all the sag between hangers and still raise the hanger a couple of inches as it passes under it.

The lifting of the hanger to a floating position eliminates the blow that would be delivered to a rigid support. Catenary hangers rigidly connected become increasingly hard as the bracket arm is approached. With a flexible hanger the increased and ever present flexibility at the point of contact, compensates in a measure for the inherent sluggishness of the roller pantagraph so complimentarally referred to in the latter part of Mr. Smith's paper.

For very heavy currents with two trolley wires side by side vertical flexibility is of great assistance in keeping the necessary contact pressure down to a modest figure and yet maintaining continuous contact with both wires at all times.

In order to have vertical flexibility the strain in the trolley wire should be moderate say from 1200 to 1500 lb. With this tension, with hangers 13 feet apart and with a No. 4/0 trolley wire, a vertical flexibility of an inch or so can be attained with an upward pressure of about 7 lb. This reduced tension in the trolley reduces the strain upon pull-offs, anchorages, strain insulators, and the line in general, thereby decreasing the original cost and the cost of maintenance.

In order to maintain the tension between reasonable limits at different temperatures provisions should be made for taking up the slack without disturbing the hangers and pull-offs.

The trolley wire is held best on curves by frequent pull-offs. This gives maximum flexibility with low stresses and moderately strong strain insulators. On earlier installation steady braces were used, but they have now been superseded by either flexible pull-offs or line steadiers. A steady brace when used as a strut gives a hard spot in the trolley wire.

Regarding pole spacing on curves, the table given is, we assume, designed to be used with no other points of pull-off than a steady brace at each pole. It is possible to maintain this same offset of the trolley wire from the center of track and use a longer pole spacing by running a back bone and using more pull-offs. This also makes a more flexible construction. If the curve happens to be on the side away from the pole line, a bracket extension can be used to support the backbone.

In conclusion it might be said that a single messenger flexible catenary has been in successful operation for the past two years upon the Saratoga Division of the Schenectady Railway. There has been no sign of wearing the galvanizing on the messenger wire due to the movement of the loop, as the sides of the same seldon if ever more than just touch the messenger wire.

R. D. Coombs: Before attempting to say anything about the experiments made by the Pennsylvania Tunnel and Terminal Railroad about two years ago, I might call attention to a few general facts, or rather, general considerations.

Since the track on which the equipment runs is not a plane, but a series of vertical curves, I think that it is entirely unnecessary to attempt to keep the trolley wire perfectly horizontal. The equipment will not run in a plane, and so I cannot see why it is necessary to keep the trolley wire in a plane. That is aside from the fact that you cannot do it.

The question of flexibility is as yet very uncertain. The Germans have used a secondary catenary, and according to their statement it is entirely successful, but their speeds and train-loads are less than our own. The experiments to which I referred a moment ago seem to indicate that a single catenary with a very light hanger, composed of a flat section, 1⅛ in. by $\frac{3}{16}$ in., looped over the messenger, and with the ordinary type of ear, was about as successful during the limited range of those experiments, as the German type with the auxiliary catenary. I am inclined to believe that a light hanger particularly in conjunction with a trolley wire having considerable stiffness and strength, possibly a steel trolley wire, as I believe was used on part of the New Haven installation, with either a copper messenger or copper feed wire to provide the necessary conductivity, would be a combination worth very careful investigation, and perhaps some experimentation.

The little hanger which loops over the secondary wire and attaches to the trolley wire, permits vertical movement, but seems to have a tendency to roll. On a portion of the experimental line, in putting up the trolley wire, it was found that the trolley wire had a twist or roll in it; and that the little hanger above the ear rolled laterally, and became to a certain extent, bound, particularly at a pull-off. That same criticism, it seems to me, would apply to one of the figures in Mr. Smith's paper. I refer to Fig. 27. I should expect that inclined hanger, which is the same as a pull-off in effect, to roll, and I ask Mr. Smith whether that tendency has been experienced?

I am rather inclined to question whether it is necessary to pull the trolley wire to an excessive tension; and I believe that to be a subject which requires more investigation. I think the rigidity, and the tension of the trolley wire, the rigidity of the catenary above the trolley wire, and the flexibility or " intelligence " of the pantagraph should all be considered together; and that the failure of no one of them should be allowed to prejudice the particular arrangement of design.

Until these features are all brought into a harmonious relationship, no single arrangement can be termed saitsfactory. The pantagraph has always seemed to me to be a suitable field for experiments, and it should be noted that the secondary flapper, according to the statements of the German engineers, has given entire satisfaction abroad.

Director Freishmuth of one of the German companies, told me on his visit to this country about two years ago, that their auxiliary arrangement on top of the pantagraph, gave entire satisfaction, and that it did not spark. Their speeds are less than ours, and I believe their train-loads are also less; but if these pantagraphs have given the satisfaction abroad which it is claimed they have given, it would certainly seem that the pantagraph is a field for further experimentation and improvement.

Fig. 14 shows the messenger wire broken at each support, that is, each span, is a unit in itself, the advantage of which Mr. Smith questioned. I believe one reason is that the short span can be assembled on the ground, the hangers placed, and the end socket can be done either on the ground or in a convenient shop. It does not require an aerial operation.

The combination of the steel trolley wire and the copper messenger is in use on the New Haven and it was to be tried on the experimental line. It was not installed, but it was because of no lack of faith in it as a device. I believe the grease from the pantagraph shoes, or a system of greasing the trolley wire will prevent any rust.

The loop, attaching the hanger to the messenger wire, in case a loop is used, should be properly fitted at the top in order to allow the hanger to be vertical.

I do not think I can add anything in a very definite way, insofar as the results of the experimental line are concerned. It was necessary to put up comparatively short sections of different types of supports, different types of suspension, and different types of catenary. And as a result there was not a sufficient length of any one type to produce a determinative test. The locomotives passed rapidly from one section to another and it was almost impossible to ascertain on which section the wear of the pantagraph shoe occurred. The relative wear could only be inferred by observation of the action of the pantagraph on a given section. At the same time it was possible by observing the action of the different types, to determine with more or less accuracy, a certain degree of relative merit.

The experiments did not continue through a round of seasonal changes, and definite results were not obtained, but I am inclined to question whether on long spans, there is any objecable action due to the tensional changes. The German construction, with the tension devices by which the wires are automatically kept at a certain tension by weights at the supports, were used, but no definite results were obtained. We obtained just as satisfactory service on sections where the device was not present.

R. C. Thurston: During a high wind and from the rolling of the car, unless the wires are in ideal condition, there is a good deal of slack wire, which will cause the trolley or the pantagraph to go to one side and dip, and while over, allow the ends of the shoe to hit the cross arm. If the wire was perfectly tight, this would not happen. When our road was first installed, we had no such trouble, but after the heat of summer and the cold of winter had expanded and contracted the wire, there was slack. But owing to the expense and the lack of time between trains, it is not always advisable to pull a slack wire tight.

The spacing rods are clamped tight to the messenger wires. I believe there should be a loop at the top of the spacing rod to allow the spacing rod to slide along the messenger wire, as the slack in the trolley wire would not then form the kinks in the trolley wire that it does now.

We have had several bad cases of brakes in the copper wire and the brake is not sudden, we found it to be an old fracture, which was probably caused by the pounding of the shoe. As these breaks do not occur in cold weather, it shows they were not from contraction of the wire through cold. The break is always formed after the car has passed over, and it always caused us to put a splice in the wire.

Chas. R. Harte: It is too often forgotten that the overhead construction of an electric railroad serves in two capacities.

As a conductor by which energy is transferred from the central station to the collecting device of the motor its function is simple and well understood; that it is also the track upon which the collector travels at high speed is a fact too frequently ignored, although it is in this latter capacity that practically all of the serious problems and difficulties arise.

In the case of a railroad, light rails laid on soft ground, where a marked displacement wave precedes the train, will, within their load capacity, give as smooth riding, and will require as little maintenance as the hundred pound rail on stone ballast as unyielding as possible. But if in either class of track there is permitted to occur a spot of opposite nature, so that there is an abrupt change in the character of the displacement wave, there immediately follows rapid wear and serious injury.

Precisely the same results are manifested under similar conditions of the overhead; a hard point in an otherwise flexible line, or yielding spots in a rigid trolley at once develop kinks, crystallization occurs, and presently the wire breaks.

Up to the present time developments have indicated that the flexible line is easier of attainment than the rigid type; the writer believes, however, that the possibilities of the rigid construction have been by no means exhausted, and hopes to see further experiment in that direction.

The unfavorable condition is that in which whatever the cause, the trolley wire tends to bend on a short radius. In the earlier lines the comparatively large sag gave a large intersection angle at the points of support, and the clips being straight and short caused kinks in the line, in passing which the collector tended to momentarily reverse the bend on the approach side, and to deliver a sharp blow against the opposite side. The supposed necessity of eliminating the large sag led to the development of the catenary construction, as pointed out by the author. But, and this would seem to be the point urged by Mr. R. D. Coombs in his discussion of Mr. Smith's paper, a truly straight trolley wire is by no means a necessity. It is not the amount of the intersection angle at directional changes, but rather the shortness of radius of the enclosed curve that causes injury. With a long radius bend, and a type of support which would either gradually damp out the displacement wave or would transmit it without material interference, a heavily sagged trolley ought to give excellent service under severest conditions. Such a type of suspension, employing spans of two hundred and forty feet with a sag of thirty inches, the wire being carried in a curved ear of special design and some forty-four inches long, has been proposed by Mr. Joseph Mayer, Consulting Engineer (see Transactions American Society of Civil Engineers, Volume LXI, page 5) but so far as the writer is aware, has never been actually tried out.

The author, in describing double catenary construction says: "The excessive rigidity of this type has been found undesirable in practical operation". As an unconditional statement this is open to question. It is quite true that the first installation of this type to receive a thorough tryout was not entirely satisfactory, but the difficulty arose from the fact that while the hangers were very rigid, the line between yielded. At the critical speed the resultant chatter of the collector became synchronous with its period of vibration, and the line received severe punishment from the heavy blows of the pantagraph, in addition to the tendency to crystallization from bend reversals. The difficulty was most successfully overcome by duplexing the trolley, attaching the lower wire to the old trolley only at the centers of the secondary spans, but it is at least open to question if equally good results would not have obtained had the line been made uniformly rigid by the use of a tee or similar stiff section attached to the hangers.

As pointed out by the author, the question of the side clearances of poles is very important on electrifications and particularly so on railroads with black signals. Eight feet from center of track to face of pole brings the latter practically in line with the signal mast in its usual position and the engineer or motorman is hedged by an apparently solid wall of poles, behind which except as it is very near, nothing can be seen. Certain types of signal employ a centrally pivoted blade, half being in front of the mast, to obviate this difficulty of sighting, but even for this, ten feet clearance from track center to face of pole is little enough.

The author's conclusion that the trolley wire should very closely follow the center line of the track will have the endorsement of practically all operating men, particularly if qualified by the further proposition that for wheel work the center of track is to be considered projected through the center line of the car, in order to meet the offsetting of the wheel by the super elevation of the rail. This same offsetting affects the lengths of brackets on curves particularly if the poles are on the outside, in which case the bracket bar will often have to be materially longer than the standard.

Operating men generally will further agree with Mr. Smith that the irregular and unavoidable cross motion of the shoe, due to various car movements and sways, entirely obviates the necessity—and most undesirable complication—of staggering the trolley wire to prevent localized wear on the collector.

To secure the desired alignment on curves the preference of the writer is with the method by bridle between poles, from which are taken equidistant pull offs. It is of course desirable to maintain this backbone dead, but on light curves the weight of the insulators is apt to cause sags which may prove troublesome. This can be helped by placing the insulators at the bridle, in which case of course the pull off itself is alive. In at least one instance the pull-off, of a single piece of seven strand steel rope, was unlayed for the proper distance, three strands going to the messenger, three to the trolley, while the seventh, whipped on the main portion, prevented further unlaying.

There seems to be little actual knowledge as to the comparative values of various types of catenary detail. In the matter of brackets the author expresses a preference for the three part pole collar as the method of attaching the over support rod to the pole. This is a point needing further investigation. The practice of passing the over support rod through a hole in the pole offers opportunity for decay to start, and weakens the pole slightly; on the other hand it has been the writer's experience that the pole collar, unless crushed into the pole, with consequent liability to decay troubles, is apt to slip and lower the end of the bracket. The connection at the bracket end of the over support should also be positive; collars held by a set screw are prone to work loose and make trouble. As to bracket bar, the compound types offer greater attachment facilities, but are presumably more subject to corrosion. Devices at the pole end which permit lateral swing in case of unbalanced pull in the trolley save the bracket in case of heavy strain, as in the case of a broken wire, but the overhead is seriously slacked off for a number of poles each way; with rigid pole connection the brackets nearest the break are apt to be badly crippled if not ruined, but the area of disturbance is much less, a factor of great operating importance. The forms which split and take the pole between the members will stand very severe punishment from a trolley pole that has jumped the wire; socket pole connections, unless pinned or otherwise secured, are very apt to be shaken apart or broken under the same conditions.

As pointed out by the author, the matter of proper tension in the wire is complicated by the fact that conditions preventing excessive sag at high temperature result in very high stresses at low temperatures. How closely these stresses may approach the actual breaking strength of the wire is not always realized. Grooved 4/0 copper trolley is usually credited by the handbooks with a breaking strength of from 8000 to 8400 lb. A series of tests made by the writer, however on commercial stock samples gave a maximum of barely 7100 lb. on the unbrazed portion, with an average at brazes of 5600 lb., two samples failing below 5000 lb. (see Transactions, American Society of Civil Engineers Volume LX page 552).

While there are some differences as to detail commercial trolley wire is in general made from a "wire bar" of rectangular section, which is first rolled down to a round rod and then is finished by drawing. Brazing usually is done just before drawing, and in the samples tested it was evident that the latter treatment was not sufficient to overcome the local annealing at the surfaces of the braze.

The tension is properly dependent upon the nature of the overhead. If hangers are rigid the line between should be given equivalent vertical stiffness either by the form of cross section or by the tension; if hangers are yielding a much lower stress is permissible.

To secure an automatic adjustment the first Syracuse, Lake Shore, and Northern catenary had in the $\frac{7}{16}$-inch stranded steel messenger, at 20 deg. fahr. and for the standard span of three hundred feet, a sag of sixty-eight inches, but the trolley was a foot higher at the center of span than at the supporting bridges (see Transactions, American Society of Civil Engineers, Volume LX page 547). It was hoped this would minimize temperature troubles, but in the writers estimation its chief virtue lay in the fact that it materially stiffened the system against lateral sway. Later installations on this and allied lines have omitted this feature.

It is generally believed by users, that trolley wire could with advantage receive further treatment than is at present usual, for the market material of to-day certainly has decidedly less resistance to wear than the earlier output.

The writer is watching a working test of especially rolled wire which gives to 4/0 grooved copper an average breaking strength of practically 9000 lbs., but there has not elapsed sufficient time to permit any comment of value. The manufacturers, so far as the writer knows, have as yet set no commercial price on the treatment. Mr. T. H. Mather of the Syracuse Lake Shore, and Northern has for some time employed a wire which receives extra finishing treatment. The additional cost was, some time ago, about 6 per cent of the price of untreated wire; at that time Mr. Mather considered the resultant economy in maintenance and repair to be several times that figure.

But it is after all an illogical proceeding to impose the duty of resisting the abrasive action of the collector upon that member of the overhead which by nature is least adapted to resist wear, and functionally is most affected by loss of section, as is the case when the trolley wire is of copper. Phono electric and one or two other bronzes have for some time been used at points of unusually heavy wear, but the employment throughout of a trolley wire designed primarily to resist wear, as in the case of the Denver and Interurban's phono electric, and the New Haven's steel, is of very recent date. The author will doubtless be interested to know that his suggestion of a steel trolley and copper messenger has actually been in service for over a year. The trolley wire is identical in section with 4/0 grooved copper; the messenger is 19 strand bare copper wire cable sagged 24 inches for standard spans of 150 feet. This is on the experimental catenary section of the Connecticut Company's Hartford-Middletown line and the steel wire is continued for about half a mile beyond the catenary in simple suspension. At night the wheel has a bright tail of light but the actual wear in over a year's service is inappreciable, and this is also true of the messenger where it was feared the loops of the sliding hangers might cut the copper. This latter would indicate less danger to galvanizing on a steel messenger from sliding hangers than has been anticipated by some.

The Connecticut Company's experimental catenary has not had long enough service for final deductions as to the most desirable type of hangers, but indications to date seem to point to the old mechanical screw clamp ear with light hanger rod rigidly fastened to the ear, and looped over the messenger. The screws should be long enough to head up after the trolley is gripped; if this is properly done the type is at least as efficient as the more elaborate forms, and is far simpler. In this connection the author expresses a preference for " a nut screwing down on the lower end of the hanger rod, as in figure 24 as it can then never work off ". In the writer's experience, while the nut cannot escape, it has been found necessary for such types of hangers to be fitted with a locknut, as otherwise the main nut backs up to the rod enough to loosen the clamp and permit serious wear.

Rigid hangers require high trolley tension, and in case of relative movement of trolley and messenger are apt to come to grief; hinged types if jointed top and bottom and rigidly gripped to messenger allow relative movement and give a little flexibility that hardly seems commensurate with the complication. Bottom slide hangers seem unduly subject to wear, but have the marked advantage that the parts lifted are all of equal weight. The foreign sliding hanger lines have a secondary messenger of very slight sag and the loop hangers are all of equal length and weight; that satisfactory results were not obtained on certain American lines where hangers varied in length from four to twenty inches is hardly surprising. Long loop-hangers hinged at the ear have a tendency to tip when lifted, and sliding down the messenger lose their characteristic feature, and as a result of the shortened effective length, pick up the trolley.

Hangers with jaws closing symmetrically with reference to the rod will, within the limits of their capacity, take various wire sizes equally well; hangers in which the jaws do not so move however, while they have a small range, do not work well on sizes other than the one for which they were designed. For shoe work the contour of the jaws is of less importance; for wheel work it is essential that the jaws give good clearance lines, or, particularly on curves they will be badly pounded.

The matter of hanger spacing is one on which is needed much practical information—in fact this need of much practical information is characteristic of the entire subject of overhead construction. On a forty-mile-per-hour installation for wheel operation, with main spans of one hundred and fifty feet, excellent results are being had with a secondary spacing of ten feet, and barely twenty miles away equally good results are obtained on an installation identical except that the secondary spacing is fifty feet. It is the general impression that for shoe work the secondary spans should be very short; the writer knows of no installation on which long secondaries have actually been tried out, but it would seem that the manifest economy, if the number of hangers can be materially reduced without impairing the efficiency, warrants careful investigation.

The author touches a point of great importance in construction in the matter of hanger rod lengths for various spans. Theoretically the sag of each span should be mathematically exact; practically unavoidable variations occur to an extent which warrants the small amount of " fudging " which may be necessary to adopt standard span hangers to the shorter spans. The importance of reducing to a minimum the labor and the chance of error on the tower cars is best appreciated after a practical experience. In electrifying an operating steam road the work trains lose from fifty to seventy-five per cent of their actual time, the lower figure being reached only under very favorable conditions; with much traffic on the line the time lost dodging trains may easily exceed the seventy-five per cent.

The author's point that strain insulators should under mechanical and electrical stress at the same time, is well taken, particularly where the strains are of the compression type where movement of the parts which in no ways affects the mechanical strength—in some cases actually increase it, due to better seating of parts—may completely destroy the insulating properties.

The difficulty of securing good strain insulators for high voltage work makes desirable the suspended bracket construction similar to that on the Rochester Terminal, and which employs a standard line insulator, in spite of the fact that its weight and area are decided draw backs, particularly in sections subject to sleet.

The author's hope that further investigations will be made in regard to roller types of collar will be shared by all who have investigated the subject and it is by no means impossible that a modification of the present form of trolley wheel may be of much value. The writer has for some time had in mind a shoe design in which the main pantagraph movement ranging through several feet should be effected by some positive mechanical device, probably a pneumatic cylinder, the air supply to be controlled by a sensitive contactor mounted on the main pantagraph. This contactor, having little inertia and therefore able to follow the wire almost instantly, would take care of variations within its range of about one foot each side of the middle point. The valves operating the main traversing device would open as soon as the contactor passed this mid point, and in most instances the response would be sufficiently rapid to keep the movements of the contactor within its limits. If, however, the depression or raise of the wire was so rapid that the main device did not attain the speed at which the change was occurring before the contactor reached its outer limit the conditions would be no different from those which at present obtain a very material portion of the time; on too rapid raise there would be an actual break in the contact; on too rapid depression the main traverse would be forced down by the overhead until its acceleration was equal to the rate of drop in the line.

Ralph D. Mershon: The author says that porcelain " can be moulded and worked into almost any desired form or size " This does not agree with my experience. I have designed insulators from time to time and endeavored to have them made out of porcelain. In some cases I have succeeded in having them made, and in some I have not. Not infrequently, where I did succeed, the price was prohibitive. As the result of the experience gained from such work in connection with a number of the insulator manufacturers of this country, I should say that porcelain, for insulators at least, can be practically moulded and worked into very few forms of limited size. The present practical limit in thickness of porcelain of high dielectric strength is about ⅝ in. In some cases it is possible to get thicknesses of ¾ in. of high dielectric strength, but such pieces are usually produced at very considerable expense, and their production is uncertain.

The author's investigations of the physical properties of porcelain are interesting, but might, with advantage, have been carried a good deal further. The procelain he tested could hardly have been of the best quality as regards mechanical strength. The highest grade high-voltage porcelain made in this country will show a tensile strength of from 1,500 to 2,000 lb. per sq. in and a compressive strength of approximately ten times this. These figures are the result of a great many tests made by myself and by others.

Of course, ceramic materials of all degrees of strength less than this are met with, but it is also possible to obtain material of greater strength. I have tested ceramic material which ran as high as 2,400 lb. per sq. in. As it happened, however, this material was not the highest grade high-voltage porcelain. It was not vitrified throughout, if it was vitrified at all. The fracture showed fissures, and in general its appearance was such as to lead one to think it would have a very low tensile strength.

·There is a great deal of work to be done yet in connection with ceramic materials for electrical work, and undoubtedly room for great improvement. It is extremely desirable to determine the conditions which affect the mechanical strength of such material, especially the tensile strength. Some investigations I have made seem to indicate that it is possible for porcelain to have a grain, something almost of the nature of a fibre, such as we find in wood or wrought iron.

A great deal depends, with different mixes, upon the amount of moisture present when the piece is formed, and whether the piece be formed by pressing or by the plastic method. It would appear, also, that, with some porcelain mixes at least, the degree of firing has a great deal to do with the strength. In some cases it would appear that a temperature considerably below that at which the mixture will vitrify, or even begin to vitrify, will result in greater tensile strength than if the heat be carried higher.

My investigations have been confined to American porcelains. Apparently some of the European porcelains run a great deal higher in mechanical strength. In the discussion of a paper recently presented before the Institution of Electrical Engineers at Manchester, England, Professor A. Schwarz gives the results of some tests he made upon porcelain. The tensile strength ran from 3,316 lb. per sq. in., for a rectangular test piece with a section of 0.2 sq. in., down to about 2000 lb. per sq. in., for a rectangular piece of 0.6 sq. in. in section. He found a compressive strength of 10,000 lb. per sq. in., for a cylinder two in. long by two in. in diameter; 40,000 lb. per sq. in. for a cylinder one in. in diameter, and 52,600 lb. per sq. in. for a cylinder $\frac{7}{16}$ in. in diameter. He ascribes the lesser strength in the larger pieces to lack of heat penetration in firing, but I think it not unlikely that the apparent fibrous structure mentioned above had also a considerable amount of influence, especially if the cylinders were formed from plastic clay. It is evident that with such formation, the smaller the cylinder, the greater the proportion of its bulk that will partake of a fibrous structure.

In this matter of comparing strengths of different samples of porcelain, we, in our present ignorance, assume that all porcelain is alike. Such comparisons are about as logical as to compare tests made on high grade steel and tests made on the poorest quality of cast iron. Until this whole subject is given a more thorough study, we shall have no intelligent basis on which to compare results obtained at different times and with materials obtained from different sources.

O. S. Lyford, Jr.: The ideal conductor for the distribution of electric power for heavy railway operation is one that is either absolutely flexible or absolutely rigid, and parallel to the running rails. For low voltage work, which in heavy service involves the collection of large currents, the tendency is towards the rigid conductor, as characterized by the third rail. For high voltage work and consequent low current the tendency is towards absolute flexibility of structure and catenary trolley construction has been the best development thus far. Improvements in third rail construction have been in the direction of greater rigidity and improvements in catenary construction towards greater flexibility.

For intermediate voltages, it remains to be seen what construction will prevail and neither of these two, as now developed, is entirely suitable. For instance in the 1200 volt direct current system the currents are high for heavy railway operation. A locomotive such as recently adopted by one of the large railroads with motors capable of developing 4,000 h.p. in starting, the maximum current at 1200 volts would be 2800 amperes and the running current for maximum weight of train 1250 amperes. A suitable conductor for distribution of current to such locomotives must necessarily be heavy and the logical development is in the direction of rigidity of construction. This means either the perfection of a safe 1200 volt insulation for third rail or the development of a rigid overhead structure. The latter will necessarily be a very heavy and expensive construction and one open to many objections from the point of view of railway operation and maintenance. The former is possible, and is already being tried out, but if designed for usual railway clearances it will necessarily be cramped.

The two papers presented to-night relate to materials and apparatus for light structures with moderate stresses and therefore apply more particularly to constructions approaching absolute flexibility. The discussion should be considered from that point of view.

Referring first to Mr. Kempton's paper, the tests reported verify the conclusion that porcelain used in compression is suitable for such strains as are likely to occur with a flexible and comparatively light overhead system. Referring to the question raised in the paper as to whether mechanical stresses weaken the porcelain stock electrically and therefore whether the combined mechanical and electrical test is necessary, it is the writer's belief that Mr. Kempton has arrived at the answer in the following statement:

> " It was thought probable that the high stress in the section of porcelain under the load opened up slight flaws in the stock, rather than causing the sound porcelain to puncture below its unstrained puncture voltage."

It is possible that if the compression were applied to the insulator stock in such a manner as to absolutely distribute the pressure uniformly, there would be no evidence that a mechanical stress within the breaking limit weakened the insulator electrically. As a matter of fact, insulators of the style illustrated by Fig. 9 of Mr. Kempton's paper are subjected to a fairly uniform and not very heavy unit stress, this being in tension.

With the various forms of insulators for use in compression, however, the stress is not distributed uniformly, as the metal parts are are necessarily elastic. For instance, in the double spool strain. insulator illustrated by Fig. 29 of Mr. Smith's paper, there is necessarily some irregularity in the application of the mechanical stress to the porcelain. This difficulty also exists with the " loop " or " fish-tail " type of insulators. It was in the testing of these two types of strain insulators that we found it necessary to apply mechanical and electrical stresses simultaneously to determine the true safe limits of the insulator. It is the writers belief that after sufficient experience with a strain insulator of a given form it will not be necessary to make the combined tests on every insulator, but in this catenary work for heavy electric traction, which will usually have to be erected over a line already in operation, any reasonable expense in testing which will avoid replacement of insulators in the completed structure will ordinarily be found justifiable.

Referring to Mr. Smith's paper, the following comments are offered.

Poles and Bridges. There is still room for the development of a light form of pole to take the place of wood. One of the principal criticisms which maintenance-of-way officials make to the electrification with overhead trolley system is the danger to persons and property in the case of a derailment or collision which may result in overthrowing the overhead structure. It has been found that with wooden poles supporting a strong catenary structure, a derailment will result in cutting away the pole without bringing down the conductors. Heavy bridge work or heavy steel pole structures will not act as satisfactorily in such accidents.

Messenger and Trolley Wires. Mr. Smith refers to the use of a dynamometer in the rection of the messenger and trolley wires. Such practice was at first viewed with scorn by the superintendent who handled the Denver & Interurban work, and he has had very extensive experience in the construction of trolley work and transmission lines. Before the job was completed, however, this superintendent was enthusiastic over the results obtained, as he found time was actually saved and the structure when complete required very little readjustment and this only during construction and not after operation was begun. Since we left the job it has not been necessary to take out any slack or make material readjustments. This seems to prove also that the tension used, namely from 2000 to 5000 pounds, depending on the temperature, is entirely practicable and produces good results.

Use of Tension Devices for Trolley Wire. There was a question in the writer's mind as to whether the success of these devices in Europe was not due to the fact that the current collector used is very light and flexible. Such collectors are practicable in Europe where train speeds are relatively low, the variations in height of trolley are relatively small and currents collected are relatively low compared to American practice, but with the service which we are called upon to operate in this country such forms of pantagraph have thus far proved impracticable. With the American form of pantagraph shoe a pressure of at least 14 lb. seems to be necessary. Such shoes were tested out on the Pennsylvania R.R. test track and the writer watched their operation closely on the German form of catenary and compared this operation with operation on German roads previously inspected. The results, in so far as they could be noted with the brief tests on the short section of track, indicated that the American form of shoe will work as well as the European form, although this is quite contrary to the expectation of European engineers. It is the writer's belief that the success of this combination will depend on the ability to eliminate hard spots from the line. This seems possible at practically all points where high speeds are necessary.

Referring to Mr. Coomb's report that in the Pennsylvania R.R. test a form of catenary construction with one messenger and one conducting wire, the latter being supported with thin flexible hangers, gave as good results as operation on the German type of construction—this presumably relates to the action of the pantagraph shoe on the two types of conductor support, and seems reasonable to expect, as the flexibility of the simple construction is practically a great as that of the German construction provided there is sufficient distance between the messenger and the trolley wire so that the hangers are at all points long enough to be flexible. One question in relation to such a construction can be determined only by a test extending over a considerable time. This is the life of the flexible hangers. The oldest catenary trolley road in operation is that of the Stubaitalbahn at Insbruch. On this line a simple catenary is used and the hangers are of galvanized iron wire, apparently about No. 12 in size. .The writer inspected this line about two years ago and noted that many of these hangers were broken, apparently due to the vibration of the trolley wire. Such breakage will not occur with the heavier forms of trolley hangers described in Mr. Smith's paper.

Referring to the European construction mentioned by Mr. Smith, it is the writer's understanding that this construction was developed by the Allgemeine Electricitats Gasellshaft to obviate the necessity of tension devices used in the Siemens-Schuckert construction. It was believed with the use of an equalizer such as is illustrated in Fig. 16, the expansions and contractions in a catenary structure due to changes of temperature would be taken care of satisfactorily, without any other adjustment.

Catenary Hangers. Referring to the various forms of catenary hanger illustrated, one point which should be looked out for is that the hangers shall not damage the galvanizing of the messenger cable. This cable is an expensive item of the catenary structure and one hard to replace without delay to the traffic. It is therefore important that the life of the cable shall be as long as possible and to this end the galvanizing should remain intact. A form of hanger which has a flat loop over the messenger wire is therefore safer than a sister hook construction or any other form in which the cable may be more or less cramped. As Mr. Thurston pointed out, the design of the loop over the messenger should be such that the hanger can be moved along the messenger easily.

Steady Strain Device. Referring to the device illustrated in Fig. 28, of Mr Smith's paper, attention is called to the fact that the brace between the trolley wire and insulator is so short that without material change in the length of the bracket it is possible to place the steady strain insulator on either side of the main insulator and therefore always have the steady strain in tension. On other words, it is not necessary to use the steady strain as a strut which may produce a hard spot, as suggested by one of the speakers.

Strain Insulators. Mr. Smith makes a very good point regarding the disc type of insulator as follows:

> " An excellent point about the disc type of insulator when used within its capacity is that there is a mechanical linkage of the guy cables on opposite sides of it, which prevents their falling apart if the porcelain breaks."

This feature should be incorporated in all strain insulator construction. It exists in the double spool strain insulator illustrated in Fig. 29 of Mr. Smith's paper. It cannot, however, be incorporated in such wood strain insulators as now employed and this is one of the principal objections to the use of wood, as either burning or breaking of the wood will throw the overhead structure out of alignment and possibly drop it.

W. H. Kempton: In speaking of porcelain and its quality, I do not want to give the impression that I do not have faith in it, but rather that I realize its limitations. All companies making high-voltage insulators, have developed the material to such a point that it is quite reliable; and while there is still room for improvement in porcelain insulators, and while many companies are trying to improve their quality and get more uniform results, still I think it is well to admit just how reliable porcelain is, and use that information in our designs. In that way we will avoid over-confidence, and thus get a design which will not break down in service.

Regarding Fig. 9 of the paper, I regret that I did not fully explain in the original paper that this is not a commercial insulator. It was made for the deliberate purpose of getting what Mr. Thomas points out; a pure tension stress for the purpose of a combined mechanical and electrical test.

As a matter of fact, the company with which I am connected manufactures large quantities of insulators along the line Mr. Thomas suggested: that is with the pin extended far up into the head and cemented in. We have made them with a mechanical strength of over 15,000 lb. That form was not touched on in this paper, as it is used as a suspension insulator. I did not expect to include that form of insulator in the discussion, and so avoided bringing the matter up.

Referring to the other question, regarding the protection of the insulator, I personally am convinced that the breaking of the petticoats on the insulators he described, was not due directly to electrical stresses. I have punctured many insulators and have yet to find one that broke, except under mechanical strain, or due to the heat from the arc. It is possible in the instance he described, that it was first punctured, and the heat from the following arc concentrated on that spot on the insulator, caused it to burst.

Another explanation might be added although it is rather far-fetched, and I do not think is correct; that is, that type of insulator has considerable capacity, and due to the high frequency of the lightning, it is possible there would be a marked vibration of the porcelain. But I do not think it possible to get sufficient vibration to shatter the porcelain.

The large disks of porcelain, as now manufactured, are pretty tough and I think it was the heat from the arc in the case cited, that broke the insulator. I have had them fail in a very similar manner in actual tests.

Assuming however that the insulators were broken directly by stresses due to the lightning, a remedy would be the use of suspension insulators made up of a number of units. One or more of these units might be broken without disabling the line, but I do not think it possible for all of them to be broken in that way.

The accompanying cut shows a suspension insulator made up of eight units. Of course, the insulator may be made up of the proper number of units to suit the voltage of the line. Each of these units is ten inches in diameter and has dry flash-over voltage of 90,000 volts.

Replying to Mr. Mershon's comments, I think his statements in a measure verify my claims. As pointed out in my paper, the samples used were made without any attempt to secure extra good quality. The figures given are such that they may be used for design work with safety. As pointed out, especially prepared samples can be made with the same mixture and carefully burned and much higher results be obtained. Such samples are always made with uniform section and comparatively small. I have made tests with very much higher results, but did not give these figures for the reason that if they were used in a design, the insulator would fail to come up to the expectations of the engineer, and the manufacturer would be discredited as also would porcelain as an insulating material having mechanical strength.

Bronze is a parallel case. Government experiments show that bronze can be made with a tensile strength of 100,000 pounds per sq. in. and over, but practical foundrymen will decline to guarantee over 50,000 lb. to 60,000 lb. per sq. in.

It would be interesting to know if the dielectric strength of the samples made by Professor Schwarz was as good as the best American product. The two qualities must be worked out together. High tensile strength can be had at the expense of dielectric strength.

Mr. Mershon's criticism of my statement regarding the range of porcelain manufacture is in a measure merited. When it is considered that high voltage material must be moulded in a plastic state, dried, and then burned at a temperature that renders it pliable, it will be seen that it is difficult to make beyond a certain size and that the shape must facilltate moulding and drying the clay.

Referring to the " grain " noted by Mr. Mershon, it might be said that it is practically impossible to mould wet clay into insulator forms without its having a more or less marked fibrous structure. It might also be added that, to the best of the writer's knowledge, it is impossible to make high voltage porcelain by the " dry press " process. In the wet process, the clay is mixed with water to a plastic state when all air can be removed from the body. When the clay dries, it leaves a dense close grained body. In the " dry " process, the clay is ground up dry and made moist enough to make it retain its shape when pressed in a mould. Mechanical pressure is depended upon to make the body compact, and experience has proven that a sufficiently dense body cannot be obtained in this way for high voltage work.

There are one or two points I should like to speak of in connection with Mr. Smith's paper: one is in regard to the length of the brackets for a spacing of eight feet between the center of the track and the center of the pole. From a rather uncomfortable experience, I found it was necessary to use a longer bracket on curves than on tangent, when the poles were placed on the outside of the curve. This is due to the rake of the pole in one direction, and the elevation of the track in the other. With these conditions it is necessary to use extra long brackets on curves, or longer ones everywhere.

Mr. Smith speaks of lining up trolley wires on the curves when pantograph trolleys are used I think it is unwise to allow as much deviation from the center line on curves as was the practice at the beginning There are four considerations to be borne in mind in this connection. One is the rake of the pole; two, the elevation of the outer rail; three, the speed; four, the play of the bolsters on the car.

At standstill or at slow speed on curves the pantagraph trolley tends to swing toward the inside of the curve; but when running round the curve at 40 miles an hour, the momentum of the car throws it over on the bolsters toward the outside of the curve so that there is a difference of from 10 to 12 in. in the position of the trolley with respect to the wire. In one case, the line had been constructed very carefully; but in spite of that the pantagraph trolley would swing out free from the trolley wire and pull down some of the line or pull the trolley from the car. It looked impossible from measurements on the line until we discovered that the construction of the car allowed it to swing over on the bolsters when going around the curve at high speed, sufficient to throw the pantagraph clear of the trolley wire. The remedy in that case was to re-line-up the trolley wire and add more poles or pull-offs where necessary to reduce the offset of the trolley wire and then fix up the car to avoid such excessive swaying

This is one of the personal experiences I have had emphasizing the care that must be exercised in the erecting of a trolley line on which pantagraph trolleys are to be used.

W. N. Smith: The remarks of those who have joined in the discussion quite generally agree as to the fundamental principles underlying catenary construction.

As was stated by the Chairman, the overhead line still offers a great number of unsolved problems. Fortunately they are of a type capable of being attacked by the profession at large. Comparatively few electrical railway engineers have been trained as designers in electrical factories, and those who have not can hardly approach the problems of motor design at the point where the most of our alternating current railway discussions begin. Intricate theories of motor design require a mathematical ability which is not so well distributed amongst engineers generally as is the plain good sense which must underlie the planning and execution of every large undertaking in railway electrification. Problems of overhead construction, and of the equipment related thereto, are mostly mechanical, and are thus open for solution to engineers generally on a broader and more liberal basis than is usually embraced in the commercial or manufacturing point of view—as has been indicated this evening.

Taking up the various comments in their order, it seems to me that Mr. Coombs answered Mr. Thomas's question in respect to the secondary arm or tip which has sometimes been employed at the top of the main pantagraph. This device has been used on the Simplon tunnel locomotives with sliding shoe on the tip. The Simplon locomotives travel with a maximum speed of 45 miles per hour and the contact shoes are of the sliding type. Even with the lessened inertia of this device, the shoes only last about 1700 miles.

It is true that my references to the beginnings of catenary construction applied only to its use in this country, as there has not been very much evidence that at the time of its introduction in America, our practice was influenced particularly by European methods.

Mr. Hixon's reference to wave action brings out a fundamental principle underlying successful catenary construction and operation where circumstances are favorable; that is to say, I believe that the best results will be obtained when wave action, as referred to by Mr. Hixon, is recognized and provided for. This depends very largely on the construction of hanger employed, and only experience can demonstrate which type of yielding or floating trolley hanger is really the best. The experiments mentioned by Mr. Hixon and Mr. Harte will doubtless help in determining this exceedingly important matter.

The fact that the old pole and wheel trolley operates so well with trolley wires having considerable sag, illustrates the importance of recognizing wave action, which is so much in evidence with the wheel type trolley; and this confirms my belief that the natural and desirable wave action in the trolley wire will be very much helped by the roller pantograph, and with less wear and tear than with the sliding pantograph. This point of view is based upon the probability that the heavy work of the future will be at high tensions, *i. e.*, at 11,000 volts or higher, and that the trolley pole and the narrow grooved wheel accompanying it will not be regarded as thoroughly reliable for high speed operation under steam railroad conditions, so that it will be necessary to have a transverse rolling or sliding contact which will not leave the wire under any circumstances and which the motorman or the train conductor will not be obliged to regard as an extra source of responsibility or worry. The problem becomes then one of flexible operation at high speed with a transverse contact device, and it is quite evident that the successful operation of such a combination will be met only by recognizing and providing for a vertical wave action in the trolley line.

Mr. Coombs reminds us of the fact, commonly overlooked that the railroad track itself is not a plane surface as it is usually considered to be, and that the train itself makes a wave action in the rails as it runs over the track. This emphasizes the necessity for directing our efforts towards upward flexibility in the trolley wire, rather than to smoothness without flexibility.

With respect to the possible twisting in the compound catenary construction, illustrated in Fig. 27, as apprehended by Mr. Coombs; it would seem to me that where the wires are strung to a fairly even tension, and the hangers of the proper length, and all parts securely and tightly drawn up, there would not be any tendency to roll when the line is properly adjusted. If one of the wires is much tighter than the other there will, of course, be a tendency for the structure to get out of position.

I agree with Mr. Thurston that it is very desirable to have the connection at the top of the spacing rod flexible, so as to allow it to move with reference to the messenger wire. This is an instance of the value of practical experience—in showing the value of flexibility, which engineers were chary of a few years ago.

Mr. Harte emphasized the interesting fact that successful operation depends on uniformity of resistance at the contact surface, *i.e.*, hard spots should be kept out of a yielding line or soft spots out of a hard line, or, in other words, the line should be either uniformly hard or uniformly yielding. The successful operation of the Denver & Interurban catenary line has been due to the fact that it was uniformly hard and smooth, and the reason why it was built in that manner was, in the first place, because it was necessary to use the sliding pantograph bow, the wheel trolley being regarded as impracticable; secondly, we had to make use of such types of hangers as were commercially available at the time, there being no flexible type hangers of known reliability then manufactured; consequently it was impossible to construct a line which we could be sure would be uniformly flexible, and we were therefore obliged to adopt the method of making the line uniformly hard and smooth, which was done in the manner indicated in the paper, and which has proved to be successful as a working proposition. Having no means for making the line flexible, we did the next best thing; and while I will readily admit that it would in some respects have been an easier line to build if it had not been necessary to draw it so tight, two years of operation and maintenance have developed no defects, and apparently it is as satisfactory to operate as though it were of the flexible type.

The experimental lines constructed with flexible hangers mentioned by Mr. Hixon and Mr. Harte will doubtless have considerable effect in determining the development of catenary details, but it now appears that both the Schenectady and Connecticut lines are operating with wheel trolleys and not with sliding bows. It seems to me that the contact-making conditions which must be ultimately fulfilled by equipment for heavy traction are not being met in these installations, and to that extent they will be somewhat inconclusive. If they should be tried out with pantagraph trolleys of the sliding or roller type, then there would be something definite upon which to base conclusions for the heavy and high speed work of the future.

The question of clearance referred to by Mr. Kempton, is, of course, one that pertains to conditions on each particular job; 8 feet was mentioned as a minimum which was actually used in a large installation without any bad results. I believe, however, that 8½ feet is better, as used on the Denver & Interurban line.

The inclination of the trolley brackets on curves was varied from the horizontal; if car leaned away from the pole, the bracket is inclined downwards; if toward the pole, the bracket is inclined upwards, in order to prevent the horizontal pantograph bar from fouling the bracket arm.

The roller type of trolley contact has been in use in Europe for some years; the Valtellina installation in Italy being perhaps the best known instance of its application there. I referred to its use on the Pacific coast as the first and only application of its use in this country. Since writing the paper I have ascertained through the *Electric Journal* that on the Valtellina line, where the overhead construction is not very tight (and not of the catenary type) the rollers have an average life of 15,500 miles and frequently carry more than 200 amperes per roller, and that in the opinion of Mr. Von Kando of the Italian Westinghouse Co. the excellent life of the contact roller is due partly to the difference between rolling and sliding friction, and partly to the fact that each element of the roller is heated by the passing current only at the instant of contact, and does not remain in contact long enough to get melted; while with the sliding contact the wear is excessive when the current is more than 50 amperes.

It seems to be agreed that the vertical flexible working conductor is very desirable, and the best reports of smooth operation with it emanate from installations where the rolling and not the sliding contact is used.

It is my belief that trolley pole and wheel are not suitable for heavy railroad operation at high tensions and speeds, and that the horizontal transverse form of contact device is indispensable under such conditions; and I suggest that the next step forward should be in the development of the roller type of contact against the yielding or floating trolley wire, in which the elements of wire tension, contact pressure, and pantograph inertia will be compromised to produce the desired effect.

It has been stated by men who have had good opportunities for actual observation, that when speeds of 45 miles per hour or so are exceeded, the conditions to be met by an overhead contact device for heavy currents are so difficult as to be beyond the field of experience at lower speeds. Granting this to be true, there is all the more reason for developing practical mechanical devices for making contact. Only experiment can decide the question positively, and it remains to be seen whether the devices above suggested can be adapted to high speed, or whether recourse must be had to some combination yet to be invented.

Edwin B. Katte (by letter): The following is a description of porcelain strain insulators used upon a recently constructed 11,000-volt aerial transmission line and a 650-volt direct current distribution system.

Specifications. The 11,000-volt strain insulators shall be of two piece construction; the 650-volt strain insulators shall be a single piece of porcelain. Porcelain surfaces shall be thoroughly glazed a uniform brown color, shall be free from pits, cracks or other imperfections and the material sound and homogeneous throughout. All insulators shall conform to the dimensions given on the attached illustration, Fig. 1 and Fig. 2, within 3/32 in. except those given for pin holes which shall conform to the drawing to within 1/16 in.

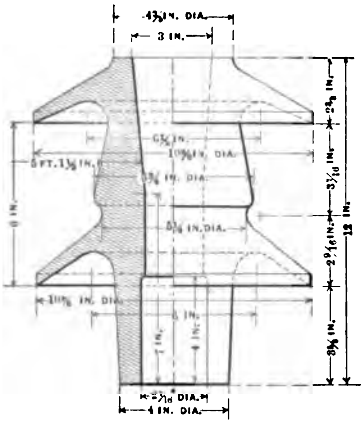
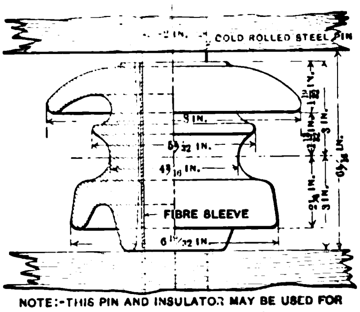


Fig. 1.—High-tension insulator



NOTE:-THIS PIN AND INSULATOR MAY BE USED FOR DEAD ENDING 150 FT. 1 MILLION C. M. SPAN.

Fig. 2— Low-tension insulator

Tests. The contractor shall supply for test free of cost 2 per cent of the insulators from each furnace charge. These shall be broken and on the exposed surface shall be placed drops of red ink which shall not spread or show signs of absorption. The exposed surface shall be free from cracks, checks, blow-holes, etc., and shall show a close and uniform grain.

A. *High Tension Strain Insulators.* Each 11,000-volt strain insulator selected by the inspector shall be mounted on a two-in. metal pin, shall be subjected to a potential of 80,000 volts applied between the pin and the wire groove for one minute without showing signs of breakdown, leakage or excessive brush discharges. When mounted in a vertical position on a 2-in. metal pin and subjected to a precipitation of ¾ in. of clear water per minute with current applied between pin and wire groove the insulators shall not break down or arc over at less than 50,000 volts. Each insulator when mounted upon a steel bar in a manner to be approved by the engineer shall safely withstand a continuous load perpendicular to the pin of 9,000 lb. applied by means of a No. 4/0 seven-strand, hard-drawn copper cable.

B. *Low Tension Strain Insulators.* Each 650-volt strain insulator selected by the inspector shall be mounted on a 2-inch metal pin, shall be subjected to a potential of 30,000 volts applied between the pin and the wire groove for one minute without showing indications of conductivity, breakdown or surface leakage. When mounted in a vertical position on a 2-inch metal pin and subjected to a precipitation of ¾ of an inch of clear water per minute with current applied between pin and wire groove the insulator shall not break down or arc over at less than 16,000 volts. Each insulator when mounted upon a steel bar in a manner to be approved by the engineer shall safely withstand a continuous load perpendicular to the pin of 10,000 lb. applied by means of a 1,000,000 circular mill, 91-strand, hard-drawn copper cable. Each insulator shall withstand, momentarily, without sign of fracture, 15,000 lb. applied in the manner specified.

SUMMARY OF TESTS

Type of insulator	Electrical requirements
11,000-volt strain	Dry, 80,000 volts for one minute. Wet, 50,000 volts without arcing.
650-volt strain	Dry, 30,000 volts for one minute. Wet, 16,000 volts without arcing.
	Mechanical requirements
11,000-volt strain	Continuous load of 9,000 lb.
650-volt strain	Continuous load of 10,000 lb.
650-volt strain	Momentarily load of 15,000 lb.

Inspection Results. Competitive bids were invited for high and low tension strain insulators and the contract finally awarded to an insulator manufacturer of high standing. Insulators were offered for inspection and acceptance with the following results:

Type of insulator	Total No. delivered	Number accepted	Per cent rejected
11,000-volt strain	156	129	17.3
650-volt strain	172	163	5.2

Mechanical Tests. From a large number of tests to determine the mechanical strength of the insulators the following have been selected as typical:

11,000 VOLT STRAIN INSULATORS

No. of test	Pounds pressure	Time pressure applied	Remarks
13	11,390	5 mins.	O. K.
13	13,400	3 mins.	Cracks developed.
13	13,735	Instantly	Failure.
14	8040	10 mins.	O. K.
14	10 720	2 mins.	Cracks developed.
14	11,055	Instantly.	Failure.

650 VOLT STRAIN INSULATORS

11	6,700	5 mins.	O. K.
11	10,050	3 mins.	O. K.
11	10,385	Instantly	Failure.
12	8,710	3 mins.	O. K.
12	12,060	2 mins.	O. K.
12	13,400	Instantly.	Failure.

Results in Service. The insulators described above have been in continuous service for about three years with the following results.

Type of insulator	No. installed	Mech. failures	Elec. failures	Broken by violence	Per cent Failure from all causes
High tension strain............	101	5	0	0	4.9
Low tension strain.............	86	8	0	0	9.4

Conclusions. It must be concluded from the above that the per cent of mechanical failures has been high considering the care with which the original shipments were inspected and tested. For the relatively low voltages there is no difficulty in securing the requisite electrical strength, but further combined efforts of engineers and manufacturers are necessary to secure greater mechanical strength in porcelain strain insulators for heavy service.

A paper presented at the 27th Annual Convention of the American Institute of Electrical Engineers, Jefferson, N. H., June 28, 1910.

CONSERVATION OF WATER POWERS
PRESIDENTS ADDRESS

BY LEWIS B. STILLWELL.

The conference of governors, which assembled at the White House, in May, 1908, in response to an invitation extended by President Roosevelt, focused the attention of the American people upon a subject which all recognize as one of fundamental national importance and one which appeals to the engineering profession with all the force which comes from special knowledge. True conservation of our natural resources means wise utilization of those resources without unnecessary waste. Such utilization of materials used in construction and of energy is the primary and essential business of the engineer. Since the days of Smeaton and of Watt, the engineer has been building the light-houses of material prosperity and releasing and directing for the common welfare, those vast forces of nature imprisoned and overlooked for centuries but now utilized on a scale which dwarfs the physical powers of man to insignificance.

During the last 25 years, a period practically coterminus with the life of this Institute to date, the art of transmitting power by electricity has grown from a laboratory experiment into a development universally recognized as one of the great factors of industrial and commercial life.

The latest publication of the United States Geological Survey, relative to this subject, estimates the aggregate water powers of the United States at minimum flow to be 36,000,000 horse power and the aggregate which presumably can be developed on the basis of six months' flow per annum at not less than 67,000,000 horse power.

A very large proportion of the water powers hitherto unappropriated are either located upon government lands or are dependent, wholly or in part, upon the run-off from government lands.

The regulations established by national and state governments which control or affect the further utilization of water powers, therefore, are of peculiar concern to the members of this Institute. A bill endorsed by the administration is now before Congress which, if passed, will confer definitely upon the President and his executive assistants full authority in respect of withdrawal of public lands and unappropriated water powers. Probably the bill will pass and if so we may expect that the question of governmental machinery and methods for handling practically this highly complex and vitally important subject will be raised in acute form.

If the views of the engineering profession are to be effective, either in moulding public opinion or in assisting the legislative and executive representatives of our people, by supplying facts essential to correct generalizations and deductions, it is important that those views be clearly stated at the right time and that apparent lack of agreement among those best qualified to measure the practical results of existing or proposed governmental regulations should not destroy their influence.

The present occasion seems opportune for the presentation of a brief and non-technical discussion of the practical bearing and effect of existing laws governing the appropriation of water powers located on public lands, which, as now construed and applied, are seriously retarding the utilization of these powers.

To those who realize the vast possibilities of a far-sighted and thoroughly scientific development and utilization of our water power resources, particularly those of the Rocky Mountains and the Sierras, no subject can be more interesting. Present practice, whether ideal or faulty, is more likely to be modified than revolutionized, and now is the time for unprejudiced and candid discussion of the regulations now in force.

(1) The Relation of Forests and Stream Flow

The Bureau of Forestry has established regulations governing the appropriation of water powers located on streams which drain watersheds included in whole or in part in Forest Reserves. Among these regulations is the imposition of a graduated rental, to be paid by the individual or corporation appropriating the water power and used by the government for forest purposes. This rental rests upon the assumption that the appropriator of the power will be benefited by the preservation of the forest, and this idea is accepted generally by engineers and by the public.

Mr. Gifford Pinchot, Chief Forester at the time when the present regulations were established, states his understanding of the physical facts upon which this charge is based in a document explaining the policy of the Forest Service, as follows:

> The National Forests include the great mountain chains of the west. The rain and melting snow of these ranges feed the mountain streams. The forest cover on the steep slopes acts like a mighty sponge, absorbing the excess of rainfall in the wet season and giving it out to the thirsty lands in the dry season. It is for the express purpose of thus 'securing favorable conditions of water flows' (Acts. June 4, 1897) that Congress has authorized the creation of national forests and expends money for their administration and maintenance. Where the forest cover is destroyed by reckless lumbering and the fires which inevitably follow, the rains immediately run off the steep slopes as from the roof of a house, producing destructive floods in the valleys and leaving no store of water for the dry season. Therefore, when a power company puts its plant on national forest land, it gets from the government two things which it ought to pay for, *viz.*, (*a*) The use of lands of great value for power purposes, for the steep mountain sides give the fall which is essential for a power plant; (*b*) the guarantee of a steady flow of water as an incident to the land occupied by the plant. This steady flow is also essential to a power plant.

During the last two years, the question of the actual or assumed effect of forests on the watershed in regulating the run-off, has been widely debated. That forest cover controls the run-off to a material extent has been vigorously asserted by engineers prominent in the government service and by many others, and on the other hand, it has been seriously questioned by a number of our leading engineers, notably by Col. Chittenden, in a paper read before the American Society of Civil Engineers, in March, 1909, and by Dr. Willis L. Moore, Chief of the United States Weather Bureau, in a report addressed to the Committee on Agriculture, of the House of Representatives, in 1910, entitled "A Report on the Influence of Forests on Climate and on Floods."

I do not propose to enter into a detailed discussion of this complex subject at this time. Col. Chittenden's paper and its discussion, as printed in the Transactions of the American Society of Civil Engineers, have covered the subject perhaps substantially as well as it can be covered by applying the inductive method to existing records.

The report of Dr. Moore and the article on "Floods", in Water Supply Paper No. 234, prepared by Marshall O. Leighton, Chief Hydrographer of the U. S. Geological Survey have also debated the subject at great length, the radical difference of opinion between these two gentlemen being due apparently in large degree, to the fact that Dr. Moore is considering total annual run-off, while Mr. Leighton is investigating the relation of " flood tendency " to precipitation.

As Dr. George F. Swain pointed out in a recent discussion of this subject at Boston, the difficulty in reaching an agreement along the lines adopted in the papers referred to results from the fact that all of these gentlemen are applying the inductive method of reasoning to a subject so complex and so varied as practically to preclude the possibility of general agreement in the inferences drawn. The physical laws which govern the phenomena under discussion are all well known, and to the scientist the deductive method of dealing with this subject is not only easier but is more convincing than the attempt to draw conclusions from incomplete records of precipitation and stream flow where even approximate knowledge of the extent to which the surface of the watershed in question is forested, or plowed, or covered by vegetation other than forest, is not available.

Such reasoning unquestionably leads to the conclusion that the preservation of forests on the watershed does to a greater or less extent regulate and control not the aggregate annual run-off but the rate at which that run-off varies during the year, and this idea is accepted generally by engineers and by the public. It is also accepted apparently by the majority of engineers who have discussed this subject in our various engineering publications, using the inductive method in drawing their conclusions.

As the essential physical facts which bear directly upon forest control of run-off, and consequently upon the relation of forested watersheds and water power, the following as stated by Dr. Moore may be accepted probably without material error:

(1) Precipitation controls forestation, but forestation has little or no effect upon precipitation.

(2) Any local modification of temperature and humidity caused by the presence or absence of forest covering the buildings of villages and cities etc., could not extend upward more than a few hundred feet, and in this stratum of air saturation rarely occurs, even during rainfall, whereas precipitation is the result of conditions that exist at such altitudes as not to be controlled or affected by the small thermal irregularities of the surface air.

(3) During the period of accurate observations, the total annual pre-

cipitation has not increased or decreased to an extent worthy of consideration.

(4) The total annual run-off of our rivers is not affected materially by any other factor than precipitation.

(5) There is no adequate evidence to justify the conclusion that extreme floods in recent years attain higher stages than formerly.

Other conclusions stated by Dr. Moore in the report above referred to the author is not prepared to accept, and as regards that forest control which is practically related to the commercial value of water powers, he believes the following to be a correct statement:

While the aggregate annual run-off of our rivers in general depends upon the total annual precipitation, the presence of forest cover on the watershed regulates the rate of run-off to an extent which in many cases materially affects the value of the water power, this regulation tending to equalize the flow and prolong it during the dry season.

With this understanding of the essential physical facts which are pertinent it is proposed in this paper (1) to discuss briefly certain provisions included in the present regulations of the Forest Service governing the appropriation of water powers dependent in whole or in part upon forest reserves, and (2) to suggest the outline of a plan which to the author appears preferable to that now in force.

The present form of permit provides a nominal charge (rental) for the land occupied by power house, dam, canals, penstocks, flumes, etc., the rate being " One dollar per acre and Five dollars per mile for the land occupied by said works ". It provides also that " the gross operation charge for any year shall be calculated by the forester upon the basis of the quantity of electric energy generated in such year at a maximum rate, which shall not exceed the following amounts per thousand kilowatt hours:

For the	1st year	2	cents
"	2nd "	4	"
"	3rd "	6	"
"	4th "	8	"
"	5th "	10½	"
"	6th to 10th years, inclusive	12½	"
"	11th " 15th " "	15	"
"	16th " 20th " "	17½	"
"	21st " 25th " "	20	"
"	26th " 30th " "	22½	"
"	31st " 35th " "	25	"
"	36th " 40th " "	27½	"
"	41st " 45th " "	30	"
"	46th " 50th " "	32½	"

The foregoing are maximum rates applicable only in cases where all the water utilized comes from the Forest Reserve and the entire head developed results from the topography of the forest: In all other cases, deductions are made as follows:

> ' From the gross operation charge for any year calculated as above:
>
> (*a*) A sum bearing approximately the same ratio to one-half of such gross operation charge as the area of unreserved land on the watershed bears to the total area of the watershed as of the beginning of each year.
>
> (*b*) A sum bearing approximately the same ratio to one-half of such gross operation charge as the length of conduit outside the Forest Reserve bears to the total length of such conduit as of the beginning of each year.
>
> (*c*) A sum bearing approximately the same ratio to the balance remaining after said deductions " a " and " b " as the quantity of electric energy generated from water stored artificially by the permittee over and above what is generated by the natural flow, bears to all electric energy generated.
>
> The sum remaining after all the aforesaid deductions have been made constitutes the net operation charge for such year.

The rationale of the deduction for water stored artificially by the permittee is obvious. That for the first two deductions described is stated in an informal explanatory document of the Forest Service, as follows:

> Since the two advantages furnished by the Government are the maintenance of a steady flow from the forested watershed, and the fall resulting from the topography of the forest, one-half of the conservation charge is calculated as based upon each of these advantages. Therefore:
>
> (*a*) if a part of the watershed which supplies the power plant is outside of the national forest, the one-half of the conservation charge calculated upon the advantage resulting from the maintenance of the steady flow by the conservation of the forest cover is reduced proportionately and (*b*) if a part of the fall which the permittee is to use in developing power is outside of the national forest, the one-half of the charge which is based upon the fall is reduced proportionately.

THE IMPOSED RATES AS A TAX ON POWER ENTERPRISES

The proposed conservation charge, at least during the early years of the contract, cannot be regarded reasonably as constituting any very serious financial burden imposed upon the individual or corporation developing the water power. If power be sold at an average price of one cent per kilowatt hour, the maximum conservation charge during the first five years of operation is equivalent to a tax of 0.61 per cent of gross receipts. During the next five-year period, it is increased to 1.25 per cent of gross receipts and it increases gradually from this figure to a maximum of 3.25 per cent of gross receipts, which rate applies during the last five years of the 50-year life of the contract. The average charge during the fifty-year period is 2.086 per cent of gross receipts, if power be sold at the price assumed, *viz.*, one cent per kilowatt-hour.

If power be sold at an average price of 0.5 cent per kilowatt-hour the average conservation charge during the period of the lease becomes 4.172 per cent of gross receipts, and the maximum, which applies during the last five years of the lease, is 6.5 per cent of gross receipts.

It is a fair question, however, whether a more rational method, and one which in certain important respects would tend to produce better results, might not be devised. The plan in force obviously is open to several objections. Among these are:

(1) The imposition of a tax upon output means that the man who installs a highly efficient plant is called upon to pay a higher conservation charge than the man who wastes water by the installation of a cheap and inefficient plant. The effect of the conservation charge in influencing type of construction, and consequent effective utilization of the water, will probably be small but unquestionably that influence is exerted in the wrong direction:

(2) The proposed method of charging imposes a heavier burden upon the man who sells his power at a low price than upon him who sells it at a high price. The tax measured in percentage of gross receipts, is obviously twice as high in the case of the man who sells power at an average price of 0.5 cent per kilowatt-hour as it is in the case of a man who sells power at an average price of one cent per kilowatt-hour.

Both of these objections were pointed out in a paper read by Mr. F. G. Baum, before the American Institute of Electrical Engineers, at Atlantic City, N. J., in 1908, but the writer has not heard them referred to since, and they deserve careful consideration.

(3) Mr. Baum also calls attention to the fact that under the plan proposed by the Forest Service " the man who takes his power to a market, say one hundred to three hundred miles away must pay to the Government for the losses incurred in doing so and pays more than the man who sells to the home market. The man who reaches out with his power is equalizing conditions, just as railroads equalize conditions by their transportation facilities ".

The Italian law, recognizing this point, reduces the rental in the case of transmitted power. The basis of this reduction, as stated by M. Rene Tavernier, Chief Engineer, Department of Public Works, Republic of France, in his valuable article on "The Public Utility of Water Powers and their Government Regulation" (Water Supply Paper No. 238) is as follows:

> For power transmitted by means of electricity to distances greater than 10 kilometers (about 8 miles) there is granted upon the annual rental of 3 francs per horse power, a reduction calculated by multiplying the square of the distance expressed in kilometers by a fixed coefficient of 0.001. In no case shall the rental be reduced to less than one-half of 1 franc per horse power.
>
> Under this formula the minimum reduction, that is to 0.50 franc, will be attained in transmission over 50 kilometers (about 31 miles).

While the method of applying the "conservation charge" has been criticised in many quarters and while the objections above pointed out are valid, the method in force possesses undoubted advantage in the fact that it is definite and readily determined by reference to records which the permittee can easily keep. The charges moreover are adjusted to encourage development of the water powers by recognizing the fact that few, if any, can earn interest on the necessary investment from the start. In enterprises of this kind, the cost per unit of output generally decreases as the output increases. The forest service charge, recognizing this fact, is made small at the start and increases gradually. Except by reducing the average charge for the period, it would be difficult to devise a plan less onerous for the permittee.

(4) While the imposed charge could not be regarded as excessive, if the power developed were entirely, or even very largely, dependent upon the preservation of forest cover upon the watershed, it represents a high rate when measured in comparison with the increase in commercial value of the power, which, under ordinary conditions, is due to the forest. If, for illustration, it be assumed that under average conditions "forest control" adds 25 per cent to the value of the water power, a tax averaging 4.172 per cent of gross receipts is a tax of 20.86 per cent of the gross value contributed by the forest.

(5) The tax is imposed upon power from all "forest reserve lands," regardless of the actual condition of the forest upon which it is based. Obviously, therefore, a uniform tax must be very much heavier in some cases than in others, as compared with the benefit upon which it theoretically rests.

(6) It tends to retard utilization of water powers and stimu-

lates the use of coal for power purposes—a result which is in direct contravention of the primary object of conservation.

(7) Something less than one-half the public domain is included within the limits of the forest reserves. To secure maximum revenue and to minimize the average retarding effect upon utilization of these water powers resulting from a system of rental, any charges which may be imposed by the Federal Government upon water power appropriation should apply to all public lands.

The author has expressed the opinion that the imposed charge would not be regarded as excessive if the power developed were entirely, or even very largely dependent upon the preservation of forest cover upon the watershed. In his judgment, however, that effect has been very greatly exaggerated by the majority of writers who have endeavored to instruct the public regarding the subject.

To sustain the announced theory of the Forest Service, it is evident that the value of the water power should be directly dependent upon forest control of the run-off. Obviously the statement that " the forest cover on the steep slopes acts like a giant sponge, absorbing the excess of rainfall in the wet season and giving it out to the thirsty lands in the dry season " and that the " power company which puts its plant on national forest land gets from the Government the guarantee of a steady flow of water " are highly figurative.

The extent to which forest cover and other surface conditions which tend to regulate run-off, succeed in equalizing stream flow, is illustrated in the following tabulated statement, showing in the case of ten (10) fairly representative rivers of the Atlantic and Pacific slopes the maximum, average and minimum run-off in second feet per square mile for periods of five consecutive years and the minimum run-off expressed (*a*) in percentage of maximum run-off and (*b*) in percentage of average run-off.

Without attempting to discuss the complex conditions which determine the relations of maximum, average and minimum run-off, it is evident that in no case does existing forest cover or any other surface condition effectively equalize the flow.

As regards the relation of minimum to maximum run-off, the most favorable case, that of the Merrimac river, shows a minimum flow of 1.86 per cent of the maximum, while for the ten rivers the minimum flow averaged is 0.837 of the maximum flow averaged. As regards the relation of minimum to average run-off, the most favorable case, the Yadkin, shows 17.6 per cent while the average of the ten (10) rivers is 9.95 per cent.

The effect of forest cover in adding to the commercial value of a water power, results from two facts, namely, first, the fact that an increase in minimum run-off reduces the necessary investment in auxiliary steam or other power plant; second, the fact that some portion of the flood waters, which otherwise would flow past the power plant, at a time when the water available exceeds the amount needed, is held back long enough to permit its commercial utilization. As regards the first of the two conditions referred to, if we assume that auxiliary steam power is

FIVE YEAR RUN-OFF TABLE

River	Gauging station	Drainage area sq. miles	Maximum run-off sec. ft. per sq. mile	Average run-off sec. ft. per sq. mile	Minimum run-off sec. ft. per sq. mile	Minimum in per cent of	
						Max.	Ave.
Kennebec......	Waterville, Me.	4380	17.5	1.96	0.0388	0.222	1.98
Merrimac.... .	Franklin Junction, N. H.	1460	16.93	1.998	0.315	1.86	15.77
Connecticut....	Holyoke, Mass.	8144	14.12	1.623	0.258	1.83	15.9
Susquehanna...	Binghamton, N. Y.	2400	19.62	2.044	0.0187	0.095	0.916
Yadkin........	Wilkesboro, N. C.	500	36.8	2.446	0.43	1.17	17.6
Savannah......	Augusta, Ga.	7294	18.83	1.56	0.198	1.05	12.7
Black Warrior.	Near Cordova Ala.	1900	26.0	1.515	0.01473	0.0567	9.73
Feather.......	Oroville, Cal.	3640	29.0	2.354	0.33	1.14	14.0
Yakima.......	Near Yakima, Wash.	3300	19.37	1.322	0.1926	0.995	14.56
Naches........	Near North Yakima, Wash.	1120	19.55	1.489	0.0268	0.137	1.8
			21.772	1.8311	0.18226	0.837	9.95

used to insure a continuous supply equal to the average which a given head on each of these rivers can develop, it will be seen that such auxiliary plants must be capable of producing power in an amount ranging from 82 per cent to 98 per cent of the water power. The difference, therefore, between the best and the worst case among these typical streams affects the cost of the auxiliary plant to the extent of 16 per cent of the cost of a steam plant capable of developing the same output as the water power.

As regards the effect of forest cover upon the relative proportions of energy output from the water power and from the auxiliary steam plant, the conditions are so complex as to prevent profitable generalization. The holding back of a portion of the flood waters saves fuel and other operating costs of the auxiliary steam plant or reduces the artificial storage required. While it is evident that this effect, under the best conditions existing upon any of the watersheds, drained by the streams referred to in the table, is not such as to justify the theory that the forest cover is the principal factor affecting the value of the water power, the author would not be justified, from present knowledge, in attempting to fix its average effect upon that value.

FEATURES OF THE PRESENT REGULATIONS WHICH SHOULD BE CHANGED

Permit Non-Transferable (*Clause* 15).

Clause 15 of the power agreement now in force reads as follows: "The permit here applied for shall be non-transferable (U. S Revised Statutes, Section 3737) and shall be subject to all prior valid claims which are not by law subject thereto".

The aim in view of course is to prevent monopoly, as a result of which an artificial price might be maintained higher than the average which would be fixed by competition of similar developments in the same market.

If effective, it is obvious that this requirement must retard development. The economic reasons which demand that water powers on the same stream should deliver their output to the same network of distributing circuits in many cases are material, and those which demand that the output of developments on different streams should be similarly combined are even more weighty. In the former case, under certain conditions, as has been pointed out by Mr. W. S. Lee, in his paper before the American Institute of Electrical Engineers, (PROCEEDINGS for

April, 1910), the net output of a stream effective for commercial purposes may be considerably increased. In the latter case, owing to the fact that the relative run-off of neighboring watersheds sometimes varies widely during successive years, the reliability of the supply of power to the user is materially increased by combination. To put the matter another way, if combination be not permitted the aggregate investment in auxiliary steam plants or gas engine plants must be largely increased, which obviously is bad economy and means an increase in cost of power not only to the producer but also to the user.

By electrically combining the output of a considerable number of water powers, interruptions of service, due to accidents to flumes, or to transmission circuits, are decreased.

The clause, in my judgment, should be modified by permitting transfer, subject to approval by the government. The right of a state or municipality to fix charges, in the case of a public utility company selling its product within the limits of such state or municipality, has been established by decisions of the Supreme Court of the United States. The danger that American communities in general, knowing this fact, will submit for any great length of time to the imposition of rates that are really extortionate, is not comparable to the economic loss which is certain to result from the imposition of conditions limiting the opportunity for profitable investment of capital. In this connection it is evident that even an assumed water power monopoly of the largest conceivable size must sell its power at a cost lower than the cost of competing power produced by steam plants.

The established right of a state or municipality to fix rates at which power is sold is an absolute protection applicable by local governments best able to judge the conditions which determine what is an equitable charge.

CONTINUOUS OPERATION OF PLANT.

Clause 18 reads as follows:

> The permittee shall, except when prevented by the act of God or the public enemy, or by unavoidable accidents or contingencies, continuously operate for the generation of electric energy, the works to be constructed under the permit hereby applied for, in such manner as to generate after such generation begins, not less than the following percentages of the full hydraulic capacity of the said works measured in kilowatt hours; in the first year . . . per cent; in the second year . . . per cent; in the third year . . . per cent; in the fourth year . . . per cent; in the fifth year . . . per cent; and in every year thereafter . . . per cent.

The object in view is to prevent a power company increasing its prices by creating an artificial power famine and to secure full utilization of the available power. Some permits have specified that not less than twenty-five per cent of the full hydraulic capacity, measured in kilowatt hours, must be generated; others as much as seventy-five per cent, depending upon special circumstances supposed to govern the case.

In many cases this clause presents serious difficulty to the power company. In the majority of instances with which the writer has been personally familiar, it has been extremely difficult, if not impossible, to predict either maximum or minimum limits of the growth of power output. Circumstances may be conceived under which a power company, operating not only the plant covered by the permit but also other plants, might shut down the first named to produce temporarily an artificial scarcity of power, but the fact that this would mean an idle investment would make this a rare case. If it be necessary to retain such a clause, it should be accompanied by a provision permitting, with the consent of the government, a reduction in the percentages originally fixed.

While discretionary power to make conditions upon which capital has been invested more onerous will retard or prevent development, the bestowal upon a Secretary of Agriculture or a Secretary of the Interior, of power to make those conditions less onerous involves no corresponding public risk, since that Secretary would destroy himself politically who should grant such authorization without proper cause. No power company can afford to invest capital under a contract which leaves it in the power of a government official to increase the burdens of the enterprise within the term covered by the permit, but the government and the public can well afford to bestow upon a responsible official authority to reduce those burdens upon proper application and presentation of valid reasons.

TERM OF PERMIT

Clause 20 of the permit in force reads as follows:

> "The permit hereby applied for shall cease and be void, upon the expiration of fifty years from the date of approval hereof, but it may then be renewed in the discretion of the duly authorized officer or agent of the United States, and upon such conditions as he may in his discretion fix: *Provided* that such officer or agent, in fixing such conditions shall consider the actual value at that time for power and all other purposes of the lines and rights of way within National Forests occupied and used under the permit hereby applied for and the actual value at that time of all

improvements lawfully made by the permittee within National Forests under the permit hereby applied for, but neither the property of the permittee, if any, outside of National Forests, nor the permit, franchises, bonds, capital stock or other securities of the permittee shall be considered in fixing such conditions."

It will be noted that this clause contains no provision for taking care of the contracts which may be in force between the permittee (or his successor) and his customers at the expiration of the fifty-year period, nor does the author find any provision covering this point elsewhere in the power agreement. It is obvious that by its absence the value of the permit during the latter years of its life, is materially impaired. Power contracts are frequently, in fact generally, executed for periods of not less than five years and frequently for ten or even twenty years.

The contract agreement should include a clause guaranteeing for a period not less than five years subsequent to its termination, the fulfillment of contracts between the permittee and customers existing at that time.

THE PERMIT REVOCABLE

Under the law as it now stands the Forest Service can grant to an individual or corporation seeking to develop water power from Forest Reserves only a permit revocable by the Secretary of Agriculture in his discretion. The so-called "Second right-of-way" act is entitled "An Act relating to rights-of-way through certain park reserves and other public lands," and bestows authority in this matter upon the Secretary of the Interior. A later law, approved February 15, 1901, transferred to the Secretary of Agriculture responsibility for the execution of all laws relative to national forests.

No argument is necessary to demonstrate that a permit revocable in the discretion of the head of a department is not an adequate basis for financing an enterprise requiring investment of capital. This vital defect of the existing law to-day stands squarely in the path of legitimate and praiseworthy enterprise seeking to develop and utilize our many water powers from forest reserves now wasted. Every proper influence should be brought to bear by those interested in the true conservation of our natural resources to secure a modification of the law removing this otherwise insuperable barrier.

AN ALTERNATIVE PLAN

The man who criticises adversely a plan which has been elaborated by others is not necessarily under obligation to suggest an alternative and, moreover in the judgment of the author, any plan which imposes a tax upon water power or fuel is at best of doubtful wisdom. Assuming, however, that upon careful consideration the American people should decide definitely and finally to impose a tax upon natural resources of the public domain, to be used in conserving and developing those resources, it is perhaps not improper to suggest the outlines of a plan which from the standpoint of public policy appears preferable to that now in force. The essential features of the plan which he would suggest are the following:

(1) A tax imposed on all sources of power found upon public lands—a royalty on coal mined and a rental upon water power. The charge for water power to be based not upon an indefinite and disputed relation of forest covering and commercial value of the power, but upon the fact that the Government needs revenue to develop and conserve our natural resources, owns the power, and, as owner, possesses an unquestionable right to impose a charge for its use. The Federal Government is now selling coal lands on the public domain at prices which, on the average, approximate one-tenth of one cent per ton of the coal which it is estimated the property can commercially yield. If the coal be used to produce power under average conditions this tax is substantially equivalent to 0.5 cent per 1000 kw-hr. as against an average rental of 20.86 cents per 1000 kw-hr now imposed in the case of water power. The theory of conservation unquestionably points to an increase in the price fixed for coal lands or a decrease in water power rental, or both. By adjusting the charges for coal and water power to approximate equality, as measured by their respective ability to produce power, the tendency of the present method to stimulate the use of coal for power purposes as against the use of water power—a tendency which, as the author has stated, is in direct contravention of the fundamental idea of conservation—will be avoided and the aggregate revenue ultimately available to the Federal Government for the purpose contemplated will be enormously increased.

The general features of the present contract agreement enforced by the Forest Service as regards fifty-year limit of the period of appropriation should be preserved. The other restrictions now imposed should also be retained except that certain clauses should be modified to meet the practical objections which have been pointed out, in so far as mature consideration may determine the validity of those objections.

The proceeds of royalties upon the sale of coal land and forest products and rentals of water powers should be used to conserve our national resources by development under broad and systematic plans—to conserve forests, build dams, improve navigation and irrigate the arid lands.

(2) The charge imposed upon water powers to be based upon the amount of water appropriated and the effective head resulting from the topography of the Government lands concerned.

Under the present plan, it is necessary to measure the water used in order to fix the third deduction from the charge based upon output. The difficulty of measuring water, therefore, must be met and it is as easy to fix the second-feet appropriated as to fix the deduction allowed for artificial storage by a permittee.

Under this plan it would be to the interest of the permittee to install a plant of high efficiency and not a plant of low efficiency as the present method of charging suggests.

An important practical point in this connection is the fact that the estimate of competent Government engineers, discussed with and agreed to by the permittee would constitute a safer basis for the investor who may undertake to finance the enterprise than he now has in the data submitted for his consideration by the promoter.

(3) There is a third suggestion which perhaps may be worthy of consideration in view of the fact that conditions as regards cost of development and characteristics of the market for power differ so widely in various parts of the country. That suggestion is that the Government engineers of the departments or bureaus concerned prepare comprehensive preliminary plans for the development of water powers of a given watershed and that these water powers collectively or severally be leased to the highest bidder, the Government, of course, reserving the right to reject all bids.

A paper presented at the 27th Annual Convention of the American Institute of Electrical Engineers, Jefferson, N. H., June 28, 1910.

HEADLIGHT TESTS

BY C. FRANCIS HARDING AND A. N. TOPPING

The Indiana Railroad Commission, having been instructed to investigate and rule upon the compulsory use of more powerful headlights on steam locomotives operating in the State of Indiana, requested that both road tests and laboratory tests be carried out by the Engineering Schools of Purdue University, under the direction of Dean C. H. Benjamin, to determine the effect of such powerful headlights upon the interpretation of signals and upon the ability of the engineer to see and recognize obstacles upon the track in front of the locomotive. These tests which were carried out in the fall of 1909, consisted of two distinct groups as follows:

Group 1. Road tests carried out on the St. Louis division of the Big Four Railroad for the purpose of comparing effects noted above of oil and electric headlights under actual operating conditions.

Group II. Laboratory and out-of-door tests carried on by the School of Electrical Engineering, Purdue University, under the direction of the authors to determine the photometric and spectrophotometric values of the above headlights as well as corresponding values for reflected light from signal roundels.

Since the completion of the above tests, the authors have carried out similar but more detailed tests on the above headlights together with a number of new types. In the belief of the authors of this paper that little has been made public along these lines, and that many engineers will be interested in this subject, the result of the latter tests are herein set forth prefaced by a brief abstract of the previous road tests.

GROUP I—ROAD TEST

The following road tests were carried out during the night of October 13th, 1909 on the main line of the Big Four Railroad near Indianapolis, Indiana. Independent observations of signal aspects were taken by eleven observers seated in an open front observation car provided with headlights of different types placed at the same distance above the track as when mounted upon the locomotive. These observations were later compared and averaged and the results of the same briefly summarized. For detailed information regarding these road tests reference should be made to the paper by Dean C. H. Benjamin, read before the Western Railway Club and published in the April PROCEEDINGS.

Procedure. Test numbers 1 *to* 6 *inclusive were carried out in the following manner:*

The observation car was run back 5,000 feet from the home signal and a long blast of the locomotive whistle sounded. The colors of the home signal were then changed by a committee appointed for this purpose which remained at the signal. The observers in the observation car did not know the changes that were to be made in the colors. After sufficient time had elapsed for the signal to have been changed, the car was moved toward the home signal and short stops were made at predetermined intervals. At each stop, each of the eleven observers recorded independently the aspect of the home signal as he saw it. These records were collected after each test and later compared with one another and with the actual aspect of the signal in each case.

Test No. 1. *Observation of Colors of Home Signal at Distances Ranging from* 300 *to* 5,000 *Feet with Electric Headlight on Observation Car and the Opposing Electric Headlight* 200 *Feet in Front of Home Signal.*

From a comparison of the observations made of a number of different aspects in this test, where both headlights were of the electric type, it was noted that at distances of 3000 ft. or over the signals were invisible; that correct interpretation of the signals occurred at distances ranging from 800 to 1500 ft. from the home signal, depending upon the observer, and that at a distance of 800 ft. identification was practically unanimous. The interesting feature about this test is the fact that at distances of from 400 to 800 ft. many observers noted green signals where there was none displayed; at 600 ft. eight of the eleven observers recorded a green signal where no light existed, although at this point a green roundel had been placed with no signal light behind it. This so-called green phantom is the effect often noted by engineers operating locomotives with powerful headlights and is supposed to be due to the reflection of the light transmitted from the headlight to the unlighted green roundel and thence back to the eye of the observer or locomotive engineer. No such effect as this was noted in tests Nos. 2, 4 and 6 where the observation car was provided with an oil headlight.

Test No. 2. Observation of Colors of Home Signal at Distances Ranging from 300 *to* 5,000 *Feet with Oil Headlight on Observation Car and on Opposing Electric Headlight* 200 *Feet in Front of Home Signal.*

Under the conditions of this test the results were quite similar to those of test No. 1, with the exception that no phantom signals were noticed. One observer only interpreted the signal correctly at a distance of 3000 ft., and at 600 ft., practically all observations were correct.

The results of this test show that distances at which signals can be correctly interpreted are affected more by the character of the opposing headlight than by that of the headlight on the observation car, and further, that phantom signals are due to the reflected light from the unlighted roundels made noticeable by the great intensity of the electric headlight.

Test No. 3. Observation of Colors of Home Signal at Distances Ranging from 300 *to* 5,000 *Feet with Electric Headlight on Observation Car and the Opposing Oil Headlight* 200 *Feet in Front of the Home Signal.*

The correct aspect of the home signal was generally recognized in this test at the full distance of 5,000 ft. and identification was practically complete at 3000 ft. Here again it should be noted that a considerable number of phantom signals were recorded due to reflection, these appearing at distances ranging from 600 to 800 ft. The above results indicate that in case the locomotive engineer is called upon to read signals at the time he is meeting a train equipped with an electric headlight, the distance and therefore the time in which he must make his correct observation is much less than when the opposing headlight is of a less powerful type.

Test No. 4. *Observation of Colors of Home Signal at Distances Ranging from* 300 *to* 5,000 *feet with Oil Headlight on Observation Car and the Opposing Oil Headlight* 200 *Feet in Front of the Home Signal.*

Under the conditions of this test practically all the observers were able to read the signals correctly at the full distance of 5,000 ft. and identification was unanimous at 2,000 ft.

Test No. 5. *Observation of Colors of Home Signals at Distances Ranging from* 300 *to* 5000 *Feet with Electric Headlight on Observation Car and no Opposing Headlight.*

Practically complete identification of the home signals was made by all observers at the full distance of 5,000 ft. In spite of the fact that there was no light behind one of the green roundels during the test, several observers recorded a green signal at distances ranging from 400 to 800 ft.

Test No. 6. *Observation of Colors of Home Signals at Distances Ranging from* 300 *to* 5000 *Feet with Oil Headlight on Observation Car and no Opposing Headlight.*

This test represents the best condition for the reading of signals since they were all read correctly by all observers at 4,000 feet and no phantom signals due to reflection were observed.

CLASSIFICATION SIGNAL TESTS

Tests Nos. 7 to 10 inclusive were made to determine the distance at which the classification signals on the front of the approaching locomotive could be read with the two types of headlights. As the classification signals displayed on the front of the locomotive indicate either that a train is a special or that another train is following on the same schedule, it will be noted that the correct reading of these signals is of extreme importance. The procedure in all of these tests was as follows:

The observation car was run back several thousand feet and a long blast of the whistle sounded. An engine with an opposing electric headlight displaying classification signals located at the side of the smoke box was run on to the same track. Upon notice from the committee which prepared the classification signals, the observation car was moved forward slowly and first stopped at a distance of 400 ft. from the opposing locomotive. Additional stops were made at distances of 100 ft. until observations became unanimous in reading the classification signals.

Test No. 7. Classification Signal Test with Electric Headlight On Observation Car and Opposing Electric Headlight on Locomotive.

In this test both white and green classification signals were displayed. At 400 ft. only four observers saw the white light and at 300 ft. only eight could see it. None of the observers saw the green light at a distance of 200 ft., while nine of the eleven observers saw the white light at this distance. The above test indicates that the opposing electric headlight limits the distance in which the engineer can correctly observe the classification signals to a very small margin. The difficulty in observing the green signal was possibly due to the predominance of green rays in the headlight used. The spectrophotometric analysis of this light is shown in Table IX.

Test No. 8. Classification Signal Test with Electric Headlight on Observation Car and Opposing Oil Headlight on Locomotive.

The green and white classification signals displayed in this test were read correctly without difficulty by all observers at 400 ft., most of the observers having seen the signals at 800 ft. The ability to read classification signals correctly, therefore, is much greater with the oil headlight opposing than in the case of the more powerful electric headlight.

Test No. 9. Classification Signal Test with Oil Headlight on Observation Car and Opposing Oil Headlight on Locomotive.

The green and white classification signals were correctly identified by all observers at 600 ft. while some observers noted signals correctly at distances ranging from 1,200 to 2,200 ft. It is interesting to note from this test that with nothing more powerful opposing than an oil headlight, with an oil headlight on the observation car, the distance at which classification signals could be read was increased over that with an electric headlight on the observation car by about 50 per cent.

Test No. 10. Classification Signal Test with Oil Headlight on Observation Car and Opposing Electric Headlight on Locomotive.

Two white classification signals were displayed and were seen correctly by all observers at 300 ft., while some observers saw them correctly at distances ranging from 600 to 800 ft. It should be noted from this test that the inability to distinguish correctly the green signal in Test No. 7 is not due to its position upon the locomotive, but rather to its color, since the two white signals in this test were distinguished at the same distance.

OBSTRUCTION TESTS

It has been argued that more powerful headlights for locomotives, by increasing the distances at which obstructions may be seen on the track, may prevent the occurrence of accidents. The following tests were made to determine the exact distance at which various objects on the track in advance of the locomotive could be seen and identified. It should be noted that in these tests the observers were on the lookout for some obstruction and observations were made at times when the car was at a standstill, both of which conditions were obviously more favorable to the correct detection of objects on the track than in ordinary railroad practice. The procedure in all of these obstruction tests was as follows:

The observation car was run back a distance of 2,000 ft. and the usual signal given with the whistle. Different objects were then placed upon the track in the various tests, the approximate localities of the obstructions being known to the observers, who, however, had no knowledge of the kind of obstructions which were to be used. When signalled by the committee which had the preparation of the obstacles in charge, the observation car was moved slowly forward and stopped at regular intervals. Independent records were made at each stop of whatever obstruction was noted by the observer. Note was also made of the distance at which the obstruction could be identified. An electric headlight was used on the observation car throughout these tests.

Test No. 11.

A speeder was placed on the track for this test. Comparison of the records shows that this was first noticed by about one-half of the observers at a distance of 700 ft. and by the remainder at 500 ft. It was not fully identified, however, until the car was within 300 ft. of the obstruction.

Test No. 12.

A car was backed on a siding so as not to be entirely clear of the main track. The majority of the observers did not notice this obstruction until the observation car was within about 900 ft. of it. Those who were not railroad men, or at least familiar with railroad practice, did not recognize this car as an obstruction, so that the test was not conclusive.

Test No. 13.

Two sacks stuffed with straw about the size of a man's body were placed between the rails and remained unidentified by all but two observers until the car was within 250 ft. of the obstruction.

Test No. 14.

Two coal cars were backed on the main track for the final test. This obstruction was noticed by practically all observers at a distance of 1,300 ft. but was not fully identified until the observation car was within 900 ft. of the obstruction.

CONCLUSIONS

The following general conclusions seem warranted from the results of the above road tests:

1. That a powerful headlight on a locomotive has one marked disadvantage, namely, that it causes reflections from glass roundels and lenses, thereby producing false or phantom signals. It seems likely that these are partly due to the intensity and partly to the spectral composition of the light.
2. That a powerful opposing headlight adjacent to block signals so obscures the latter as to make it difficult to read them correctly at distances exceeding 1,000 ft.
3. That an opposing oil headlight of ordinary intensity allows such signals to be read correctly at 4,000 ft. or less.
4. That even with no opposing headlight, the distance in which the signal can be read correctly is slightly reduced by the use of a powerful headlight.
5. That a more powerful headlight on an approaching engine obscures the classification signals on that engine to a marked degree. This is particularly true of green signals in the glare of a powerful headlight whose spectral intensity is high in green.
6. That an opposing oil headlight of ordinary intensity allows either white or green signals to be read at a distance of 400 ft. or even more.
7. That obstructions on the track cannot ordinarily be seen with a powerful electric headlight at a sufficient distance to

prevent accidents, since a train travelling at a high rate of speed cannot be stopped in the distance at which obstacles sufficiently large to cause a wreck were first detected.

GROUP II—LABORATORY TESTS

This group of laboratory tests consists of four separate series made on seven different lamps of various types. The lamps are referred to in this paper by number and may be briefly described as follows:

No. 1. Luminous arc, upper electrode copper, lower electrode presumably magnetite composition.

No. 2. Carbon arc, carbons inclined 45 deg. to the horizontal.

No. 3. Luminous arc, similar to No. 1.

No. 4. Electric arc, upper electrode carbon, lower electrode copper.

No. 5. Kerosene oil lamp.

No. 6. Acetylene lamp.

No. 7. Luminous arc, same as No. 1, but instead of being fitted with a reflector, supplied with a lens.

Each of the above headlights was fitted with a reflector supposedly parabolic in shape, except No. 7 which, as before noted, was arranged with a lens before the lamp. The reflectors on Nos. 4, 5 and 6 were polished silver, and those on Nos. 1, 2 and 3 seemed to be polished aluminum.

Four series of tests were made upon these lamps as follows:

Test No. 15. A determination of the illumination produced by the headlight at a fixed point in the axis of the reflector.

Test No. 16. A determination of the total light flux generated by the lamp.

Test No. 17. A determination of the illumination produced along a course of 1300 ft. in front of the headlight.

Test No. 18. A spectro-photometric analysis of the light from each lamp.

In addition to the above, tests were made upon signal roundels taken from service.

Test No. 19. A spectrophotometric analysis of the light reflected from roundels.

Test No. 20. A determination of the reflection coefficients of roundels with and without signal lamps.

It is not necessary to point out in this paper the greater difficulties in obtaining exact results in photometric and especially in spectrophotometric analyses of the light furnished by the electric arc lamp over those encountered in the comparison of most other illuminants. This is particularly true in the case of the electric arc headlights where not only the fluctuations of the arc itself are the direct cause of sudden variations in intensity, but also because of the fact that the arc may at times get out of the focus of the reflector and thus greatly multiply the variation in intensity of the reflected light. It should be pointed out, therefore, that the accuracy is probably greater in the following tests made with oil and acetylene headlights than in the case of the electric arc headlights, although every precaution was taken in all tests to obtain constant reading conditions. The results recorded in the following pages represent the average of a number of readings taken by several observers.

Test No. 15. *A Determination of the Illumination Produced by the Headlight at a Fixed Point in the Axis of the Reflector.*

In this series of tests the headlights were mounted in a dark room arranged for photometric purposes in such a manner that the axis of the reflector passed through the position of a Lummer-Brodhun type of sight box located at the opposite end of the room at the fixed distance of 25.7 feet from the position of the lamp. To balance the illumination of the arc, on the opposite side of the photometer screen, an incandescent lamp of appropriate intensity maintained at a definite voltage was arranged to be controlled by the observer at the sight box. Also, under the control of the observer and moving with the lamp was an electro-magnetically operated punch enabling him to record on a sheet of paper upon a drum the position of the lamp corresponding to a photometric balance between the headlight and the comparison lamp. This device was described by Matthews in a paper before the A.I.E.E. in 1901.* By its means a large number of independent observations corresponding to each condition were easily taken and thus a proper average obtained. With the hope of reducing the large number of possible errors in photometering and electric arc, the substitution method was used throughout, *i.e.*, the comparison lamp while on the bar in working position was frequently compared with a standardized lamp put in position on the headlight side of the sight box.

On account of the extremely high illumination produced by the headlight, it was found necessary to reduce the intensity at

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*"An Improved Apparatus for Arc Light Photometry," Chas. P. Mathews, TRANSACTIONS, A.I.E.E., Vol. XVIII, p. 677.

the sight box in most cases by the use of the well known rotating sectored screen. The only exception to this was with the oil headlight. The constant of the rotating screen was carefully determined and the value checked.

The headlights were all operated as nearly as possible under conditions as specified by the manufacturers. Thus, lamps Nos. 1, 2, 3 and 7 were operated in series with their respective resistances on a pressure of 550 volts, lamp No. 4 with a constant current of 28 amperes, No. 6 with a gas pressure from a tank supplied by the manufacturers, and No. 5 with as high a flame height as could be maintained without the lamp smoking.

From the theory of the reflector, it was decided that the light probably did not follow the law of inverse squares, and since the law of the illumination was to us unknown, it was decided not to attempt to express the intensity of the headlight, but rather the intensity of the illumination produced by it. It was hoped that time would permit the inclusion in this paper of the results of tests planned and in progress for the determination of the law or laws of the variation of the light from these reflectors, but it was found impossible to get these tests finished in time.

The results of test No. 15 are found in Table I expressed in candle-feet of illumination. Considerable fluctuation of the intensity was noted during the test on each lamp and the average value given in the table is the average of from twenty to eighty readings. It was thought that the range of variation for any one lamp might be of interest and the maximum and minimum values of the illumination are accordingly given in the table together with the percentage variation above and below the average.

In column 19 of the same table is found the ratio of the illumination of each lamp to that of the oil lamp, which on account of longer and more common use was taken as a standard for the others. It is of interest to note that the highest illumination was produced by No. 7, and that the illumination from this lamp is a little more than twice as great as the illumination from No. 1, the only difference between the two lamps being that No. 7 is equipped with a lens and No. 1 with a reflector. It is also to be noted that the ratios of the illumination produced by the arc headlights to that of the oil light are of the same order, varying from 23.5 to 49. It is not to be supposed, however, that these ratios would be the same at all distances in front of the headlights, in fact, the results of test No. 17 show quite the contrary. This likely is due to the fact that the law of variation of the intensity of the light is, or may be different for each reflector.

Test No. 16. *A Determination of the Total Flux Generated by the Lamp.*

To make this test, the reflector and all unnecessary equipment was removed from the headlight which was then hung in a circle of mirrors constituting a portion of the mirror photometer described by Matthews in the paper previously cited. These mirrors were located 15 deg. apart enabling the intensity of the light from the lamp to be determined at angular steps of 15 deg. above and below the horizontal. The coefficients of reflection of the mirrors had been previously determined.

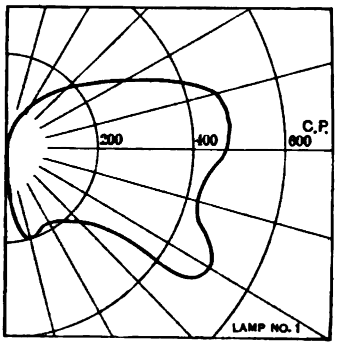

FIG. 1—Distribution of lamp No. 1

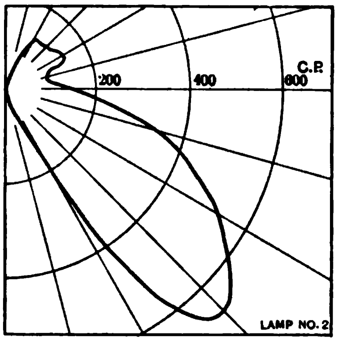

FIG. 2—Distribution of lamp No. 2

The sight box of the photometer was located at the same point as in test No. 15, and the settings were taken in the same manner, with the lamp operating normally, and with all the mirrors covered except those corresponding to the particular angle in which the intensity was being determined. The light from the uncovered mirrors was reflected directly to the photometric screen in the sight box. The intensity determined is from an average of from 20 to 50 independent settings of the photometer taken during a time varying from 5 to 10 minutes. It is believed, therefore, that the results thus obtained represent the average condition of operation.

From these intensities a distribution curve of light from each lamp was plotted and the Kennelly method for determining the total light flux in spherical candles was applied. This method is described by its originator in the Transactions of the Illuminating Engineering Society. In using this method the distribution curve was divided into 15 deg. zones which, it was thought, would insure the accuracy of the determination to a point equal to that ordinarily obtained in photometric work. This method of determining the total light flux from the distribution curve was preferred to the method of obtaining it by a single setting on account of the fact that, in some of the lamps, a shadow was cast at the extreme angles above and below the horizontal by a part of the frame work supporting the arc mechanism. In the method used, the error which would have been introduced by using the single setting method was reduced by assuming such values of intensity at these angles as seemed likely from the trend of the distribution curve. It is not claimed that this can give results of extreme accuracy. It is true, however, that a small variation in the intensities in these directions has little effect upon the total light flux as determined.

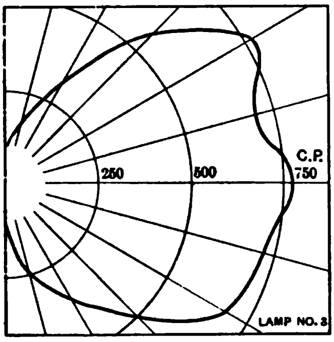

FIG. 3—Distribution of lamp No. 3

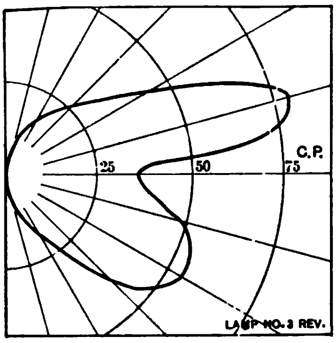

FIG. 4—Distribution of lamp No. 3 (reversed)

The distribution curve for No. 2 could not be obtained with the arc in its normal position because of the fact that this position is with the carbons at an angle of 45 degrees from the vertical. On that account, a distribution curve taken in the vertical plane cannot be used to determine the mean spherical candle power. To obtain a distribution curve for this lamp, it was mounted so that its carbons hung in a vertical plane and the distribution curve taken as in the other types of lamp. It was not considered, however, that this curve would coincide with the curve that would obtain were the lamp hanging in its normal position, because of the fact that the regulating mechanism has its center of gravity disturbed by this change resulting in a length of arc different from that in normal operation. The value of the mean spherical candle power obtained from this curve is found in Table 1 Column 14. An attempt to correct for this abnormal condition was made by taking the intensity of the lamp when suspended normally in a direction corresponding to an angle of 37½ deg. from the horizontal with the carbons in a vertical position. The value thus obtained was considerably larger, than the intensity at the same angle with the lamp in its abnormal position as in the first case, the ratio between the two being 1.35. The intensities taken in the first determination were then multiplied by this ratio and the mean spherical candle power determined from these corrected values. Naturally, this is a considerably higher value than that obtained at first. It seems likely that the value thus obtained is more nearly correct. The values of these light fluxes are found in Table I column 14, and in column 15 are found values of the illumination at the photometer sight box corresponding to the total flux found in column 14. These values of illumination were obtained by dividing the light flux for a given lamp by the square of its distance from the photometric screen. Thus for lamp No. 1, 790 mean spherical c.p. $\div (25.7)^2 = 1.197$. This may be called the hypothetical value of the illumination were the reflector absent. To obtain an idea of the effectiveness of the reflector the actual values of illumination obtained at the fixed point with reflector on the lamp were divided by the hypothetical values in column 15, giving results shown in column 22. The value thus obtained may be called the " Multiplying Factor of the Reflector ". It

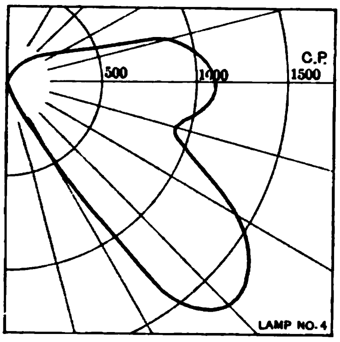

Fig. 5—Distribution of lamp No 4

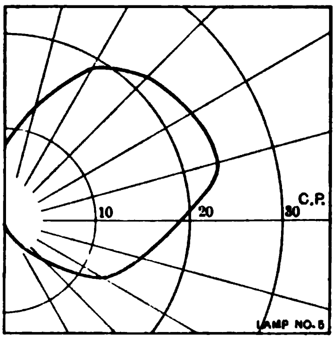

Fig. 6—Distribution of lamp No. 5

will be observed that this factor is not the same for all reflectors, varying from 58.7 for No. 4 to 241 for No. 2.

From the exceedingly high value of this factor for No. 2 the comparatively low total flux of this lamp and the peculiar distribution of light from a carbon arc, it seems probable that the value of this factor is a function of the distribution of the light about the source. In this particular case the inclination of the carbons from the vertical, causes the most intense ray to fall directly in the vertex of the reflector. In no other case does this occur. In the case of No. 4 which has a distribution curve very similar to No. 2, since the electrodes are vertical, the strongest ray, *i.e.*, 45 deg. below the horizontal, does not strike the vertex of the reflector. It may be noted in this connection that the multiplying factor of this reflector is the lowest of any. An explanation of this condition may be found in the fact that the proportion of total light flux falling in the vertex of the reflector is smaller for this lamp, as shown by the curves and the values in Table I, than for any other.

The foregoing is to be understood only as a possible explanation of the variation in what has been called the multiplying factor of reflectors which were clean and in apparently good working condition.

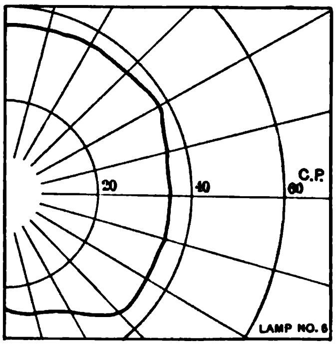

FIG. 7–Distribution of lamp No. 6

Test No. 17. *A Determination of the Illumination Produced along a Course of* 1300 *Feet in Front of the Headlight.*

The nature of this test, which was conducted on moonless nights, is much the same as test No. 15, differing from it principally in the method employed. The attempt was made to duplicate as nearly as possible conditions as to position of headlight and illumination produced thereby as they would occur in practice.

In pursuance of this idea, a tower platform 15 ft. 6 in. high was built out of doors at one end of a course 1,300 ft. in length. The reason for selecting this height was that on the locomotive used in the road tests the headlight was mounted 11 ft. 6 in. above the track. The sight box of the portable photometer was four ft.

high and by placing the headlight on the platform at a height of 15 ft. 6 in., it was possible to determine the illumination as it would occur on the track. The headlights designed for electric traction use were mounted at a height above the photometer level corresponding to that at which they are normally carried on the car.

The photometer used was a Lummer-Brodhun mounted on a tripod. For the purpose of excluding stray light it was fitted with a hood consisting of two tubes of sheet iron 20 in. long by two inches in diameter, blackened within with lamp black. These tubes were attached to the sight box, one on each side entirely covering the opening so that no light could fall upon either side of the screen which did not pass through the tubes.

For comparison, standardized incandescent lamps were used, which during the tests were maintained at a voltage corresponding to their previously determined intensity by means of a rheostat. Power for these comparison lamps was obtained from a storage battery through a line erected parallel with and adjacent to the course, and having sockets connected in at every 100 ft.

The course, which was practically level, was laid off with chain and transit, and for the first 500 ft. stations were established every 50 ft., and after that, every 100 ft. The method of making the test was as follows:

With the headlight in operation and directed along the course in such a manner that the nearer edge of the reflected beam first touched the ground at about 400 ft. in front of the lamp, the photometer was set up over each station in turn, with its tube directed toward the headlight. The comparison lamp, held by one person, who also held at the lamp one end of a 100-ft. steel tape, was moved at the will of the observer at the sight box until a photometric balance was obtained. Several observations were made at each station by different observers, which on account of fluctuations in the source of light, at times varied considerably. The values of illumination presented in Table II represent the average of these readings.

The variation of headlight illumination with distance as determined in this test is clearly shown in Table II as well as in Figs. 8 and 9 whose curves are plotted from the data in the above table. Fig. 8 is plotted to a larger scale and includes headlights numbered 2, 4 and 7 which showed the greatest intensities. It should be noted that there is a marked similarity in the general form of these three curves and the relative intensities of the illumination in spite of the fact that they are taken from different types of headlights. In Fig. 9, the intensities of the remainder of the headlights are shown together with a portion of the curves reproduced from Fig. 8 to smaller scale. From this one figure, therefore, a comparison can be made of the intensities of all types and makes of headlights tested. The contrast between curve No. 5 representing the common type of kerosene oil locomotive headlight and the other curves, representing more powerful types, is very marked, and it is interesting to note that at the maximum distance of 1,300 ft. considered in these tests, three headlights, numbered 2, 4 and 7 gave an illumination considerably above the maximum possible at any distance with the kerosene oil headlight.

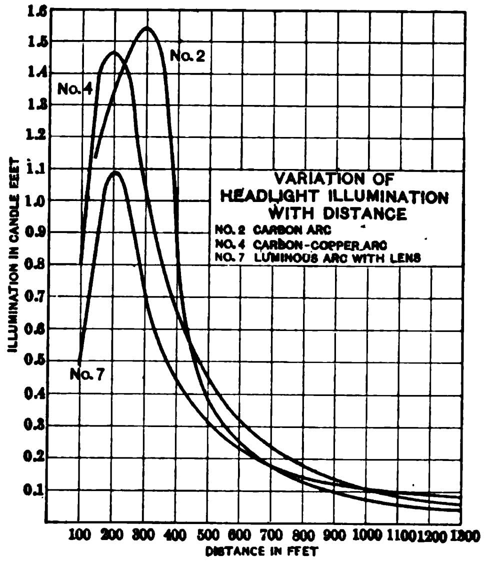

Fig. 8

It will be noted from the curves, Fig. 8 and 9, that in nearly all cases the illumination starting at some value near the lamp increased to a maximum at from 200 to 400 ft. from the lamp, and again decreased as the distance was increased.

That the point of maximum intensity is at some distance from the lamp may be accounted for from the fact that at distances less than that at which the maximum occurs, the illumination is largely due to the direct and not the reflected rays. At points which are illuminated by both direct and reflected rays, the illumination is naturally higher.

Test No. 18. *A Spectrophotometric Analysis of the Light from Each Lamp.*

In order to determine the relative intensities of the various primary colors in the direct rays of the several types of headlights, a Martens-Koenig spectrophotometer was used. With this instrument the intensity of the light in the yellow portion of the spectrum, corresponding to the wave length of sodium light, (0.0005890 cm.) was balanced against that in the same portion of the spectrum furnished by a carbon incandescent lamp

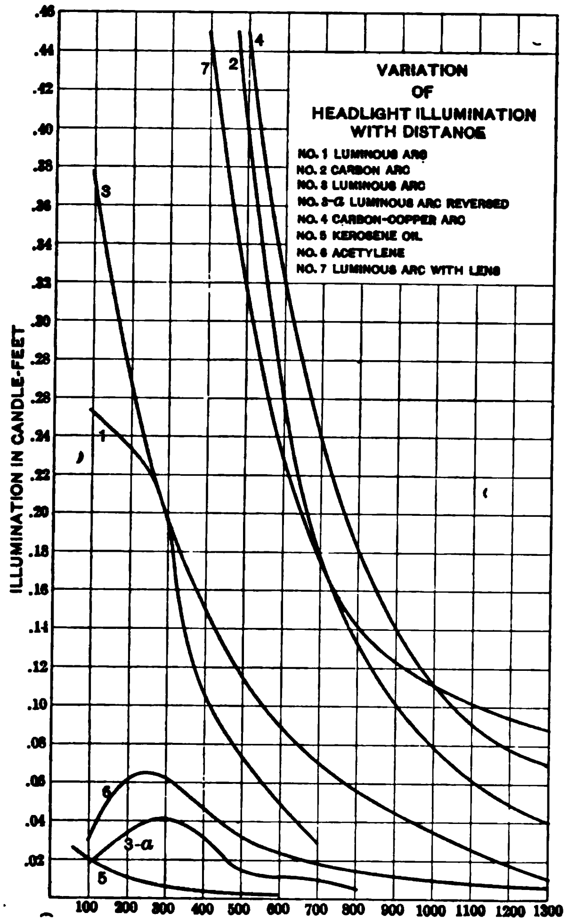

Fig. 9

operating at constant rated voltage. The ratio of intensities in other portions of the spectrum was then obtained by turning the Nichol prism of the instrument through a measurable angle, thus polarizing a portion of the light from one of the sources. This ratio is then proportional to the square of the tangent of the angle from the point of complete polarization through which the Nichol prism has been turned to obtain a balance. The carbon incandescent lamp which was used in this case as a secondary standard was later compared with daylight reflected from the sky. Readings of the spectrophotometer were made only when the intensity of the arc was shown by the Lummer-Brodhun screen to be the same as when balanced at the wave length of sodium.

In the following tables, numbered from III to XII inclusive, together with Figs. 11 to 14 inclusive, which include curves plotted from these tables, may be found the squared tangents of the angles representing the intensity of the light compared with that of the carbon incandescent lamp. The corresponding values for daylight are shown in the next column of the table while the ratios of the intensity of the particular light to that of daylight are shown in the last column. These latter values are plotted as ordinates in the following curves while the corresponding wave lengths of light listed in the second column of the tables are plotted as abscissæ.

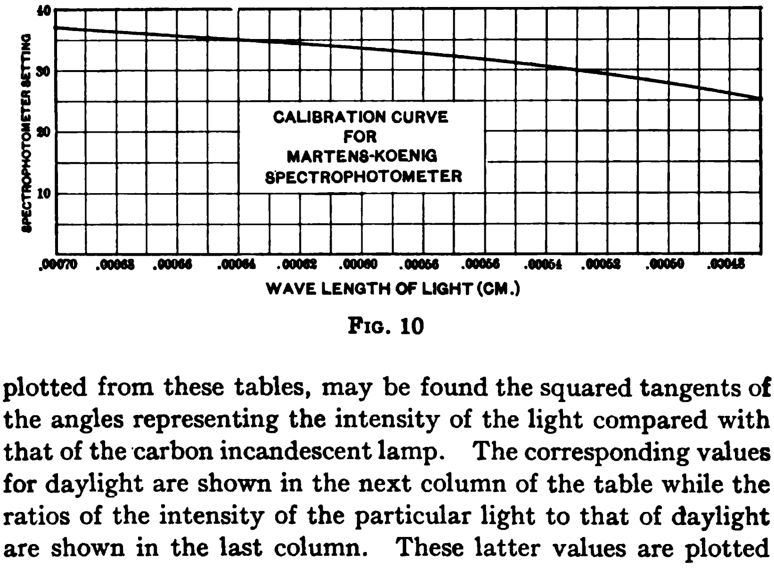

FIG. 10

In further explanation of the curves given in Fig. 11 to 15 inclusive, it should be noted that in each figure curve *D* represents the ratio of intensity of the carbon incandescent lamp to daylight. It is possible, therefore, to compare the spectral intensities of the lights being considered, with daylight not only, but also with the incandescent secondary standard lamp.

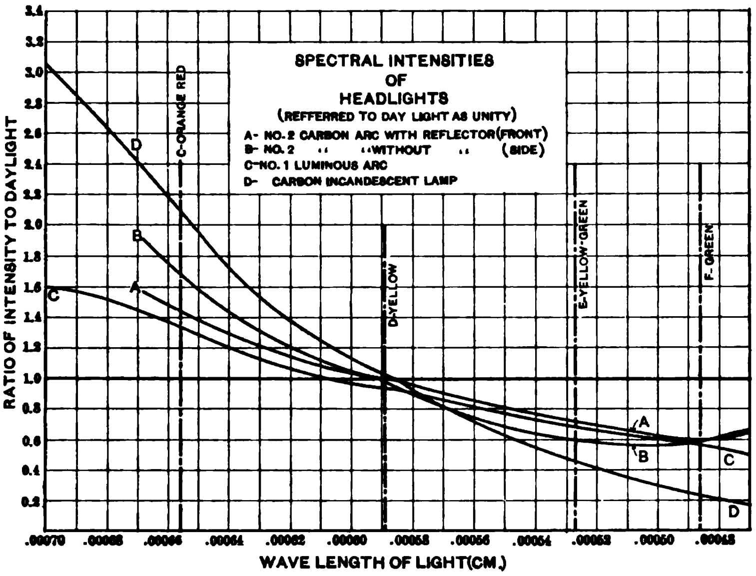
SPECTRAL INTENSITIES
OF
HEADLIGHTS
(REFFERRED TO DAY LIGHT AS UNITY)
A- NO. 2 CARBON ARC WITH REFLECTOR (FRONT)
B- NO. 2 " " WITHOUT " " (SIDE)
C- NO. 1 LUMINOUS ARC
D- CARBON INCANDESCENT LAMP
RATIO OF INTENSITY TO DAYLIGHT
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
C-ORANGE RED
D-YELLOW
E-YELLOW-GREEN
F-GREEN
A
B
C
D
.00070
.00068
.00066
.00064
.00062
.00060
.00058
.00056
.00054
.00052
.00050
.00048
WAVE LENGTH OF LIGHT(CM.)

FIG. 11

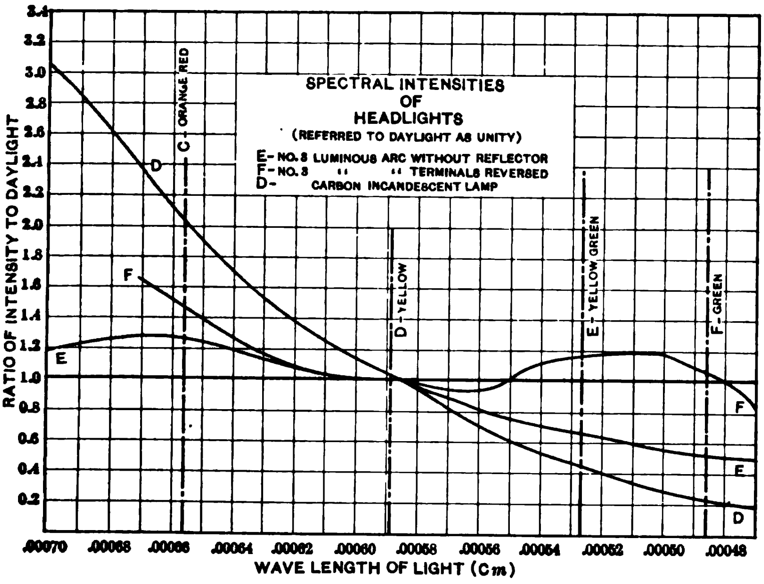
SPECTRAL INTENSITIES
OF
HEADLIGHTS
(REFERRED TO DAYLIGHT AS UNITY)
E- NO. 3 LUMINOUS ARC WITHOUT REFLECTOR
F- NO. 3 " " TERMINALS REVERSED
D- CARBON INCANDESCENT LAMP
RATIO OF INTENSITY TO DAYLIGHT
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
C-ORANGE RED
D-YELLOW
E-YELLOW GREEN
F-GREEN
D
E
F
.00070
.00068
.00066
.00064
.00062
.00060
.00058
.00056
.00054
.00052
.00050
.00048
WAVE LENGTH OF LIGHT (Cm)

FIG. 12

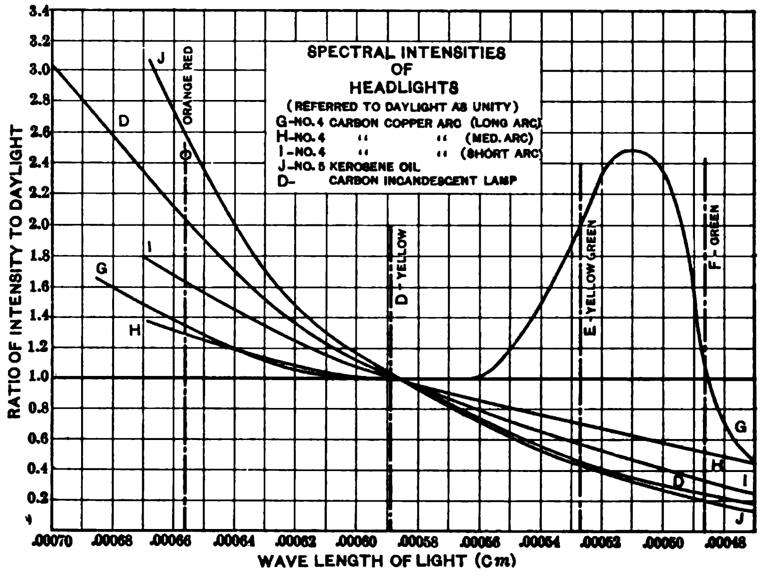
SPECTRAL INTENSITIES
OF
HEADLIGHTS
(REFERRED TO DAYLIGHT AS UNITY)
G-NO. 4 CARBON COPPER ARC (LONG ARC)
H-NO. 4 " " (MED. ARC)
I-NO. 4 " " (SHORT ARC)
J-NO. 5 KEROSENE OIL
D- CARBON INCANDESCENT LAMP
RATIO OF INTENSITY TO DAYLIGHT
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
.00070
.00068
.00066
.00064
.00062
.00060
.00058
.00056
.00054
.00052
.00050
.00048
WAVE LENGTH OF LIGHT (Cm)
C-ORANGE RED
D-YELLOW
E-YELLOW GREEN
F-GREEN
J
D
I
G
H

FIG. 13

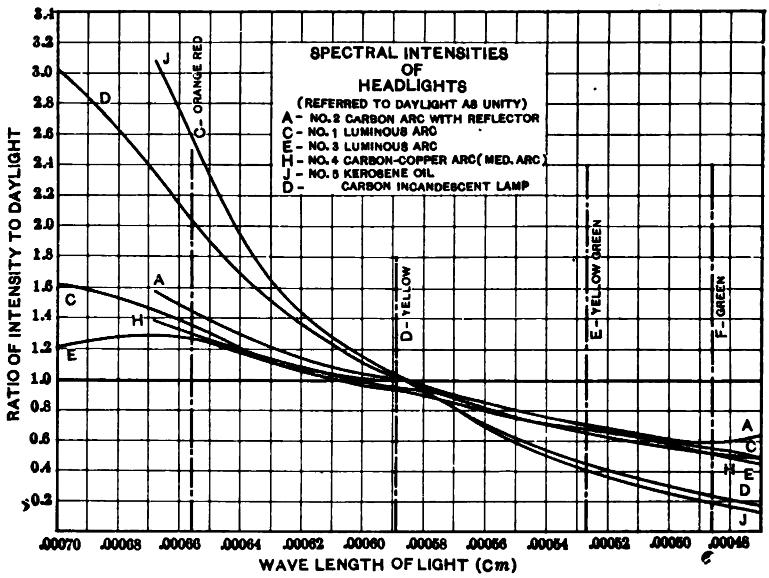
SPECTRAL INTENSITIES
OF
HEADLIGHTS
(REFERRED TO DAYLIGHT AS UNITY)
A- NO. 2 CARBON ARC WITH REFLECTOR
C- NO. 1 LUMINOUS ARC
E- NO. 3 LUMINOUS ARC
H- NO. 4 CARBON-COPPER ARC (MED. ARC)
J- NO. 5 KEROSENE OIL
D- CARBON INCANDESCENT LAMP
RATIO OF INTENSITY TO DAYLIGHT
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
.00070
.00068
.00066
.00064
.00062
.00060
.00058
.00056
.00054
.00052
.00050
.00048
WAVE LENGTH OF LIGHT (Cm)
C-ORANGE RED
D-YELLOW
E-YELLOW GREEN
F-GREEN
J
D
A
C
H
E

FIG. 14

By referring to Fig. 11 it will be seen that the intensity of the luminous arc headlight in the various portions of the spectrum is not materially different from that of the carbon arc, the former being slightly lower in the red than the latter. All types of headlights, with the exception of the kerosene oil shown in Fig. 13, have less intensity in the orange and red and greater intensity in the green and violet than the incandescent lamp, as would be expected. Fig. 12 shows an interesting feature in connection with the luminous arc headlight with terminals reversed which provision is made in some cases for temporarily

TABLE III. SPECTRAL INTENSITIES OF CARBON INCANDESCENT LAMP REFERRED TO DAYLIGHT

Setting	Wave length (mm.)	Average reading	Cotangent squared
37	0.000700	29.8	3.04
36	0.000668	33.1	2.36
35	0.000640	37.4	1.71
34	0.000812	41.7	1.26
33	0.000586	45.1	1.00
32	0.000564	49.0	0.758
31	0.000548	52.0	0.610
30	0.000532	55.0	0.494
29	0.000516	58.0	0.393
28	0.000502	60.5	0.322
27	0.000490	63.0	0.260
26	0.000480	65.0	0.218
25	0.000470	67.0	0.182

TABLE IV. SPECTRAL INTENSITIES OF HEADLIGHT NO. 1

Setting	Wave length (mm.)	Average reading	Tangent squared	Tangent squared daylight	Ratio intensity to daylight
37	0.000700	36.1	0.530	0.329	1.61
36	0.000668	38.1	0.613	0.425	1.44
35	0.000640	40.1	0.710	0.585	1.21
34	0.000812	42.1	0.815	0.795	1.02
33	0.000586	44.1	0.935	1.00	0.935
32	0.000564	46.1	1.075	1.32	0.815
31	0.000548	48.1	1.240	1.64	0.755
30	0.000532	50.1	1.42	2.03	0.700
29	0.000516	52.1	1.65	2.55	0.646
28	0.000502	54.1	1.90	3.11	0.610
27	0.000490	56.0	2.21	3.85	0.574
26	0.000480	57.8	2.51	4.60	0.545
25	0.000470	58.9	2.74	5.51	0.497
24	0.000460	59.8	2.96		
23	0.000450	60.0	3.22		

reducing the intensity of headlights. Such a reversal introduces a relatively high intensity in the green portion of the spectrum probably due to the burning away of the copper electrode. A similar but more marked effect is shown in Fig. 13 in connection with an arc headlight of another type using a lower electrode of copper, with which it was found that, if a long arc were permitted to form, very high intensities in the green portion of the spectrum were introduced, probably due to the cause mentioned above. From the green appearance of the light given at times by this electric headlight, which was used in the road tests, it is quite probable that this condition sometimes obtains in practice and it is believed that the possibility of obtaining green phantom signals is increased by this fact.

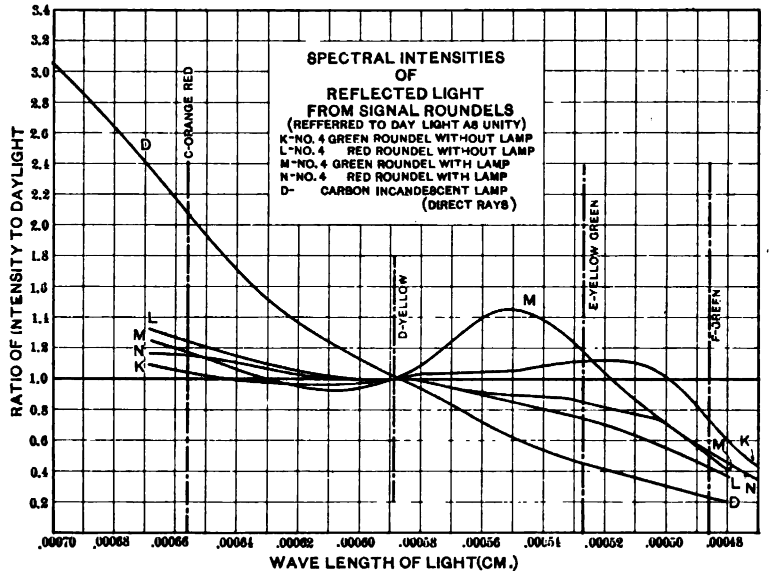

FIG. 15

Test No. 19. *A spectrophotometric Analysis of the Light Reflected from Roundels.*

In this test the same spectrophotometer was used and the method of procedure was the same as in test No. 18, with the exception that the light analyzed was first reflected from signal roundels. Headlight No. 4, which was used in the road tests, furnished the light for this analysis. Tables XIII to XVI inclusive show the results obtained in this test which are plotted in Fig. 15. The point of particular significance, in explanation of the phantom signals found in the road tests, is the fact that the intensities in the green portion of the spectrum of light reflected from green roundels are much greater than those reflected from red roundels. It is further noted that the effect of placing an unlighted signal lamp back of the green roundel, as is usually

TABLE V. SPECTRAL INTENSITIES OF HEADLIGHT NO. 2 FRONT WITH REFLECTOR

Setting	Wave length (mm.)	Average reading	Tangent squared	Tangent squared daylight	Ratio intensity to daylight
36	0.000668	39.2	0.666	0.425	1.57
35	0.000640	41.1	0.760	0.585	1.30
34	0.000812	43.0	0.870	0.795	1.09
33	0.000586	45.0	1.000	1.00	1.00
32	0.000564	47.0	1.142	1.32	0.865
31	0.000548	49.0	1.320	1.64	0.805
30	0.000532	50.8	1.50	2.03	0.740
29	0.000516	52.9	1.745	2.55	0.685
28	0.000502	54.5	1.960	3.11	0.630
27	0.000490	56.7	2.31	3.85	0.600
26	0.000480	59.0	2.76	4.60	0.600
25	0.000470	62.0	3.54	5.51	0.641
24	0.000460	66.0	5.05	—	—
23	0.000450	71.1	8.50	—	—

TABLE VI. SPECTRAL INTENSITIES OF HEADLIGHT NO. 2 TURNED SIDEWISE NO REFLECTOR

Setting	Wave length (mm.)	Average reading	Tangent squared	Tangent squared daylight	Ratio intensity to daylight
36	0.000668	42.0	0.810	0.425	1.91
35	0.000640	42.6	0.840	0.585	1.44
34	0.000812	43.5	0.900	0.795	1.13
33	0.000586	44.2	0.944	1.00	0.944
32	0.000564	45.3	1.020	1.32	0.773
31	0.000548	46.5	1.11	1.64	0.677
30	0.000532	48.4	1.26	2.03	0.620
29	0.000516	50.5	1.47	2.55	0.576
28	0.000502	53.0	1.75	3.11	0.563
27	0.000490	56.0	2.20	3.85	0.570
26	0.000480	59.3	2.83	4.60	0.615
25	0.000470	62.0	3.53	5.51	0.640
24	0.000460	63.9	4.15	—	—
23	0.000450	64.6	4.42	—	—

TABLE VII. SPECTRAL INTENSITIES OF HEADLIGHT NO. 3

Setting	Wave length (mm.)	Average reading	Tangent squared	Tangent squared daylight	Ratio intensity to daylight
37	0.000700	32.0	0.390	0.329	1.19
36	0.000668	36.3	0.540	0.425	1.27
35	0.000640	39.8	0.691	0.585	1.18
34	0.000812	42.4	0.830	0.795	1.04
33	0.000586	44.8	0.985	1.00	0.985
32	0.000564	46.4	1.10	1.32	0.834
31	0.000548	48.0	1.23	1.64	0.750
30	0.000532	49.9	1.40	2.03	0.690
29	0.000516	51.5	1.57	2.55	0.616
28	0.000502	53.2	1.78	3.11	0.572
27	0.000490	55.0	2.03	3.85	0.527
26	0.000480	56.9	2.35	4.60	0.510
25	0.000470	58.7	2.70	5.51	0.490
24	0.000460	60.3	3.07	—	—
23	0.000450	62.0	3.53	—	—

TABLE VIII. SPECTRAL INTENSITIES OF HEADLIGHT NO. 3 TERMINALS REVERSED

Setting	Wave length (mm.)	Average reading	Tangent squared	Tangent squared daylight	Ratio intensity to daylight
36	0.000668	39.9	0.836	0.425	1.65
35	0.000640	41.0	0.869	0.585	1.28
34	0.000812	42.5	0.916	0.795	1.055
33	0.000586	45.0	1.00	1.00	1.00
32	0.000564	48.3	1.122	1.32	0.955
31	0.000548	53.0	1.327	1.64	1.068
30	0.000532	57.0	1.540	2.03	1.16
29	0.000516	60.0	1.732	2.55	1.175
28	0.000502	62.5	1.921	3.11	1.185
27	0.000490	64.0	2.050	3.85	1.09
26	0.000480	65.0	2.144	4.60	1.00
25	0.000470	65.0	2.144	5.51	0.835
24	0.000460	64.5	2.097	—	—

TABLE IX. SPECTRAL INTENSITIES OF HEADLIGHT NO. 4 MEDIUM ARC

Setting	Wave length (mm.)	Average reading	Tangent squared	Tangent squared daylight	Ratio intensity to daylight
36	0.000668	37.4	0.765	0.425	1.375
35	0.000640	40.0	0.839	0.585	1.20
34	0.000812	42.3	0.910	0.795	1.042
33	0.000586	44.8	0.993	1.00	1.985
32	0.000564	46.9	1.069	1.32	0.864
31	0.000548	49.0	1.150	1.64	0.804
30	0.000532	50.7	1.222	2.03	0.734
29	0.000516	52.4	1.299	2.55	0.658
28	0.000502	54.0	1.376	3.11	0.608
27	0.000490	55.4	1.450	3.85	0.545
26	0.000480	56.8	1.528	4.60	0.504
25	0.000470	57.8	1.588	5.51	0.455
24	0.000460	58.5	1.632	—	—

the case in practice, apparently increases, to a very marked extent, the intensity in the yellow-green portion of the spectrum of the reflected light.

Test No. 20. *A Laboratory Determination of the Reflection Coefficients of Roundels with and without Signal Lamps.*

After it was found in the previous test that the placing of a signal lamp back of a green roundel greatly increased the intensity of the reflected light in the yellow-green portion of the spectrum, it seemed worth while to determine the reflection coefficients of both green and red roundels with and without signal lamps placed directly behind them in the position which they occupy in practice. These results are clearly shown in Table XVII from which it will be noted that the reflection coefficients of red roundels are slightly greater than those of green roundels but that in both cases, the coefficients are greater when the roundels are mounted in front of signal lamps. It seems probable that the increase in this coefficient is due to the presence of the lens of the signal lamp.

TABLE X. SPECTRAL INTENSITIES OF HEADLIGHT NO. 4. LONG ARC

Setting	Wave length (mm.)	Average reading	Tangent squared	Tangent squared daylight	Ratio intensity to daylight
37	0.000700	37.5	0.588	0.329	1.79
36	0.000668	38.3	0.623	0.425	1.47
35	0.000640	39.9	0.700	0.585	1.20
34	0.000812	42.0	0.810	0.795	1.02
33	0.000586	45.0	1.00	1.00	1.00
32	0.000564	49.0	1.32	1.32	1.00
31	0.000548	55.2	2.06	1.64	1.26
30	0.000532	62.3	3.61	2.03	1.78
29	0.000516	68.2	6.25	2.55	2.46
28	0.000502	70.0	7.51	3.11	2.42
27	0.000490	68.0	6.10	3.85	1.58
26	0.000480	61.4	3.35	4.60	0.728
25	0.000470	58.1	2.57	5.51	0.465
24	0.000460	58.2	2.60	—	—

In conclusion, it may be well to call attention to other tests not formally listed herein, which were made in connection with the laboratory tests to reproduce, if possible, the phantom signals noticed in the road tests. Headlight No. 4 was mounted upon the platform described in test No. 17, and red and green signal roundels with and without signal lamps were placed in a position corresponding to that of the home signal. Although the signal lamps located behind the roundels being tested were not lighted, yellowish green reflections were obtained from the roundels which were quite as brilliant as other signals placed near by for comparison, and might have been easily mistaken for a green signal.

TABLE XI. SPECTRAL INTENSITIES OF HEADLIGHT NO. 4. SHORT ARC

Setting	Wave length (mm.)	Average reading	Tangent squared	Tangent squared daylight	Ratio intensity to daylight
36	0.000668	41.1	0.760	0.425	1.79
35	0.000640	42.6	0.841	0.585	1.44
34	0.000812	43.9	0.921	0.795	1.16
33	0.000586	45.0	1.000	1.00	1.00
32	0.000564	46.1	1.075	1.32	0.815
31	0.000548	47.1	1.155	1.64	0.705
30	0.000532	48.0	1.230	2.03	0.606
29	0.000516	48.9	1.305	2.55	0.512
28	0.000502	49.2	1.335	3.11	0.429
27	0.000490	49.6	1.380	3.85	0.358
26	0.000480	49.8	1.400	4.60	0.304
25	0.000470	49.95	1.42	5.51	0.258
24	0.000460	50.0	1.42	—	—
23	0.000450	50.0	1.42	—	—

TABLE XII. SPECTRAL INTENSITIES OF HEADLIGHT NO. 5

Setting	Wave length (mm.)	Average reading	Tangent squared	Tangent squared daylight	Ratio intensity to daylight
37	0.000700	52.1	1.641	0.329	4.99
36	0.000668	48.9	1.31	0.425	3.08
35	0.000640	46.9	1.14	0.585	1.95
34	0.000812	45.8	1.055	0.795	1.33
33	0.000586	45.0	1.000	1.00	1.00
32	0.000564	44.7	0.980	1.32	0.742
31	0.000548	44.3	0.950	1.64	0.580
30	0.000532	44.0	0.930	2.03	0.459
29	0.000516	43.8	0.918	2.55	0.361
28	0.000502	43.3	0.858	3.11	0.276
27	0.000490	42.8	0.855	3.85	0.222
26	0.000480	42.0	0.810	4.60	0.176
25	0.000470	40.7	0.739	5.51	0.134
24	0.000460	38.6	0.635	—	—

It is believed the results of the laboratory tests will be of interest from the photometric standpoint and that some pe-

TABLE XIII. SPECTRAL INTENSITIES OF REFLECTED LIGHT FROM A GREEN ROUNDEL WITHOUT LAMP

Setting	Wave length (mm.)	Average reading	Tangent squared	Tangent squared daylight	Ratio intensity to daylight
36	0.000668	34.3	0.465	0.425	1.09
35	0.000640	37.4	0.585	0.585	1.00
34	0.000812	41.1	0.760	0.795	0.955
33	0.000586	45.0	1.000	1.00	1.00
32	0.000564	49.6	1.38	1.32	1.05
31	0.000548	52.7	1.72	1.64	1.05
30	0.000532	56.2	2.22	2.03	1.09
29	0.000516	59.3	2.83	2.55	1.11
28	0.000502	61.0	3.25	3.11	1.04
27	0.000490	60.9	3.21	3.85	0.835
26	0.000480	59.4	2.85	4.60	0.62
25	0.000470	57.7	2.50	5.51	4.54
24	0.000460	—	—	—	—

TABLE XIV. SPECTRAL INTENSITIES OF REFLECTED LIGHT FROM A RED ROUNDEL WITHOUT LAMP

Setting	Wave length (mm.)	Average reading	Tangent squared	Tangent squared daylight	Ratio intensity to daylight
36	0.000668	36.9	0.562	0.425	1.32
35	0.000640	39.4	0.671	0.585	1.15
34	0.000812	42.0	0.810	0.795	1.02
33	0.000586	45.0	1.00	1.00	1.00
32	0.000564	47.8	1.21	1.32	0.916
31	0.000548	50.5	1.47	1.64	0.896
30	0.000532	53.0	1.75	2.03	0.862
29	0.000516	55.0	2.03	2.55	0.795
28	0.000502	56.8	2.33	3.11	0.750
27	0.000490	56.3	2.24	3.85	0.582
26	0.000480	55.8	2.16	4.60	0.470
25	0.000470	54.5	1.96	5.51	0.356

TABLE XV. SPECTRAL INTENSITIES OF REFLECTED LIGHT FROM A GREEN ROUNDEL WITH LAMP

Setting	Wave length (mm.)	Average reading	Tangent squared	Tangent squared daylight	Ratio intensity to daylight
36	0.000668	36.0	0.529	0.425	1.25
35	0.000640	38.3	0.622	0.585	1.06
34	0.000812	40.8	0.745	0.795	0.936
33	0.000586	45.5	1.03	1.00	1.03
32	0.000564	53.3	1.79	1.32	1.36
31	0.000548	57.0	2.36	1.64	1.44
30	0.000532	58.0	2.55	2.03	1.26
29	0.000516	57.5	2.46	2.55	0.965
28	0.000502	56.8	2.33	3.11	0.75
27	0.000490	55.8	2.16	3.85	0.561
26	0.000480	54.1	1.90	4.60	0.413

culiarities noted in the use of powerful headlights in railroad operation are explained thereby.

CONCLUSIONS

As a summary of the results, the following may be noted:

First. That the magnitude of the illumination is a function not only of the total light flux emitted from the lamp, but also its distribution.

TABLE XVI. SPECTRAL INTENSITIES OF REFLECTED LIGHT FROM A RED ROUNDEL WITH LAMP

Setting	Wave length (mm.)	Average reading	Tangent squared	Tangent squared daylight	Ratio intensity to daylight
36	0.000668	35.1	0.494	0.425	1.16
35	0.000640	38.9	0.650	0.585	1.11
34	0.000812	42.0	0.810	0.795	1.02
33	0.000586	45.0	1.000	1.00	1.00
32	0.000564	47.3	1.170	1.32	0.886
31	0.000548	49.5	1.370	1.64	0.835
30	0.000532	51.3	1.55	2.03	0.763
29	0.000516	52.5	1.69	2.55	0.663
28	0.000502	53.0	1.75	3.11	0.563
27	0.000490	52.9	1.74	3.85	0.451
26	0.000480	52.5	1.70	4.60	3.70

TABLE XVII. REFLECTION COEFFICIENTS OF ROUNDELS

Angle deg.	Green	Green with lens	Red	Red with lens
7½	0.0418	0.0478	0.05	0.0512
15	0.0375	0.0437	0.048	0.0514
22½	0.0352	0.0468	0.0486	0.0505
30	0.0413	0.0459	0.0467	0.0453

Second. That that reflector in which the largest proportion of total light flux falls in the vertex will have the highest multiplying factor.

Third. That the lens type of projector has a higher multiplying factor than the reflector type, other things being equal.

Fourth. That the spectral intensities of the luminous arc headlights are not noticeably different from those of the carbon arc, although the former are slightly lower in the red portion of the spectrum than the latter.

Fifth. That headlight No. 4 having a lower electrode of copper may so operate in practice as to produce relatively high intensities in the yellow-green portion of the spectrum. This is also true of headlight No. 3 with terminals reversed.

Sixth. That oil headlight No. 5 gives intensities higher in the red and lower in the green than all other headlights tested.

Seventh. That the reflected light from green roundels has a higher intensity in the green than that from red roundels and that this intensity is greatly augmented when a signal lamp is placed behind the roundel as in practice.

In closing this paper it is desired to acknowledge the very great assistance furnished the authors by their associates in the University.

DISCUSSION ON "HEADLIGHT TESTS." JEFFERSON, N. H., JUNE 28, 1910.

C. A. B. Halvorson, Jr.: There are a few points to which I would call attention.

So far as I am able to judge, the benefit to be derived from the use of a powerful headlight is the feeling of security and confidence given to the engineer. With the track ahead in darkness or poorly illuminated, his nerves may be kept constantly " on edge " making him liable to blunders. Or, on the other hand, he may become reckless and simply trust to luck. I base my opinion on experience gained under actual operating conditions and from talks with engineers.

No reference is made to tests on wet or foggy nights. On such nights the ground and the sleepers as well as all other unpainted wooden objects along side the track appear black from absorption of water. Or, in case of a heavy fog bank this will appear as a solid illuminated wall shutting out the view of anything ahead.

There is another point in the conclusions to which I wish to refer. It is stated that " A powerful opposing headlight adjacent to block signals so obscures the latter as to make it difficult to read them correctly at distances exceeding 1,000 ft." It seems to me that this would be easily overcome by drawing up a set of rules governing the use of headlights. This has been done on some roads. When two approaching trains come within view of one another, the luminous arc of both headlights are extinguished and the less powerful incandescent lamps lighted. This practice obviates the difficulties mentioned.

Instead of advocating less powerful headlights, I would recommend increasing the efficiency by raising the current to 7 amperes. The ordinary luminous headlight as operated to-day is run at 4 amperes, consuming about 500 watts at the terminals. Improvement in the accuracy of the mirrors is also needed.

It was my pleasure to make a test on the D. & H. line between Albany and Whitehall, using a locomotive headlight operating with a 7-ampere magnetite arc, and we could easily discern persons walking on the track at a distance of 1700 ft. A combination of mirrors was used in this headlight, consisting of a large parabolic metallic mirror and a 9-in. Mangin mirror. The results obtained with this headlight were very fine, indeed.

With reference to reversing the polarity of the arc in order to dim the light, I would suggest that an ordinary incandescent lamp would probably give much better results than a reversed arc. Such a lamp placed out of focus of the mirror as an auxiliary to the luminous arc seems to me the best solution of the glare trouble.

Most of you are probably familiar with the luminous arc. It is a very long arc and the light is given from a core which is intensely bright. When a Mangin mirror is used, the light projected is practically an image of the arc. The beam, therefore, will be of small width, the principal extension being in a vertical plane. By using small diameter electrodes it should be possible to confine the light to the space between the rails. and this has actually been accomplished. In this way all trouble on account of reflection from roundels, etc., can be eliminated.

The third conclusion states that " The lens type of projector has a higher multiplying factor than the reflector type, other things being equal ". This may be true when the comparison is made with ordinary metallic mirrors. Comparing the lens form with the Mangin mirror form of headlight I doubt that the statement holds good. I would like to know whether Professor Harding has made any tests along these lines.

John B. Taylor: Some data as to the make-up of the observing committee seems desirable; first, whether the same eleven men were interested in all the tests, and, second, whether they were trained railroad men, and if not, what was their particular occupation in life. I understand tests will show about one man out of every two dozen to be color blind, so that we should know whether all these men went through a color blind examination, before they were given a position of this committee. I would ask also whether the lower values of distances given for recognizing the signals and obstructions were usually determined by one or two exceptional men, or whether they are fair low average values?

George H. Stickney: The brief inspection which I have made of the paper seems to indicate that, under existing conditions of signals, etc., the use of high power headlights was not found beneficial, inasmuch as they interferred with the reading of signals.

The purpose of the headlight is two-fold, namely to assist the engineer in seeing ahead, and to warn people of the approach of the train. With low-power headlights the former function is practically lost, and in foggy weather the range of warning is quite limited. For these purposes therefore there is unquestionably a demand for powerful headlights.

The objection to their use apparently relates entirely to the reading of signals. In regard to this point there seem to be a number of possibilities of eliminating or reducing such interference. For example, the headlight beam may be directed very slightly downward so as to fall below the eyes of the engineer of an approaching locomotive. At the same time the signals could be placed above the range of the beam. Very accurate control of a light beam is obtained, for instance, in a stereopticon projector, so that it would seem possible to produce this effect without limiting the range of illumination along the track.

Harry Barker: The opening paragraph of the paper states that the Indiana Railroad Commission was instructed to investigate the rules regarding the compulsory use of more powerful headlights on steam locomotives operating in the State of Indiana. I would ask if Professor Harding could inform us as to the ruling of the Commission? I understand, that in spite of Professor Benjamin's report, mentioned later in Professor Harding's paper, and in spite of the somewhat adverse findings of the special sub-commission, or of the individuals of the Railroad Commission, the Commission has, nevertheless, ordered that high-power lamps be used. If that is so, it might be interesting to know some of the qualifications of these instructions.

C. P. Steinmetz: This paper is very interesting, though some of the results at first appear unexpected; *i.e.*, the result that the more powerful headlight is inferior, in certain respects, by making the signals less distinguishable. If we apply that reasoning still further, it would follow that the best way would be to have no headlight at all, because then you would see the signals best.

Now, on the other hand, if we have a headlight, and need a headlight, it appears reasonable to expect that the more powerful the headlight is, the further distance we can see obstructions or other defects of the roadbed, and the further distance one can be seen; therefore, the most powerful headlight would be the most satisfactory one, except as regards the signals. It would be interesting to investigate whether this objection regarding signals could not be overcome by applying the same remedy. If we need a high-power headlight, why not also use higher powered signal lights to make the two again comparable with each other, and at the same time apply this remedy which has been suggested here, that is, to control the beam of the headlight so as not to throw it directly on the signals.

We all know if we send a powerful beam of a searchlight against a small and low intensity light, we do not see the latter light very well, and we do not need any test to tell us this. Besides, it appears to me that the case of looking at signal lights against an opposing headlight is rather an exceptional case. If there is another train coming, with a powerful light, either we must be sure of our signals, or must slow down. I do not think it is generally the case that two locomotives, when not certain of their signals, will approach each other at full speed. We may turn the headlight away, or turn it out, or do anything else, or may slow down, and if we slow down even for a distance of a few hundred yards, that distance will be sufficient to enable us to avoid any obstruction.

I believe the question requires further consideration and investigation before we can accept the theory that the headlight of a train can be too powerful.

Charles F. Scott: One use of the headlight referred to a few moments ago is to give a warning of approaching trains to people not connected with the railroad. In some cases, the headlight can be seen long before the approach of the car can be heard.

As electric trains come into use, and do not have smoke to indicate their presence at a long distance, the headlight at night gives a very fair indication of the position of distant trains, which would be of very great use on single track roads.

With regard to seeing of signals, the suggestion is made that a different form of signal, a position signal, might be advantageous instead of a colored signal. A position signal might be seen very clearly, irrespective of the color of the signal.

With regard to operation at full speed, and in connection with a point made by the last speaker, namely, the suggestion that if there is an approaching train with a powerful headlight, it is well to slow down, it may be remarked that there are cases, such as on double track roads, or four track roads, with block signals placed at frequent intervals, in which trains do run in opposite directions at high speeds, with signals at frequent intervals where the approaching headlights may dazzle the eyes of the engineer.

All these little points show the intricacy of the problem, and I think the paper, as a whole, brings out in a very emphatic way the need for the kind of investigation and scientific analysis which has been given to a problem of this kind. I presume that practically all of us, would have said off hand that the arc light would be an excellent headlight and its general adoption desirable. But these various indirect points, the dazzling of the eye of the approaching engineer, the obscuring of signals, the changing of the colors of signals by reflected light, all of which indicate the importance of a thorough scientific investigation of the subject, show the high value of papers such as the one we have just had.

George A. Hoadley: There is just one point not touched on, and that is this; the very great difficulty there is of forming any judgment, within satisfactory bounds of accuracy, as to the distance of a powerful headlight. To a person on the track, it is impossible to tell if the headlight is three hundred yards away, or one hundred feet, so it seems to me the headlight which gives a perfectly parallel beam of light, that does not strike the track, is an objectionable form of headlight. If the light strikes the track, the observer has an opportunity to determine the distance of the headlight from the point at which he is standing.

Harry P. Wood: I would ask Professor Harding if he made any test to determine the proper height of a headlight above the track? In the electric road the headlight is close to the track, and I understand, as regards engineers in the cab of a locomotive, there is a difference of opinion as to whether the headlight should be at the center of the smoke-box or above the smoke-box. I think the lower headlight will be better than the headlight which is placed higher up, as in the lower position the beam of light will not be entirely in the direction of the engineer's vision.

J. C. Lincoln: I should like to know if Professor Harding made any test to determine whether the green reflection, which seemed to throw some doubt on the signals, could be gotten rid of by the suggestion just made, of throwing the light on the truck, so that no direct light from the headlight would strike the signal whatever?

C. Francis Harding: This subject of compulsory use of more powerful headlights on railroads, especially on steam railroads, is a comparatively live one in the middle west at the present time. Because of the fact that it has been given especial attention in that section of the country, and for the reason that it has been thought that engineers in general and especially those connected with steam railroad work, would be interested in this discussion, it is presented in this form to-day.

Referring to the question of the feeling of the engineer on the engine, I would say that all of the signal engineers with whom I have talked, and also many of the older steam locomotive engineers, have expressed themselves emphatically in favor of the old type of headlight, so far as security is concerned, and in fact some of the older engineers who made up the Committee of the Brotherhood of Locomotive Engineers, who first proposed this bill to the Indiana Legislature, told me that they could run equally well without any headlight at all, that they did not depend upon the aid of a headlight for determining their location or determining the schedule time in passing various objects —that they had markers of their own along the track, such as houses, gate openings, bridges, etc., and that they could easily get this information without any headlight, in a manner that was entirely satisfactory to them.

Regarding the question of fogs, I will say that some of the night tests at the University were carried out during foggy nights, and when we have a bank of fog in front of the headlight, looking parallel with the track, we have in front of us practically an opaque screen, brilliantly lighted, but very near the headlight, through which it is almost impossible to see, and that opaque screen seems to be more of a barrier, the greater the intensity of the light.

With regard to the matter of extinguishing or reducing the intensity of the lights in approaching other locomotives, I will say that, of course, that practice is used with interurban cars to a large extent, and it is probably a practical suggestion in the case of a good many steam roads, but an objection to that has been brought up by one of the signal engineers of a road entering Chicago. He says that an engineer on a train entering Chicago at the schedule speed has to read a signal every fifty-five seconds, and it would be impossible to diminish the intensity of the light, momentarily, while reading signals—it would therefore be necessary to reduce the light during the entire run.

Regarding the picking up of objects other than those considered in this test—the various observers on the road test in going from Indianapolis out to the scene of the test, were able by counting the poles to pick up overhead bridges, fences, etc., at a maximum distance of a quarter of a mile. All of these objects were white, or nearly so, and it was remarkable to note the difference in distance in picking up objects which were light and those which were dark. It happened that all the objects used in the test were dark, or nearly black, and it was surprising to all observers to note the results shown in the tests, that we could run down within a very few hundred feet of a black object and not detect it even with a powerful headlight.

I will say that the Mangin mirror type of reflector for headlights was not tested, and the statement in the conclusion of the paper simply applies to the particular lights tested, one with a lens and the other with a reflector, the other features of the light being identical.

Regarding the make-up of the observing committee, I will say that the Railroad Commission was represented by three men, the railroads of the State by three men, the University by three men, and two other parties selected at random. The men were not tested for color blindness, but the comparisons of the results of the different individual papers recorded independently would seem to show that no such condition existed in the eleven observers selected—that none of the members of the observing committee were color blind. I think an inspection of the original data would convince one of that fact. The readings at lower values, *i.e.*, shorter distances, seem to be pretty general, that is, not always noted by the same individuals with an opposing electric headlight while with an opposing oil headlight there is considerable similarity in observations of a single individual with respect to distance.

With regard to the matter of focussing below signals, or opposing engineers, it would seem to the speaker that this must limit the distance at which the headlight can be of use, unless the headlight is to be placed very low on the locomotive. If I understand the suggestion correctly, if we are to limit the height of the beam at a given point below the signal, or below the engineer's eyes on the approaching locomotive, then we must limit the distance that that beam will be spread out longitudinally along the track or else we must lower the headlight to a point below its usual position.

At this point I might take up the question of the placing of the headlight on the locomotive. These locomotive headlights were all tested in the position in which they are used by the Big Four Railroad, namely, just in front of the stack on top of the boiler. Some of the roads use the headlight in front of the boiler, and on a level with the center of same. The interurban headlights tested were used in the position in which they are located on the interurban cars, about four or five feet above the track.

The only objection that I have heard to the mounting of the headlight below the top of the boiler front, is that sometimes it is of advantage for the dispatcher in the stations along the line to detect the number of the locomotive, and this number is often placed in front of, or at the side of the headlight. The zone, and therefore the time, in which the dispatcher is permitted to note the number on high speed trains, is obviously greatly limited if that headlight is placed in front of the boiler. This position also, of course, involves limiting the distance of the illumination in front of the locomotive, unless the headlight is tilted upward.

With regard to the inquiry as to the ruling of the Commission, I will say that the Brotherhood of Locomotive Engineers first proposed the bill, including a minimum of 2,000 candle-power for headlights. Later these tests were made and a report was sent to the Commission. The conclusion of the report, in a nutshell was that the committee felt that a happy medium could be reached in a headlight more powerful than the present headlight, and of proper spectral qualities, which would enable objects to be detected at a greater distance than the present headlight, but not sufficiently powerful to interfere with signals. The Commission interpreted this statement as an argument in favor of reducing the candle-power of the headlight and changed the ruling from 2000 to 1500 candle-power, although I think that no one knows what the 1500 means, as it does not state whether it is with or without the reflector. Since the illumination does not follow the inverse square law the ruling should apply to the illumination in candle feet at specified distances in front of the headlight when equipped with a reflector.

The ruling of the Commission is that all of the roads in Indiana, beginning with one third of their equipment in July, 1910, one third in January, 1911 and one third in July, 1911 shall equip their locomotives with headlights having a minimum of 1500 candle-power.

In regard to the advantages of a more powerful headlight in detecting obstructions on the track, I will say that it is, of course, obvious that the more powerful the headlight, the greater the distance at which the objects can be distinguished but it was the feeling of the Committee that the detecting of obstructions on the track was a minor consideration when compared with the correct reading of signals.

With regard to slowing down to read signals, or after detecting objects on the track, I might illustrate my point by referring to the statement of one of the locomotive engineers when called upon by an officer of the road for certain information. The officer asked the engineer what he would do, when running seventy miles an hour, with a powerful headlight, if he saw an object on the track a quarter of a mile ahead, which would cause an accident if struck by the train. The engineer said that he would not apply the brakes to stop for it. The officer asked him for his reason. The engineer said that if he were to stop for every obstacle that he saw on the track a quarter of a mile away, that he thought might be struck by the locomotive, he would not be able to make the schedule—that he depended upon the object getting off the track, and not upon stopping the train in advance of the object.

With regard to the use of signals other than lights, at night will say that the suggestion has been made that semaphores be used, and the lights on the headlight be dispersed rather than concentrated, so that the position of the semaphores would be seen at night sufficiently well to use them in place of the lights.

The distance of the headlight from the observer and the distance of objects along the track in the rays of the headlight are also important questions, and I am glad that they were brought up. It is surprising how inaccurate the judgment of an experienced railroad man is in determining the distance of an approaching locomotive, or even of objects on the track, as seen in the rays of a powerful headlight. This was tried out unofficially, and guesses anywhere from one hundred to two thousand feet, and sometimes up to a mile, were made of distances of objects in front of the engine, as well as distances in front of approaching locomotives.

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THE MODERN OIL SWITCH WITH SPECIAL REFERENCE TO SYSTEMS OF MODERATE VOLTAGE AND LARGE AMPERE CAPACITY

BY A. R. CHEYNEY

The oil switch has become a fundamental part of all large generating systems, and so well has it fulfilled its function that not only has it superseded practically all other forms of switches for such service at all voltages, but manufacturers unhesitatingly claim that it can be constructed so as to safely open short circuits under the worst possible conditions in systems of unlimited kilowatt capacities, the only limiting condition, of course, being that the consumer be willing to pay for it.

In spite of this assurance, repeated warnings that the present switches are becoming a source of possible danger in the rapidly growing central station systems of our large cities are being heard, although neither manufacturer nor operator has seemingly thus far placed any absolute safety limit on just how large a system the present switch is entirely capable of protecting.

Switches may be divided into three classes, each class being further sub-divided into extra high voltage, moderate voltage and low voltage. The three main classes are based upon the maximum generating capacity that the switch may reasonably be called upon to interrupt. The classification, therefore, becomes in fact switches for small systems, for systems of moderate capacity, and switches for use in systems of the largest size. So long as the operating man does not object, the rating of this latter type of switch will continue to be for systems of " unlimited capacity," as any experimental evidence to the contrary is at the expense of the operating system itself.

It is further manifest that oil switches may be built to safely and continuously carry any current that may be required. The use of the switch as a circuit-breaker is the limiting factor in the case. Every switch thus used must not only be able to safely carry or interrupt the load of its particular section, but it must also be capable of safely and repeatedly interrupting short-circuits under severe conditions, with the whole capacity of the generating, transmission, and receiving systems behind it.

The switch with which this paper is mostly concerned is the type almost universally used in the large generating systems of our cities, where the voltage usually runs from 13,000 to 6,000 volts per phase, and is manufactured in various sizes, the 2,500-volt switch with a capacity up to about 3,000 amperes, the 15,000-volt switch up to 2,000 amperes, and the 35,000-volt switch up to 300 amperes rated capacity. Under these conditions the temperature rise in the oil cylinders or tanks is generally kept as low as possible, 28 deg. cent. being sometimes specified.

The switch of both large and small ampere capacity for extra high potential systems seems to have rapidly made a place for itself in the high-tension transmission systems of the country, and to have been extremely satisfactory in most instances. One 60,000-volt switch, it is claimed, opened twenty-five consecutive short-circuits, with a generating capacity of 10,000 kilowatts, within a space of one-half hour, and although the oil was carbonized to a considerable extent, the switch opened the arc entirely satisfactorily on the last break. In another instance two 60,000-volt breakers which had been in service for three years have opened several hundred short-circuits, many of them severe, without a change of oil. The generous dimensions of these switches are sufficient to show that the design is amply safe with regard to distances between conductors, the manufacturers claiming that they figure on an oil which has dropped in insulation until it may be broken down from 6,000 to 10,000 volts on a 0.2-in. gap between needle points. It is impossible in practice, with systems of this nature, to maintain the oil at an exceedingly high insulating value without a great deal of labor and inconvenience, particularly on account of the moisture that is absorbed from the atmosphere. In these switches for high voltage systems, which are now on the market in capacities up to 400 amperes at 110,000 volts, experience seems to show that a large volume of oil greatly increases the factor of safety. Some manufacturers also claim that in switches of this class a horizontal is superior to a vertical break as the pressure due to the head of the oil above the contacts is more effective in preventing the arc from reaching any large dimensions. Switches with a horizontal break are usually made with a thin knife blade in order that it may cut through the oil with the least disturbance. Judging from the written expressions of the users of these high-tension switches, it is evident that for the conditions under which these switches operate they are giving very satisfactory service.

Until the introduction of the steam turbine with its high rotative speeds and correspondingly low self-induction, the present plunger type of switch seemed to fulfill every expectation in moderate voltage systems of large generating capacity. The enormous growth of connected load and, at the same time, the adoption of the turbine as a prime mover, have brought about conditions unforeseen; and not only has the ability of modern switch construction to safely care for the new conditions been questioned, but experimental evidence would lead to the conclusion that either a new form of switch is urgently needed or else a marked change in switchboard construction and station operation.

The high-power switch for 6,000- to 13,000-volt service has at all times required careful supervision, constant attention to smaller details of its operating mechanism, and periodic tests, in order to ascertain that it was always ready for service. This, of course, is not unreasonable. Heavy short-circuits, however, have frequently demonstrated the fact at the present time in our large stations no circuit-breaker which has once opened under heavy short-circuit conditions is entirely safe to be put back on the line again without a thorough overhauling of contacts, cleaning up of the switch and its compartments, on account of the large amount of oil which has been blown out by the explosive pressure of the arc, and also the refilling of the switch cylinders. It is frequently necessary to insert an entirely new set of contacts and to file down the rod tips. This whole operation involves a period of at least two hours, and if spare feeders are not available may lead to considerable annoyance, while, in any case, it may involve a temporary disablement of a large and important investment in apparatus.

Changes, such as the substitution of steel for brass pots, the addition in some instances of insulating dashers to assist in keeping the oil within the pot and also to facilitate the breaking of an arc, and improved operating mechanism and contacts, cover practically all the main points that have been improved upon, since the introduction of the 8-in. cylinder eight or ten years ago, notwithstanding the enormous increase in maximum short-circuit output of the turbo-generator over that of the engine-driven alternator of equal capacity and the fact that the size of units has increased from 5,000 kw. to 20,000 kw. The substitution of boiler-iron tanks for wooden tanks and the gravity opening, with a means of obtaining a certain forced oil flow across the contacts on opening the switch, are a few of the changes in another type.

The Committee on High Potential Disturbances of the Association of Edison Illuminating Companies, 1909, notes that several of the larger companies are making use of reactances in connection with their turbines. These are installed either in the neutral leads of the turbo-generator or in the phase leads themselves. The reactances also facilitate parallel operation. A committee of the same body during the previous year suggested a limit of 40,000 kilowatts of installed machinery as a maximum generating installation that could be safely protected by a modern switch. As, in several instances, the switch has caused considerable damage, frank discussion in the line of improvement of the switch design is asked for.

As a matter of record, with 15,000 kw. of turbines in service, the latest type of oil switch has been quite recently practically emptied of its oil, the remaining oil being reduced to a state of absolute blackness and the contacts and rods so badly burned that they were unfit for further use without renewing, makes it evident that some change is needed in our present switchboard or switch design.

Modern operation generally calls for the use of a single operating bus-bar for reasons of both reliability and economy. Choke coils to limit the generating capacity in one section of the bus to a value of perhaps 20,000 kw., or a capacity slightly above that quoted when the switch was disabled, would seem hardly practical. As the load continues to grow with enormous strides, it would certainly seem that a more powerful type of switch should be found. As far as ascertained, resonance rises of potential due to the opening of an arc in an oil switch are of comparatively rare occurrence. It is natural to suppose that, whatever changes are made, the arc will still be broken under oil.

A few remarks of a general nature on switchboard construction and arrangement may not be out of place. A feeder switch, or circuit-breaker includes properly the knife switches separating the switch from the underground cable system, the series transformers, relays, control wiring and the switch itself with its fireproof compartment. It would not, therefore, seem illogical to adopt a type of construction in which all of these parts are relatively close together, instead of being scattered perhaps hundreds of feet apart as is frequently the case. For instance, the series transformer; the relays, the current through the coils of which, incidentally, should also pass through the circuit ammeters of the operating board, and the actuating mechanism of the switch belong together. The cable knife switch should be so placed as to be visible when working on the circuit breaking switch itself—in other words, in the base of the switch compartment. The bus bar knife switch should also be visible to any one working on the selector switches to obviate any chance of mistake in switching, and, furthermore, to protect the operator. This means, then, the bus bar and selector switch compartments must be one, so constructed that every switch section is independent and that the complete demolishing of one switch will not in any way affect either the neighboring switches or the bus bars themselves. This arrangement, mentioned above, will not only greatly reduce the space required for present switchboards, but will assist materially in proper maintenance and repair.

It is possible that it may become good practice where the plant equipment includes two switches in series for each feeder—one automatic and the other non-automatic—to allow the time element relay to open both switches in order to assist in breaking the arc, although this should not be necessary with a reliable switch. In connection with the use of choke coils the suggestion has been made that these coils be short-circuited by a heavy switch which would be opened by a relay when required. It is doubtful if any switch yet constructed would be quick enough to give the effect desired and on this account, and also on account of simplicity, choke coils, if installed at all, should be so designed as to care for operating conditions without the intervention of an iron core or moving mechanism.

As an illustration of the exceedingly heavy duty required even of a 300-ampere switch on a single feeder cable in the case of a 50.000-kw. steam turbine station of 6,000 volts, the instantaneous short-circuit current would amount to $50.000/\sqrt{3}\,E \times 50 = 240{,}600$ amperes per phase, or a kilowatt output, assuming a power factor for the short circuit of 40 per cent, of $50{,}000 \times 50 \times 0.40 = 1{,}000{,}000$ kw.

A 100,000-kw. plant under similar conditions would give an output of 2,000,000 kw. It is expecting a great deal of a 300-ampere switch to suppose that it could be safely figured on to care for such an enormous amount of energy. Yet the facts remain as stated. There are several modifying conditions, however, which enter into the problem. In the first place, short-circuits as a rule are not absolute short-circuits, and in this way the number of amperes actually interrupted is probably far less than that calculated. It must also be borne in mind that even if a circuit-breaker on a feeder were provided with an instantaneous relay, the time element of the switch itself is considerable, so that by the time the arc had been opened, the armature reaction of the machines would have, to a certain extent, become effective, thereby dropping the voltage and still further lowering the amperes at the break. If the safety of the switch alone is considered, it would doubtless be expedient to install inverse time element relays in connection with the feeders which would give an exceedingly long time interval in connection with the 100 per cent or more overload setting of the breaker, in order that they might give perhaps a three or four second interval between the occurrence of the short circuit and the opening of the switch. While specific information with regard to the length of time which is required for the armature reaction of alternators to become effective is lacking, there is no doubt that a mean might be drawn between conditions most favorable to the switch and those upon which depend the stability of operation of the main and substation synchronous machinery. Were it not for the possible rise in potential due to the breaking of the arc when the current is perhaps at a maximum instead of at zero point of the wave—which is another fact upon which further light is much needed and upon which the oscillograph without doubt will prove of great assistance in effecting a solution—the operating man would much prefer to have a short circuited cable cut off instantly before the trouble has had time to reach its heaviest proportions or has become severe enough to interfere with the frequency or voltage of the system.

The problem of the oil switch demands the more nearly exact solution of these questions. The protection which might possibly be afforded against the effect of static surges by the aluminum cell arrester might well be considered in this connection. With this protection, it would seem that the advantage lies practically altogether in favor of opening the switch itself as quickly as possible, by which it is understood that the greatest reasonable amount of time should be given by means of the relay to the switch before the latter starts to open the arc without, on the other hand, taking chances of throwing off the synchronous machinery. Under the best of conditions, however, we can but see that the switch is a relatively weak link in a system involving millions of invested capital.

The breaking of a circuit consists of inserting more or less gradually into the circuit a resistance which grows at a variable rate from zero to a maximum. At the moment the switch is leaving the contact, the greater the $C^2 R$ loss in heating, and especially if the circuit be inductive, the greater the amount of arcing. The rapid falling off in amperes as the resistance is increased by distance, when a considerable amount of metal is vaporized, and by this means the breaking of the arc is considerably hindered, is probably not at first accompanied by any great drop in the heating effect on the oil and the contacts, the $C^2 R$ loss for a certain length of time being perhaps practically constant. This, in part, is probably the cause of the explosive pressure set up in the cylinder by the oil vapor assisted by the actual displacement of oil by the arc itself. The prolonged arcing is evidently also the cause of the large amount of carbonization which takes place on opening a heavy short-circuit under oil with the modern switch.

Although there has not been a great deal written upon the exact nature of what takes place when a heavy arc is thus broken, experimental evidence has shown us that the quality of the switch oil will without doubt play a very important part in the switch of the future. The electrostatic stress set up between two charged conductors in a light mineral oil such as is used in switches and transformers, will, under proper conditions, even though no appreciable current is allowed to flow, release considerable quantities of gas without appreciable change in the oil itself, and as this gas is naturally rich in hydrogen, may it not be that the explosive violence of some of our short circuits is due to the combination of this gas and the gas driven off by the heat of the arc with oxygen, possibly of the air? The carbonization which takes place when a heavy short-circuit is broken is sometimes sufficient to make a deposit on settling of ⅜ of an inch in a 4-inch column of oil, or a total volumetric proportion of 10 per cent between the amorphous carbon and the clear oil above. The actual sample measured was taken from an oil switch cylinder from which two-thirds of the oil was blown out by the violence of the explosion. The physical analysis of the fresh oil (No. 6 transil oil) was as follows:

Flash	353 deg. fahr.
Burn	402 " "
Gravity at 60 deg. fahr	31.4 B.

As regard acidity, the oil was very nearly neutral, 0.09 per cent of potassium hydrate being required to neutralize same. There was no organic matter present. Various tests were made to ascertain the specific resistance and the dielectric strength of the above oil under the following conditions; first, the new oil; second, the blackened oil as taken from the switch; third, the clear oil after filtering off the carbonization. Careful tests were made under different conditions such as the sparking distance between needle points, between flat disks, between two ¾-in. balls, between a needle point and a disk, between a needle point and ball, etc. In some of the tests it seemed that the filtered oil after heavy carbonization showed an increase in specific resistance over the new oil. The dielectric strength also seemed materially increased after carbonization and filtering. The carbonized oil as taken from the switch showed a specific resistance of only one-fourth that of the new oil or of only one-eighth the resistance per cu. cm. of the oil after removing the carbonized particles by filtration, although another series of tests of other samples of the same oils failed to confirm the above figures; still there was a marked difference between the samples, although any increase in specific resistance or in dielectric strength failed to materialize except in one instance. The following figures, however, which are abstracted from the second series of tests represent the sparking distance between two ¾-in. balls at approximately 22.5 deg. cent. under a depth of oil of 2¼ in.

Sample	Gap	Volts
No. 1—Blackened oil (filtered)	0.15″	12,000
	0.20″	29,000
No. 2—New oil	0.15″	12,000
	0.20″	29,500

The following figures, representing the break-down point in inches at 30,000 volts pressure, as measured by an electrostatic voltmeter, checked by needle points, are also given:

Sample	Needle points	Needle and ½-in. disk	½-in. Ball and ½-in. disk	Between ½-in. balls
	in.	in.	in.	in.
No. 1—Blackened oil......	0.635	0.610	0.320	0.220
Blackened oil filtered........	0.530	0.750	0.250	0.190
No. 2—Blackened oil......	0.420	0.675	0.615	0.310
Blackened oil filtered........	0.300	0.600	0.290	0.185
No. 3—New oil...........	0.575	0.755	0.502	0.665

Temperatures in the above table all 26.5 degrees C.

All distances were measured by michrometer, the voltage adjustment being secured by finely adjusted resistances in the primary of a 40,000-volt testing transformer. As this may have introduced possible error due to change in wave form the figures are given as being perhaps at best, only approximately correct.*

Whether or not the changes in an oil produced by carbonization under heavy arcing improves or reduces the values of the remaining filtered oil for use in oil switches, it seems quite urgent that oil for switch purposes be chosen with great care, and manufacturers should make public satisfactory specifications to cover such oils and the testing of the same. It is by no means certain, as is frequently claimed, that a good transformer oil will make a good switch oil. Carbonization under heavy arcing is undeniably unavoidable. The study, however, of the physical and chemical nature of the actual conditions existing while the arc is being drawn through the oil with regard to the oil itself may lead to valuable conclusions that will somewhat strengthen the present oil switch situation.

It may be necessary to reduce the carbon content of the oil or possibly the hydrogen and more volatile components, even perhaps at the expense of changing the viscosity. Careful specifications will be welcomed by operating companies.

The severity of the arcing is naturally dependent upon the pressure of the oil surrounding the arc, the temperature of the

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* Other interesting figures in connection with the same kind of investigation are given in a paper read before the Manchester Local Section of the Institution of Electrical Engineers, by W. Pollard Digby, and D. B. Mellis, of which an abstract appears in the London Electrician, April 1, 1910. Important papers on this subject by Messrs. Skinner, Kintner, Steinmetz and others have appeared in the technical press.

oil and contacts, the velocity of switch opening, and, of course, by the ampere density at the point of break. The amount of vaporization of the contacts should be reduced to a minimum by properly proportioning the switch parts, by artificial circulation of the oil across the contacts as they are separated, and by increasing the velocity at the break to as high a degree as is possible. Severe arcing, even under oil, may without doubt be sufficient to set up heavy oscillations in a large underground system and, although much has been written upon the advisability of retarding the switch in its action, it frequently seems very advisable to have an absolute short-circuit broken as quickly as the switch will open it, the limiting factor being the reliability of the switch itself.

The oscillograph in the near future will also doubtless add to our knowledge of the conditions existing in a severe arc closely confined, as in the case of an oil-switch cylinder under pressure. As stated above there seems to be considerable difference in opinion among engineers with regard to whether the opening of a switch should be in a horizontal or vertical direction. While many of the high-tension switches in the West use a horizontal break, depending upon a large volume of oil and a narrow knife blade for contacts, practically all of the high-power switches of moderate voltage have a vertical throw, in some cases opening by gravity, which has the advantage that the switch can never accidentally fall into contact; while in other types the switch opens upwards.

There has been developed, although apparently it has never yet been introduced as a commercial article, an oil-switch in which the oil is at all times under pressure which is maintained by a compressed air system—a pressure line of perhaps 150 or 200 lb. caring for a number of switches, and a gravity or return line returning the discharged oil to the system. This principle seems to be exceedingly promising insofar as breaking the arc is concerned, the switch cylinders being either always full of oil under pressure, the opening of the contacts allowing a heavy stream of oil to be forced directly across the arc and through the hollow contact to atmospheric pressure, or as in another case, where the tripping coil opens an oil valve which admits large quantities of fresh oil under pressure to come into direct contact with the heated terminal directly at the base of the arc. It is undeniable that the mechanical squeezing out of the arc is what we need.

The forcing of considerable streams of cooled fresh oil across the contact face to the atmosphere, thereby eliminating all carbonization and gasification from the oil switch itself, gives a pleasing prospect of what the future may have in store. The breaking of a heavy arc by the weight of a nine- or ten-inch column of oil, especially in small or confined areas is going to be somewhat of a doubtful matter especially as the sizes of operating systems increase.

Another matter which should be carefully considered in connection with the vertical cylinder oil switch is the magnetic repulsion between the oil switch cylinders at times of heavy short circuits. Insulator bases are required, of great mechanical strength, to safely withstand this unusual strain which is perhaps similar in its nature to that which causes the opening of high tension switches under similar conditions, and it may be perhaps that broken base insulators may be traced partly to this cause.

In the matter of oil-switch contacts, practically every form imaginable has been tried particularly in the smaller switches. It need only be mentioned, therefore, that there seems a strong tendency to rely upon the cooling effect of the oil and the large radiating surface of the pot or oil tank to carry off the heat from contacts which in air would run exceedingly warm. An oil switch contact should on account of the very nature of the insulating medium be of at least as large proportions as a similar current carrying contact for use in the air; especially so since carbonization, sedimentation, moisture and other causes may interfere with the contact; and, above all, because it is practically out of sight at all times.

Switches of the more powerful types are generally sufficiently provided as to contact area, but there are certain switches of high current carrying capacity designed for mounting on marble switchboards, for hand or solenoid operation in which the contact surface is naturally too small. The switch, including the oil and the oil tank itself, run exceedingly warm with the contacts most carefully adjusted. This seems a mistake and should never exist in any oil-switch which is placed in a position of responsibility. The temperature of such a switch contact cannot be noticed by handling as can that of a low tension knife switch, so that the greater amount of power per ampere precludes any cutting down of contact area if at the expense of a rise in temperature over normal conditions. Information as to the increase of conductivity of a contact due to increase of pressure is not very plentiful for contacts under oil.

The operating mechanism of large oil-switches can be of the pneumatic, hydraulic, solenoid or motor type. The pneumatic control seems especially adapted for switches of extra high voltage and of certain types, although these switches are very frequently solenoid operated. In the switches of systems of large ampere capacity, the choice between solenoid and motor types of mechanism seems an open one. Both types are fulfilling their proper functions in a satisfactory manner, so far as can be ascertained.

The method of control and the wiring of the same vary with conditions. Generally, the pilot switch that stands in the " off " position and inclining toward the contact last in use is adopted, principally for reasons of wiring connection. The style of pilot switch which remains in contact until thrown into another position is a most excellent switch, and for some reasons, especially in synchronizing, is preferable to the open type, if connections allow of its use. Certain switchboard designers prefer the pull-button switch where all the contacts are on the under side of the operating table, thus precluding any possible switch action due to the dropping of any conducting body upon the operating table, and thus operating switches at inopportune times.

Generally, the simplest switch seems the best, and with a switchboard comprised of plain knife switches so that the operator can always see that his contact conditions are satisfactory, the limit of simplicity has been approached. Synchronizing by pulling out a switch seems perhaps the least bit awkward as contrasted with throwing it in. Not only is it advisable as stated below that the circuit ammeters shall indicate any open circuit condition of the relay coils, but it is advisable if possible that the control wiring be so installed that the operator is informed by his pilot lamps in case of any failure or open-circuit condition in actuating current supply through the relay or the pilot switch itself.

Standardization in the case of oil switches has been made somewhat difficult, so that an excessive number of spare parts must at times be kept in stock. It seems unfortunate that several types of motors, for instance, all of the same general size, speed, and voltage shall be necessary, frequently perhaps on account of the changes of the distance between shaft center and base or a slight change in the base clamping arrangement. The same, of course, applies to motors on governors, main field rheostats, field-break switches, etc. In laying out a new station the designer should see that the number of types of auxiliary motors are reduced to a minimum, so that instead of six or eight or even more types, two or three will fulfill the conditions.

The interlocking of high power switches has not generally seemed advisable up to the present date excepting through the control wiring scheme. It is, of course, always advisable that this be so arranged that the synchronizing plug or switch shall carry the actuating current of the selector oil-switch so that it will be impossible for the operator to synchronize a machine with one operating bus and throw it on the other. Interlocking is furthermore undesirable in many instances as the buses are frequently doubled up for various operating reasons, this arrangement affording a very flexible means of caring for the every day happenings of the central station system. In a system in which each generator and feeder consists of a main circuit-breaker and two selector switches any set of selector switches may be utilized for tying together the buses, although the generator switches will generally be used.

Interlocking in the smaller types of switches designed for mounting directly on a switchboard panel or otherwise has not as a rule seemed advisable. The great tendency toward cheapness of production has actually interfered with proper design of some of the smaller switches to such an extent that it is suggested that all unnecessary complications should be avoided and the money invested placed in the switch itself, providing only a first class yet simple operating mechanism. The smaller type of switch may be hand—solenoid—or motor-operated. When used as a circuit-breaker it must be installed in systems within the limits of capacity as given by the manufacturers. Its use on systems of the heavier class is not advisable unless in substation installations when it may be safely used as a single throw device for a bus selector switch, provided that a heavy type of switch is used as a circuit breaker. This lighter switch finds a very abundant field on account of its relatively low cost, especially on voltages from 2,400 to 13,000. It is frequently used as a remote control switch, as a manhole or pole-type switch, and on the outgoing 2,400-volt wires from alternating-current transformer substations. There is lacking, up to the present time, any adequate time element device for this useful switch, so that unless special relays are used on the switchboard, circuit-breaker setting by means of the tripping coils generally means the opening of every switch in the series on short circuit, which is extremely objectionable. The usual practice, therefore, in this connection, is to solidly block everything possible and to remove all blocks only at the time of known danger or when switching. This at best is a dangerous practice and it is hoped that at a near date some satisfactory time element device will be furnished with all such switches for station use, as this will not only make possible selective setting of the various switches, but will possibly protect the switch itself.

In the alternating-current substations of a generating system of any considerable size the double throw form of polyphase switch in which both of the main bus bars, for instance, of the substation enter one switch, is generally inadvisable, especially in the switches of large ampere capacity and one self-contained oil tank such as is being furnished at the present day. It is preferable to install two first class oil switches, one for each bus in such a situation that repairs to switches and regular overhauling can be carried on safely and all chances of trouble between buses, and also the necessity of lowering an oil tank with very small clearances while the switch is alive, is practically entirely done away with. This double-throw type of oil-switch in which the dimensions are reduced to a minimum and the design is influenced to a large extent by commercial conditions, is especially dangerous if used as a circuit breaker. The operating mechanism, furthermore, of many of the switches of this type is very frequently of too light a nature to be consistent with the responsibility thrown upon the switch. Further defects which are brought about by the necessity for economy of space in the same type are weak insulators, and weak insulator support, also the difficulty of aligning the contacts and the contact yoke and of keeping them in proper alignment. Loose insulators, loose studs, and leaking tanks are of very frequent occurrence with some types of switches.

If light duty switches are installed in situations where they can be called upon to open short-circuits beyond their rated capacity in kilowatts, the oil is badly carbonized, the tanks are liable to become damaged, the contacts burned excessively, and the switch emptied of its oil if not actually short circuited. The oil tank for these light duty switches should be given an ample margin of security and purchasers of switches, particularly those which are to be used on systems of large size even though they are not to open exceedingly heavy arcs should specify tanks of heavy sheet metal properly riveted and absolutely oil tight. A great deal of trouble has been experienced through leaking of switch tanks in which, mainly for reasons of cost, the weight of the metal has been reduced until the tank itself is much inferior to that of several years ago. A one-eighth inch boiler plate tank, properly riveted is superior in every way to the light weight tanks now so well known. These latter remarks apply particularly to switches for use on switchboard panels. There are certain occasions when commercial conditions step in and a switch is desired at a minimum of cost, even at the expense of a certain degree of security. The operating switchboard of any main or substation, however, is not a location where security can in any way be dispensed with.

There is urgently needed a new type of oil-switch of the cheapest form, preferably of the single-pole type, which shall be automatic in case of predetermined overloads, and which shall be capable of being installed in place of present line boxes on overhead 2,400-volt distribution lines. There is a wide field for the introduction of just the right switch in this connection. At the present time, the market offers no satisfactory device. As these switches could be made in enormous numbers and as the design may be made so that the factor of safety excepting only the matter of insulation, is not exceedingly high, it would seem that it should be possible to manufacture at wholesale such a device that would in a measure compete, even in cost, with the present enclosed fuses and line or manhole cut-outs.

Experience has demonstrated that constant vigilance is necessary with regard to every part of a generating system if service conditions are to be maintained at the highest point of reliability. Especially so is this true of the oil-switch in large systems. Certain defects can be noticed by visual inspection; others require the operation of the switch one or more times, while the inspector closely watches the mechanism and tanks. Still others can only be found by actually taking the switch apart and reassembling it. The inspection necessary, therefore, covers the knife switches, the insulators and contacts, oil-switch mechanism, tanks, rods, base insulators and compartment. To best accomplish this, the work of switch inspection may be sub-divided as follows:

1. Daily inspection of mechanism, tightening up of possible loose nuts, etc., general cleaning of switch. This covers all that can be observed with a reasonable amount of attention while the

switch is in service, and is given every switch whether carrying current or " dead."

2. Weekly inspection, covering the operation of the switch from four to six times to observe clutch conditions, tripping coils or contacts, open-circuits in wiring, loose parts, bolts, nuts, etc. This test also insures the switch being securely bolted down to its compartment. All doors are taken off or swung open, and tanks, rods, yokes, etc., examined leaky oil tanks cleaned up and any dirty base insulators cleaned off. This latter inspection has frequently located broken base insulators, insulators loose in their iron mountings, loose bolts securing base insulators, loose yokes and wooden shafts, and on one occasion a yoke and set of rods which had actually become disengaged from its clamp on the vertical wooden rod and fallen into the closed position, thereby closing one phase of the switch absolutely without the operators' knowledge. Defective alignment of cylinders, particularly in the case of the older type of switches, and improper switch action are also thus located. This inspection also locates leaky oil tanks, defective cable connections and terminal insulation.

3. Once a year every switch is completely taken down, each part cleaned and oiled, contacts brightened, supplied with fresh oil, and any minor defects that may have crept in are remedied as far as possible.

These three inspections have been found to cover fairly well the operation of the oil-switch in service. The whole of the work outside of the inspection itself is cared for by one man, excepting that the annual overhauling makes it necessary to add one helper to the force. This is in a plant of some 90 high-power switches.

The yearly inspection has discovered at times defects of a very serious nature which would not have otherwise been located, excepting through the failure of the switch mechanism to operate in service, and also troubles with the switch cylinders, rods or contacts. It is desirable that this systematic inspection be recorded, a separate card being used for every switch on which the various defects are noted. The main purpose, however, as stated above, is that the switches may be in working condition at all times both as to mechanism and the switch itself. Failures to operate when called for, defective contacts, low or defective oil, loose parts within cylinders, defective rod tips, or broken insulators may, any one of them be the means at a most inconvenient time of causing trouble. Further records of switch condition besides the details given from the above cards are obtained by grouping the various defects in order that the weak points of the switch may constantly be kept in mind. The number of times the switch is thrown under inspection exceeds in all probability the times that it is actually used in service and has a tendency to cause a certain amount of switch trouble itself by loosening the bolts and contacts. It, however, is the only means available whereby the switch action may be entirely depended upon.

Type H Switch Record—1909
Minor adjustments not noted

	In service	Weekly test	Yearly overhaul	Total
Failed to open	0	0	0	0
Failed to close	6	10	0	16
Pumped	0	5	13	18
Oil renewals	7	0	81	88
Oil thrown on short-circuit	7	0	0	7
Contacts renewed	7	0	13	20
Base insulator loose or broken	0	19	9	28
Failure to open short-circuit	0	0	0	0
Defective contact at brushes	0	0	12	12
Broken castings, bearings, etc	0	0	5	5
Bent crank shafts	0	0	1	1
Clutch, trip coil and control finger troubles	0	35	2	37
Friction in mechanism	0	0	27	27
Troubles with compartments	0	0	2	2
Closed accidentally	0	0	0	0
Opened accidentally	0	0	0	0
Switches operated, times				35,000
Short-circuits opened	12	0	0	12

The daily inspection thus eliminates the minor troubles apparent to a trained observer; the weekly inspection makes it possible to practically eliminate all external troubles in the switch compartments and in the mechanism, and especially failures to operate when called upon, whether due to open tripping coils, defective clutch coils or otherwise, and practically insures the switch against trouble due to pumping; while the yearly inspection cleans up the switch as a whole, making it possible to start a new year with switches fresh and complete from top to bottom.

The actual expense for material in switch maintenance is probably equal to the labor item. The results obtained in a year's service, including operation and inspection of some 90 switches, subdivided into trouble of the mechanism and those of the switch proper are shown in the foregoing table.

In conclusion it may be briefly stated that the present state of oil-switch development, particularly described above, with especial regard to its continued use in the large installations of the future, has not given the operating man quite the same vision of perfect security and unlimited capacity as he would desire. A more powerful switch is seriously needed, a switch which will stand up in continuous service for at least a year without the necessity for overhauling every time a short-circuit is opened. It would not seem unreasonable to wish for this condition in any piece of machinery; and without doubt the oil-switch will be brought up to the standard desired when the operating companies and the manufacturers get sufficiently close together. The use of oil in the future switch seems assured. The problem is the right way to use it. From the standpoint of the present enormous and growing investments that are being protected by the device, and with a clear knowledge of the result of failure, there is no doubt that between the designer and the user and with perhaps the assistance of the physicist and chemist that the problem will be readily solved, when once its real importance is fully comprehended.

DISCUSSION ON " THE MODERN OIL SWITCH WITH SPECIAL REFERENCE TO SYSTEMS OF MODERATE VOLTAGE AND LARGE AMPERE CAPACITY ". JEFFERSON, N. H., JUNE 28, 1910.

Peter Junkersfeld: Oil switches or circuit breaking devices seem to require some further development. There is need for something different, apparently, from that which we have at the present time. My own observation is confined, principally, to what Mr. Cheyney classes as the moderate voltage, high capacity switches. This class of switches seems to be very popular. A favorite question asked of the power station man is—" Do your oil switches always open the circuit, have they ever failed to open the circuit properly?" The usual answer, perhaps given with a little hesitation, is " No, they have never failed to open the circuit." I myself have answered that question a good many times, and have been frequently tempted to add—" Yes, they have always opened the circuit, but at what cost and with what results?" The system I have in mind has at present three hundred oil switches in three different generating stations, and if the substations were included, the total would be over five hundred. The number of times that the switches were distressed was few—very few in comparison to the total number of switches. The percentage of the times when all of the oil, or a large part of the oil, was thrown out of the oil vessel, to the total number of entirely satisfactory switch openings, is also a small percentage, but it is still too large, for the reason that the amount of property involved and the number of people inconvenienced is such that the reliability, so to speak, should be increased.

There is a very urgent demand for this increase in reliability. Moreover, from the standpoint of first cost, it would seem we are perhaps getting a little bit out of balance. The very fact that occasionally a switch is perhaps, entirely wrecked, means that there is a demand and a necessity for very expensive bus-bar structures, and everything of that sort, to prevent the trouble from spreading, and this has reached a point where in many systems the cost of the various oil switches, switchboard equipments and bus-bar structures, etc., is practically equal to the generating end of a steam turbine unit.

That, as I said, from an economic viewpoint, looks as if we are going too far, but we are driven to it in order to provide the degree of reliability of service demanded. It would seem also, that in this matter of interrupting circuits, there is really no mechanical analogy, that I can think of, for the moment at least, for attempting to stop the enormous momentum in electrical circuits. Mechanically, if we stop a moving mass, we apply the brakes gradually, but with an electric circuit we attempt to stop it almost instantaneously. It would seem we should insert something in the circuit, such as has been suggested, and on which work has been done in the last year, in the way of reactance. That would seem to offer a solution insofar as it would reduce the burden now placed on the oil switch. However, the progress in that direction has not been as great as we could wish, because there are many difficulties in designing and building of reactances to stand these large powers. Moreover, the experience with oil switches for very large capacities seems to have been almost entirely with one general construction, and in the present state of the art, only one thing seems to be possible for use with very large units and that is to require a somewhat larger oil switch.

Ford W. Harris: This paper is one much to be commended both on account of its being a logical array of facts from a man who knows, and on account of its general tone of fairness and moderation. Mr. Cheyney believes the oil switch is the weak link in his chain of apparatus and it is very hard to speak fairly of the weak link.

This subject of oil switches is daily assuming a greater importance due to the constantly increasing capacities of our large stations. For some years the design of oil switches has remained stationary and what was five years ago a thoroughly dependable device is now being looked upon with suspicion.

There is no question that there is not at this time on the market any oil switch which can be depended on to open heavy short circuits on powers above 10,000 kw. at 11,000 volts or below without certain manifestations of distress.

These manifestations of distress may be grouped into three classes:

1. The throwing of oil from the tanks.
2. Excessive burning of contacts.
3. Distortion of rupture of tanks due to heavy pressures generated in them.

These troubles are in themselves serious but there are two facts that in a great measure should reassure the operating engineers of the country in regard to the present status of the oil switch; these are:

1. That in no case of which we have record has an oil switch failed to clear the circuit, providing it was in normal condition upon the occurrence of short.
2. That it is only on powers above 10,000 kw., and only then if this power is concentrated at the switch, that any trouble whatever occurs.

Mr. Cheyney seems to feel that the present unlimited breaking capacity guarantee on the heavier switches is unreasonable. For some years after these switches were put in service these guarantees were absolutely correct as no complaints developed. As, however, power houses grew larger and turbine-driven generators became common the three troubles previously given developed. The manufacturing companies found themselves confronted with a growing difficulty for which they knew no remedy. Operators in general seemed to feel that the function of the switch was to open the circuit and that this was what was guaranteed. The throwing of oil and kindred troubles are, in themselves, not incompatible with such guarantees and at the present time are an understood accompaniment of oil switch action on heavy short circuits.

This latitude of the manufacturers was not based on inertia but on the difficulty of the design problem presented. The study of short circuits is a study of calamities. The testimony of people who have seen short circuits is of little value. Practically the only remedies were in the laboratory and the study of actual short circuits produced wilfully on heavy power stations with their attendant life and property hazards. Since these large power stations are rare and since no operator will wilfully short-circuit his bus bars, except under considerable pressure, progress must of necessity be slow.

The laboratory study was undertaken and proved very illuminating, and within six months three large power stations have permitted wilful short circuits of great magnitude. The result has been a considerable mass of data which will be later incorporated into a fairly complete exposition of oil switch theory. Better yet, these tests and certain practical service tests indicate the line further development should take. It now seems perfectly possible to develop devices which will repeatedly open without injury to themselves or the circuit any current which may be generated. It is thus seen that the manufacturers are not resting idly on their present designs but are pushing forward with good prospects of success. We hope within a few months to present to the Institute a complete record of such success.

There is, however, another side of Mr. Cheyney's paper. There are, of course, varying degrees of excellence in the oil switches now on the market. The present designs are pretty much standardized along certain fundamental lines.

These fundamentals of design are pretty generally observed by all oil switch manufacturers in this country and abroad. The designers of the switch on which Mr. Cheyney's paper was based evidently aimed to produce a switch of great rupturing capacity and have adopted a design that necessarily violates some of these fundamentals. Some of Mr. Cheyney's trouble seems to be due to this. It seems to me that a statement of these fundamentals and a discussion of their bearing on the problem may not be out of place. I would, therefore, submit that in any high-tension oil switch the following main principles should be incorporated.

1. There should be no exposed live metal parts. Switches in which oil pots are alive even if they are enclosed in a cell with a door form a very dangerous life hazard and a source from which dangerous arcs start.

2. Switches should be so arranged that gravity will tend to

open the switch so that if mechanism is in the open position the switch will be open. The falling closed or staying closed of a switch which should be open is fundamentally wrong. The breakage of mechanism at any one of several points on such a switch would result in life and property hazards that cannot be ignored.

3. An oil switch should have all breaks under oil. In the heavier capacity switches of the type in question an auxiliary main brush is used to finally close the circuit in parallel with oil break. The destruction of contacts in oil will throw the whole duty on the air break with a probable total destruction of switch and a bad oil fire.

4. Mechanisms to be permanent and reliable should be self-contained. The fastening of one part of mechanism on top of brick cell and supporting the remainder on porcelain insulators and expecting permanent alignment under the enormous stresses of short circuits is bad practice which should be avoided. Each pole should be operative outside of the structure and permanently aligned to some substantial frame at the factory of its maker.

5. Solenoid operation rather than motor operation. As one who has designed good, bad and indifferent switches, both motor and solenoid operated, I cannot too strongly urge the claims of the simpler cheaper and permanent solenoid as against the motor. What is needed in any switch is a sure short and powerful stroke and to obtain this by gearing down a small torque at high speed into a compressed spring must result in a complicated mechanism. These mechanisms and the motor itself require frequent inspection and adjustment. The trouble mentioned by Mr. Cheyney as " pumping " is a very serious one. As I understand it, this means that in opening or closing, the switch fails to stop at the appointed place but throws in or out violently several times. The effect on a circuit of such an action cannot be good, and the effect of throwing a short circuit alternately off and on generators must be very bad. Such action on a solenoid operated switch is obviously impossible. The 18 cases mentioned by Mr. Cheyney of such " pumping " were luckily all caught by his inspection.

In general it may be said that Mr. Cheyney's inspection as detailed by him is very thorough and is an exceptional condition. It is reasonably certain that such inspection cannot be expected except in a very efficiently managed station and that the table of troubles made up by Mr. Cheyney represent the very best of operating conditions. In thus outlining his inspection he has indicated what one operator is willing to do to keep apparatus in first-class condition and while such exceptional care cannot regularly be expected, an improvement in this particular can profitably be made in many stations.

C. W. Stone: On the first page of Mr. Cheyney's paper he says " that it is probable that we could get the manufacturers to construct switches to open safely short circuits under the worst possible conditions in systems of unlimited kilowatt capacities, the only limiting condition, of course, being that the consumer be willing to pay for it." I rather doubt this possibility. I do not believe we can get switches that will open under the worst possible conditions, that is, instantaneously. If Mr. Cheyney means a type of switch which opens slowly after the disturbance is largely over, then I would agree that it is possible.

Mr. Cheyney says that a large volume of oil greatly increases the factor of safety. My experience has been the other way—a large body of oil does not increase the factor of safety, unless we assume the same type of switches in both cases. Take a switch mechanism similar to the type H switch; if these oil pots contained a larger body of oil, there is no doubt but the effectiveness of the switches is increased, but if we compare this type of switch with any other standard plunger type of switch, and use a larger body of oil, the H switch will open many times the capacity. Even in the larger high voltage switches, such as the 110,000-volt switches, a large single plunger type switch will in all probability open a heavier short circuit than a large square, or oval, or round tank similar to the other types of switches in use on the Pacific coast.

Another objection to the large amount of oil is if there are one hundred and fifty switches in a station, it is not desirable to have so much oil in a station on account of increased fire risk.

Mr. Cheyney mentions the enormous growth in the transmission systems, and therefore the necessity for larger switches. Why, if we limit the capacity of our system, or the sections of our system, and install reactance, such as has been proposed in a number of cases, and such as is being done, or at least being projected, is it necessary to have larger switches? I think the reactance will tend to limit possible damage in case of short circuits, and possible disturbances of the system; that is, disturbances will not grow to such an extent if the reactances are used. Mr. Cheyney mentions that later on, and I agree with him fully.

I think the object of the oil switch is to clear the circuit from trouble. We can keep the trouble on a little longer, and thereby save the switch. Is it not preferable to destroy the switch, if we can clear the circuit, and according to all the experience I have had the switch always opens the circuit. Suppose we cut off the damage from the switch, will not that damage something else on the system which will cost more to replace?

Mr. Cheyney says " Choke coils to limit the generating capacity in one section of the bus to a value of perhaps 20,000 kw., or a capacity slightly above that quoted when the switch was disabled, would seem hardly practical." There is no doubt but that this is a very difficult problem to solve, but I do not think there is any reason to suppose that in a few months that problem will not be solved satisfactorily.

Mr. Cheyney also says that the knife switch in series should be placed in a compartment below the oil switch. I know this is the practice in a number of cases, but I do not agree with it. I think it is the worst place you could choose. The object of the knife switch is to cut the oil switch out of circuit, when the oil switch is to be inspected. If you have immediately below the oil switch some live terminals, why are you not increasing the risk of the operator when he tries to make an inspection of the oil switch, as he must necessarily work within three or four inches of the live circuit? I think that is undesirable. I have also felt that the knife switch below the oil switch is dangerous. unless locked in position, because in bad short circuits the knife switch has been thrown open, before the oil switch could act, due to the violence of the short circuit.

Mr. Cheyney mentions the effect on the system due to heavy short circuits, that is, interfering with the frequency or the voltage of the system. I think if we use reactances we would limit that effect and provide for such disturbances.

I note that Mr. Harris objects to exposed metal. I think it is a very good plan to cover up all the metal you can, but if you do it at the sacrifice of something else I think you had better expose the metal. My experience is the safest switch is the switch in which the metal is exposed and surrounded by a brick compartment. Then any trouble which may occur will be confined to that brick compartment. The mere fact of putting insulation around the oil pot simply tends to increase the fire hazard.

My experience is not exactly the same as Mr. Harris' in regard to the " pumping " of oil switches. I have seen a good deal of trouble in several cases, due to severe pumping, with solenoid-operated switches. I have seen these switches pump just as much as the motor operated switches. My experience is that the solenoid operated mechanism is more costly and complicated, and less liable to operate in case of low voltage on the operating circuit than the motor-operated mechanism. A motor-operated mechanism can be designed so that the opening of the circuit is independent of the motor, whether the motor moves or not. I think this type of switch will usually clear the trouble better than any type of solenoid switch I have ever seen.

D. B. Rushmore: The functions to be performed by oil switches vary greatly, and the resultant troubles in their operation depend to a large extent upon the particular service for which they are used. Small hand-operated switches are often opened and closed but a few times during the twenty-four hours. Large high-tension switches are as a rule very seldom operated. Other switches which may be used for intermittent motor service in connection with control apparatus may operate at intervals of a few seconds. We thus have a wide field of application and no one switch can be expected to be equally satisfactory under all the various conditions of operation.

During the last few years there has been a very rapid increase in the generating capacity tied together in the large Edison systems, and these present one of the most difficult problems of switching.

As a criterion regarding the satisfaction which a piece of electrical apparatus may have been giving, nothing is better than a study of the facts in connection with its use. It is a matter of record that certain types of oil switches in use have had complaints concerning their operation which amounted to a fraction of one per cent, and a piece of apparatus with such a record can be called highly satisfactory.

Mr. Cheyney's paper should not in any way be taken as an attack on oil switches. Very seldom is a record made of good, successful performance. It is only in the failures and disturbances that we are particularly interested, for it is desirable that our attention be concentrated upon these. Generators fail, transformers blow up, and every piece of electrical apparatus is liable to disturbance of some kind.

Of late a great deal of experimenting has been done with oil switches, the results of which are embodied in apparatus rather than in a history of experimental work. The horizontal switch of which Mr. Cheyney speaks is used to a certain extent in California. Before being manufactured there, it was brought out in the East by one of the smaller electrical companies. It has, however, certain limitations, and under some conditions affects unfavorably the limitations of power house design. Up to the present its use has not become very general.

Certain types of switches before they have been put on the market have been subjected to endurance tests in opening hundreds of short-circuits in rapid succession.

High-voltage switches are in an altogether different class. The difficult problem before operating and manufacturing companies is the one of developing switches for use on circuits where very large capacity of generating apparatus is installed, and especially where automatic relays are used with the switches.

In high-tension switches the difficulty is largely one of insulation. For use with the highest voltages, it is not an easy one to solve, and in switches recently developed where the specifications called for a high-potential test of 300,000 volts a considerable amount of experimental work was necessitated in connection with the development of such apparatus, the results of which have, however, been entirely satisfactory.

On the market to-day may be found a considerable number of what might be called " home-made " high tension switches, and these are to some extent used on the transmission systems on the Pacific Coast. At least one large power house has been destroyed as the result of the use of these switches. With them automatic attachments are but seldom employed, and they may be more properly considered as disconnecting oil switches, rather than as performing the functions for which a switch is usually installed.

On many systems the capacity of generating apparatus has increased far beyond what it was when some of the switches were installed. The throwing of oil in the switch is a safety feature, and is not an indication of the failure of the switch. Almost never is it reported that the switch fails to open the circuit.

New types of switch will be developed in the future, and with harmonious working between the operating and manufacturing companies, the new problems which constantly present themselves with the growth of systems and the development of the art will be given the same careful study which they have received in the past and will meet with the same satisfactory solutions.

C. P. Steinmetz: Before criticising the oil switch, let us see what it has done. Most engineers will agree that the operation of our present very large power stations has become possible only by the development of the oil switch. At the same time most manufacturing as well as operating engineers, will concede that still further improvements may be possible in the oil switch. Let us see what the problem is which we have to meet.

I do not agree with Mr. Harris' statement of the fundamental principles of the oil switch. It rather appeared to me that the requirements propounded in his discussion are not fundamental principles, but constructive details, mostly of a mechanical nature.

To still further improve the operation of the oil switch there are two ways; first, reduce the power which the oil switch has to control; second, improve the oil switch. The former is the problem of which the engineers have heard a great deal in the last year or two, because it is a problem which has to be worked out by the operating engineers, and manufacturers together—it means cutting the system into sections, by putting in reactance, so as to limit the maximum power which can be developed at any place. That is one of the first things which has to be done, because no oil switch can ever be designed, nor any other apparatus, to control unlimited power.

The second problem is to improve the oil switch. Though we do not hear so much about it, it is being recognized and worked out as industriously, if not more so, than the other problem.

In the paper we read about the desirability of using air pressure. This matter has been studied very thoroughly, pressure gauges have been put on the switch at various points to measure the pressure produced by the operation of the switch, by the energy of the arc which produces a rapid evolution of gas, and so brings to bear upon the break the pressure caused by the momentum of the oil, pressures which are far greater than any possible air pressure. After all, what the oil switch does, is to break the arc under the enormous pressure created by the momentum of the oil, which is to be pushed out of the way of the arc, and that pressure exerted is far greater than any pressure which you could maintain over the oil.

The action of artificially produced pressure has also been studied. I recall some very interesting experiments which were made by operating an oil switch under pressure. We had a pressure gauge on, the needle of which went off the scale at 2,000 pounds, and immediately afterwards the top of the oil switch, together with the oil—it was a heavy steel tank of bomb construction—went up into the air.

The oscillograph is a valuable assistant in the study of the oil switch, and many thousands of oscillograms have been taken in studying the performance of the oil switch, and in studying the performance of the circuits controlled by it, and we know a great deal about it, very much more than usually supposed, though we do not know as much as we would like to know.

You will realize the importance of the problem before you when you think what the oil switch has to do. Consider a system like that of the Commonwealth Edison Company, in Chicago, with a short circuit at the bus bars. The instantaneous power generated is between 6,000,000 and 8,000,000 kw. Now stand at the foot of the Horse-shoe Falls at Niagara and think of the problem involved in instantly stopping its power, and there you have the problem of the oil switch on a high power system. It is not an easy problem, and it is difficult to realize what we have to deal with. It is not the few hundred thousand kw. of the generators with which we have to deal, but the many times larger momentary power.

Now, what is the destructive effect on the oil switch? It is energy, but energy is power times time, and this means you can reduce the destructive energy by shortening the time. On the other hand stands the well established fact that the opening of the enormous power in too rapid time, destroys the system back of the oil switch. If you open the circuit too rapidly, the oil switch may be saved, but you destroy the cables and everything else. If you open it too slowly, you blow the oil switch to pieces by the energy produced there. Between these extremes you have to compromise.

The oscillograph records give us information how far we can reduce the energy of the oil switch by increasing the rapidity of the opening, without endangering the system, and that is work on which we are engaged. The fundamental principle of oil switch design thus is to open the switch with the minimum energy production in it, but at a rate slow enough not to produce destructive effects in the system controlled by the oil switch.

I have spoken of the oscillograph, and incidentally I may correct a misconception. It has frequently been believed that the oil switch opens the circuit at the moment of minimum stored energy, that is at the moment when the potential energy stored as magnetic and as electrostatic energy is a minimum. However, the oscillograph records, as far as I have been able to study them, point to the fact that, irrespective of the stored energy in the system, the oil switch opens at the zero value of current. For instance, in the charging current of a 100,000-volt transmission line, of say 150 to 180 miles, we have an electrostatic energy much larger than the electromagnetic energy, still the oil switch breaks at zero current, which is practically coincident with maximum voltage; that is, with maximum stored energy.

That is fortunate, because the cause of destructive effects is not the electrostatic energy of the system, but the electromagnetic energy. The electrostatic energy is limited by the voltage. We know, no matter what oscillation is produced by the electrostatic energy, the voltage can never more than double. It is less than double voltage, and since the double voltage is momentary, any insulation which can continuously stand normal voltage can momentarily stand double voltage. But in the rupture of the current the magnetic energy is unlimited; it can be anything up to the magnetic energy of the short circuit current, which is many times greater, especially in these high power systems, than any static energy, but that energy, fortunately, is not destructive in the oil switch, because the oil switch opens at the zero of current and thus zero of magnetic energy. It is very interesting to observe this on high voltage systems.

As I stated, there is sufficient evidence available to-day in oscillograph records, and it is being worked out at the present time, but that work is necessarily slow.

W. I. Donshea: Mr. Cheyney refers to a number of instances of the oil switch, of the type he has under consideration, successfully doing the work for which it was designed, and he mentions specifically one switch which opened 25 consecutive short circuits within a space of one-half hour, and also two similar switches which in three years opened several hundred short circuits without a change of oil. But he says, " The enormous growth of connected load and, at the same time, the adoption of the steam turbine as a prime mover, have brought about conditions unforseen; and not only has the ability of modern switch construction to safely care for the new conditions been questioned, but experimental evidence would lead to the conclusion that either a new form of switch is urgently needed, or else a marked change in switchboard construction and station operation."

The speaker is of the opinion that this view is not warranted, and he would cite the experience of a company which has in use about six hundred and fifty of these switches, of which four hundred are located in the two power houses and the remaining two hundred and fifty in the twenty-six annex stations. The rated generating capacity of the two power houses is 160,000 kw., (all connected to one bus) of which 121,000 kw. are in steam turbine prime movers, that is of the type which the author mentions as imposing exceptionally severe duty on the switching apparatus. These switches are giving satisfactory service, and they have not failed in a single instance to disconnect the most severe short circuit to which the system has been subjected. This experience indicates that the present conditions were foreseen and that both the manufacturers and the operating companies were keenly appreciative of the importance of the interests they controlled, and had already designed on the one side and accepted on the other, apparatus which is capable of preserving both safety of equipment and continuity of service.

The author also refers to the need of overhauling the switches, examining contacts and replacing the oil and says," This whole operation involves a period of at least two hours, and if spare feeders are not available may lead to considerable annoyance, while in any case it may involve a temporary disablement of a large and important investment in apparatus." But it is not customary to install a system of the magnitude suggested by the author without an ample surplus of capacity in feeders as well as in the other parts of the equipment. It is universal practice with such large companies to keep in service a sufficient number of generators, each with so high an overload capacity that any one of them may be disconnected without materially affecting the system voltage; a sufficient number of feeders (laid through duplicate routes) to the distributing stations, and connected there to machines, which, like the generators in the power houses, are in number and overload capacity ample to maintain the voltage of the system. On this point I might quote from Mr. W. F. Wells in a discussion of a similar subject in May, 1905: " In general sufficient equipment is installed and operated to render it possible at all times to disconnect instantly any individual or group unit, without interfering with the service. As the number of units increases, the proportion of investment in emergency or spare equipment diminishes and soon becomes of relatively minor importance. The interest and depreciation charges on account of this spare equipment are partly offset by the greater flexibility in operating and the decreased transmission losses." But unquestionably there is no large company such as contemplated by the author which would not recognize the principles of insurance as applied to reserve equipment as well as to fire and other hazards.

The author treats interestingly the subject of oil which has been exposed to severe arcing, but the results of tests which he reports are so variable that they seem to commend the practice of discarding all oil which has once been subjected to the strain of dissipating a severe arc.

In the concluding paragraphs the author says, " Constant vigilance is necessary." It is perfectly true that frequent inspection of all apparatus is both prudent and profitable. In the two power houses mentioned an inspector makes a tour through the switch rooms once an hour for the purpose of examining all parts which are exposed to view, and of locating excessive heat in any switch enclosure. In addition to this, all switches are cleaned once a week, and they are dismantled and reassembled once a year. Whenever a switch opens under load the oil is removed, (and this oil is either thrown away or used for other purposes) the contacts are overhauled, the entire switch thoroughly examined and new oil is put in. In short, every effort is made to maintain the entire switch equipment in a condition which is at all times as good as new.

What I have said about the existing switch must not be taken as indicating that I feel it is perfect or that there is nothing better to come, but it is a good switch; it is not a one man's idea, but as a previous speaker indicated it is a resultant of the policy of co-operation and consultation which has always existed between all the manufacturing and the operating companies. To use a homely expression, " both sides have been onto the job."

V. Karapetoff: It was interesting to note in this discussion that a more rational method for opening circuits behind a large amount of power is being discussed, and several speakers have mentioned the use of reactance coils. I should like to know more in detail the actual connections when reactance coils are used, that is to say whether such coils are connected between separate feeders, so as to limit the interchange of energy, or if they are permanently in series with each individual feeder; also, if such reactance coils must contain no iron? I should like also to inquire if the scheme has been tried of having series reactance coils normally short-circuited by the oil switch and automatically introduced into the system by the opening of the switch?

G. F. Sever: I ask Mr. Cheyney why he uses the value of 50 in determining the amperes per phase? That is not quite clear to me.

A. R. Cheyney: This paper seems to have been productive of a very valuable discussion. First of all I want to disclaim all intention of seriously criticising any particular switch, merely desiring in my paper to show the actual results which we have experienced with oil switches in actual service, and hoping that in the discussion new points with regard to design and operation might be uncovered.

In answer to Prof. Sever's question, I would state that the figure 50 used in calculation of short circuit current of alternators is a figure frequently given by which we may multiply the normal full load current in amperes in order to obtain the instantaneous value of the short circuit current.

In reply to Mr. Harris, I would state that in connection with the table of inspection from which he quotes, the examples of pumping did not occur in any instance with a switch in service. There was, therefore, no pumping of machine or feeder switches on short circuit with machines out of step.

I fully agree with Mr. Stone with regard to large and small volumes of oil in a switch, as he states a rupturing capacity of a switch with a larger cylinder and a larger amount of oil present is considerably greater than that of a switch with a small cylinder. The best means of obtaining a maximum rupturing capacity in a switch was one of the main points which I intended to cover in the paper.

The knife switches used in connection with the oil switch should of course, be separated from the switch connection proper by a fire-proof barrier, the point in this connection I wished to bring out being that it is quite important that the man working on switches should be able to see for himself the switch which absolutely protects him from possible injury. He can then rest assured that by no chance can the knife switch be closed without his knowledge.

Uncertainties with regard to the real necessity for reactances are being rapidly cleared up so that while a year ago we talked of reactances being necessary between two stations of 100,000 kw. capacity each, and possibly in connection with sub-dividing the bus-bar of a 100,000-kw. plant, now we are considering the proposition of reactances being absolutely necessary if we wish to protect the switch itself between sections of a generating station each of 20,000 kw. or under.

Professor Karapetoff has asked what wiring connections are used in installing the reactances. These are installed in several ways in accordance with the conditions confronting the designer of the plant. In the bus bar they would, of course, be directly in series with each bus conductor between sections. When installed on generating units they are sometimes connected directly in series with each conductor at the generator terminals and possibly also in connection with the grounded neutral. The chance of resonance troubles due to this series connection, particularly in large underground systems, has not yet been very fully discussed before the Institute to the best of my knowledge.

We are thus face to face with the following solutions:—First, install at very frequent intervals heavy reactances which will in all cases divide the station into sections of 20,000 kw. each as a maximum. Second, use the present switches without reactance and take the chance of serious damage to same and possibly a simultaneous interruption of service from the dropping out of step of a considerable part of the synchronous machinery. Third, the development of a more powerful switch. The latter solution seems to me so very desirable that I should hesitate to give up at this time all hope of its possible accomplishment.

E. M. Hewlett (by letter) In reviewing Mr. Cheyney's paper, the writer is much impressed with the excellent performance of the oil switches. It is gratifying to note that in all cases in service the switch opened the circuit on overloads and short-circuits and that the tests were thorough enough to develop practically all the faults during the test period. Considering that there were nearly 100 switches involved, it would seem that the oil was changed on an average of a little less than once a year per switch and less than two adjustments were required per switch per year.

Regarding simplicity of design, this point cannot be too strongly emphasized. It must, however, be remembered that the operating conditions imposed on the oil switches contribute in a large measure to the design. The switches are called for to be remote control, capable of being operated at some distance from the switchboard, automatic, sometimes with time limit and indicating devices to indicate the position of the switch, and many other extra functions. It should be appreciated that these extra conditions and requirements have been demanded when considering the complexity of the switching device.

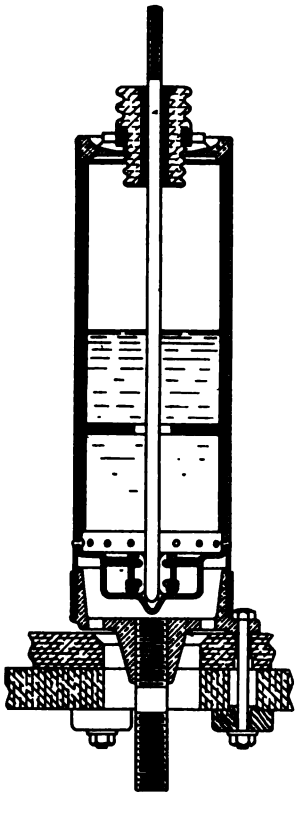

FIG. 1

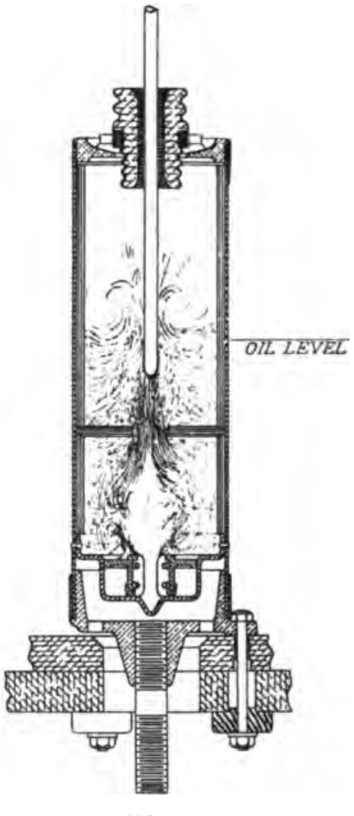

FIG. 2

In order to discuss the oil switch situation it seems best to separate the subject into the mechanical and the electrical operation. The mechanical operation may be remote control by the means of compressed air, solenoids, motors, rods and bell cranks, according to the requirements of the case, using the best method fitted for the conditions.

The H form of switch with its motor driven mechanisms is designed for remote control operation, so that a large number of generator and feeder circuits can be gathered together where they can be conveniently observed and controlled by an attendant.

The three-phase H oil switch in its present form consists of six steel oil vessels, eight inches in diameter, with casting at the top supporting porcelain bushings through which the contact rods may operate. These rods, or arcing tips, make contact with a special four-segment contact under spring tension located in the bottom of the oil vessel, and are submerged in transil oil which has a high voltage breakdown point and will not easily carbonize. The depth of oil over the contacts in each vessel is eight to 10 inches, approximating two to three gallons per vessel. At the bottom of the oil vessel is a heavy clamp which serves as a mechanical support and at the same time provides an electrical circuit. For capacities over 300 amperes brushes are attached to the crosshead, which carry the main load current but do not break any load. Two oil vessels with contacts are used in each cell, thereby giving a double break for each of the three phases.

The high rupturing capacity of the H form of switch is due to the baffle plate or pressure chamber construction; Fig. (1) *i.e.*, the arc is sprung in the pressure chamber at the lower part of the switch and the gas generated by the arc expands and forces the oil under pressure through the same aperture that the arc is drawn through as it follows the contact rod (Fig. 2). This stream of oil under pressure driven into and across the path of the arc makes a very effective means of opening electrical circuits of large capacity with a small quantity of oil, the oil receptacle and baffle plates being made to withstand the pressures.

Owing to the flexibility of this construction it is permissible where large amounts of power are to be controlled to further isolate by means of separate compartments for each oil vessel with its individual break. As an extra insurance it is possible to install the mechanism above this layout, thereby affording protection to the attendant when adjusting neighboring switches, at the same time preventing the possible spreading of high power arcs to the low potential or control circuits.

From tests and experience it does not seem advisable to go to the extreme of placing the main contacts under oil, as it introduces serious complications.

The K form of switch, in which two or more arcs are sprung in one oil vessel, is used in switching moderate amounts of power and can be designed for ordinary cases until the pressure developed and the amount of oil required make it necessary to consider other design. This K form of switch is top connected and permits a very flexible bus bar layout. A switch of this nature is limited in its rupturing capacity due to its rectangular or oval tank, and the difficulty of confining the pressure and directing the oil in such a receptacle.

Regarding Mr. Cheney's statement on oil switch improvement, a high rupturing capacity H switch has been designed for stations with 20,000 kw. turbo-generator units.

Regarding the possibilities of switching apparatus, oil switches can be made to handle any generator or capacity desired; it being a question of space limitations, expenses and a knowledge of the circuit characteristics.

With very large generating capacities a switch designed to open the circuit instantaneously might be so large in dimensions that it would be prohibitive as a station device and the better plan seems, in order to keep oil switches of reasonable dimensions and moderate expense, to limit the conditions by sectionalized busses, reactances, time limiting devices, etc.

A paper presented at the 27th Annual Convention of the American Institute of Electrical Engineers, Jefferson, N. H., June 29, 1910.

DISRUPTIVE STRENGTH WITH TRANSIENT VOLTAGES

BY JOSEPH L. R. HAYDEN AND CHARLES P. STEINMETZ

I. GENERAL

Experience with high voltage transmissions and distributions shows that high frequency oscillations and other disturbances of limited power do not exert as high a disruptive effect, at least on oil and solid insulation, as should be expected from their voltage. Discharges have been observed between the terminals of high-potential oil transformers through the air, which require voltages far beyond those which the transformer insulation could stand, and the absence of a break-down of the transformer could not always be explained by the screening effect of the reactance of the transformer leads.

In his early investigations on high-frequency currents, nearly a generation ago, Professor Elihu Thomson observed that, relative to air, oil has a much greater disruptive strength for high-frequency oscillations than for steadily applied alternating voltages. More recently Professor E. E. F. Creighton has, as the result of his investigations, expressed the opinion that there is an appreciable, though very small, time lag even with air; that is, disruptive discharge does not occur instantly with the application of the voltage, but some time elapses before disruption occurs. This time depends on the nature of the insulating material, and also on the shape of the discharge path. This phenomenon is of industrial importance in the protection of electric circuits against over voltages of short duration, in two ways:

A spark gap of small time-lag may protect the insulation of apparatus against momentary voltages, even if set for a discharge voltage higher than the voltage which the apparatus could stand when continuously applied, if the time-lag of disruptive strength of the insulation of the apparatus is much greater than that of the protecting spark gap.

On the other hand, if the time-lag of disruptive strength of the insulation of the apparatus is shorter than that of the protecting spark gap, the latter would not give effective protection against momentary voltages, even if at steadily applied voltage it discharges much below the disruptive strength of the apparatus.

An investigation of the disruptive effects produced by transient voltages was therefore undertaken. Some of the results found with air and with dry white paraffine oil, are given in this paper.

For producing single high-voltage impulses of very short duration, the method used by Professor Creighton in his study of lightning phenomena was applied: a continuous voltage is impressed upon the primary coil of a high-voltage transformer, through a non-inductive resistance. During the rise of the continuous current in the transformer primary, a voltage impulse is induced in the (high-potential) secondary of the transformer. The height of the voltage impulse and its duration are determined by the continuous voltage of the supply circuit, and by its resistance. The total energy input to the transformer is determined by its inductance L and the final value of the continuous input i_0, as the energy of the magnetic field of the transformer, $\frac{i_0^2 L}{2}$.

II. METHOD OF TESTS

To study small amounts of energy at high voltages, a small transformer had to be used, and considerable difficulty was first found in avoiding oscillations due to the internal capacity of the transformer winding. The arrangement of circuits shown in Fig. 1 was found satisfactory in giving single high-voltage impulses of low energy, free from oscillations. Constant watchfulness however was necessary, as the least poor contact or leak in any of the circuits immediately created an oscillation and thereby produced erratic results.

In Fig. 1, T is a high-potential transformer, with ratio of turns 1 to 300. Its high potential leads connect to the spark gap G. The screw thread of G is 1.6 mm. per turn, so that $\frac{1}{16}$ turn changes the gap by 0.1 mm.

At the low potential side, the transformer is shunted by an adjustable non-inductive resistance r_3, and connected through a second adjustable non-inductive resistance, r_2, to the continuous supply voltage e_2.

As a source of direct voltage there was used a 40-ampere 140-volt mercury arc rectifier R, supplied through the reactive transformer T_1 with 60-cycle 110-volt alternating current from the city lighting system. To suppress the voltage pulsations of the rectifier, a high reactance x_1, of about $L_1 = 1.0$ henry inductance, was inserted into the circuit, and the circuit then shunted by a condenser of about $C = 25$ mf. capacity. A non-inductive resistance r_1 was shunted across the voltage e_2, and adjusted so as to give a continuous load of $i_1 = 2.5$ amperes.

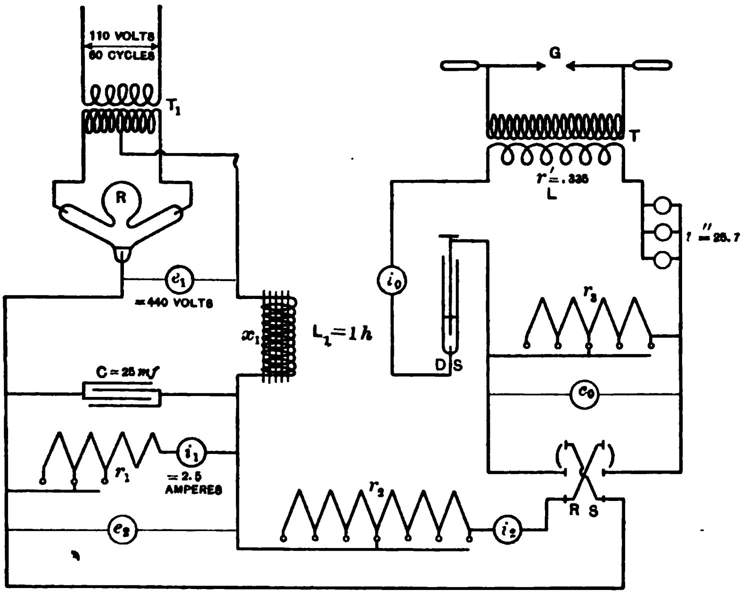

Fig. 1

In some tests, a non inductive resistance r'' was inserted, in series with the transformer. For this resistance, three incandescent lamps were used in multiple; one metallized filament lamp, and two luminous heater lamps. The combination of the positive temperature coefficient of the former, and the negative temperature coefficient of the latter gave a resistance which was nearly constant up to 4 amperes (about 400 watts), and at the same time extremely non-inductive. Its characteristic is shown in Fig. 2.

The impulse produced by closing the transformer circuit was used, as the impulse in opening the circuit is indefinite in voltage, and usually oscillatory. The circuit was closed by a drop switch *D S* Fig. 1; a 7-mm. copper rod dropping 30 cm. into a mercury cup. As the residual magnetism of the transformer exerts a considerable effect, the impulse was always produced by closing the circuit in the reverse direction from that in which it had been closed before. For this purpose the reversing switch *R S* was inserted between the shunt resistance r_3 and the series resistance r_2.

With $i_0 = 2$ amperes in the transformer *T*, and an inductance $L_1 = 0.75$ henry, the current in the condenser *C* was 0.12 ampere. As the frequency of the pulsation is 120 cycles, this gives,

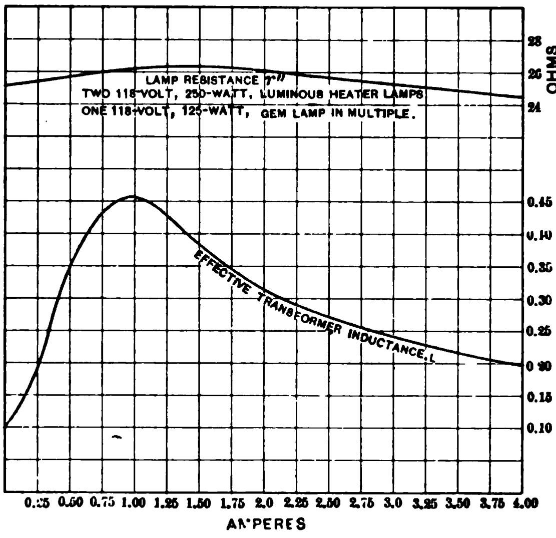

FIG. 2

for $L_1 = 1.0$ henry, a pulsation of 5 volts out of 440, or rather less, since part of the condenser current is due to higher harmonics. This pulsation did not extend into the transformer *T*, but the current pulsation in this transformer, read by a 1 to 1 transformer, was less than 0.01 ampere. To check the absence of any pulsation, after every set of tests the spark terminals *G* were slowly brought into contact with each other, and it was observed, whether at the moment before touching a continuous discharge was noticeable. This check was found very sensitive in discovering the beginning of any loose contact, leak, etc., in the system, before it exerted any appreciable effect on the readings.

TABLE I

October 4. 1909

Needles; Resistance

i_1	e_1	i_2	e_2	i_0	e_0
2.5	440	—	—	—	—
2.3	436	1.9	368	1.0	24
2.4	440	1.05	384	0	100
2.35	436	1.25	380	1.0	24

Dist. turns	No. of trials	No. of discharges
6	10	10
6½	10	10
7	10	10
7½	10	10
8	10	10
8½	10	10
8	10	8
9½	10	0
10	10	0
9½	10	0
9⅜	10	1
9¼	10	4
9⅛	10	7
9	10	9
8⅞	10	10
Continuous discharge 0		

i_1	e_1	i_2	e_2	i_0	e_0
2.4	436	1.05	384	0	100
2.35	436	1.25	380	1.0	24
2.5	440	—	—	—	—

e_0	dist. cm.
50	1.00
100	1.47
150	1.77
200	1.96
250	2.04
300	2.12
350	2.16

The method of operation was as follows: The resistances r_3 and r_2 were adjusted so that with the transformer circuit open, the voltage e_0, and with the transformer circuit closed, the current i_0, had predetermined values. All the meters e_1, e_2, e_0 and i_1, i_2, i_0 were read, with *R S* open, with *R S* closed and *D S* open, and with *R S* and *D S* closed. Then *R S* was opened, *D S* opened, *R S* closed in reverse direction, *D S* closed, while observing the gap *G*; then *R S* opened, *D S* opened, *R S* closed in reverse direction, etc., until 12 observations were made. Of these, the first two were not considered. The first setting of the gap was chosen so as to give a discharge at every impulse. Then the gap was lengthened and the tests repeated, and so on until no discharges passed. Then the gap was shortened in small steps, and again at every step 12 impulses observed, until every impulse passed. The gap terminals were next brought into contact to observe any continuous discharge, and then all the meters read once more, to insure that no change had taken place during the test. Ten seconds were allowed after every operation, to reach stationary conditions. The drop switch *D S* was never used for opening the circuit, and the mercury was frequently changed. A set of such tests is given in Table I.

By interpolation, the number of turns, that is, the length of gap, is found, at which 50 per cent of the impulses, that is, five out of ten, discharge across the gap.

Tests were made at the voltages $e_0 = 50$, 100, 150, 200, 250, 300 and 350, corresponding to the discharge voltages, by the ratio 1 to 300, of $e = 15$, 30, 45, 60, 75, 90 and 105 kilovolts, and with currents $i_0 = 0.25$, 0.5, 1.0, 2.0, 3.0 and 4.0 amperes. The complete set for $i_0 = 1.0$ amperes, of which the record of Table I is one point, is also given in Table I, and the various sets of tests made with needles in air, for $i_0 = 1.0$, are given in Table II. The different sets of tests are averaged.

TABLE II
Needles in air

e_0	$r'' = 0$ June '09	0 July '09	26 ohms Oct. '09	26 ohms Oct. '09	0 Oct. 09	Avg.
50	*d* =	—	1.00	1.00	0.94	0.98
100	—	1.46	1.47	1.44	1.50	1.47
150	1.79	1.71	1.77	1.80	1.77	1.77
200	1.94	1.92	1.96	1.92	2.00	1.95
250	—	2.08	2.04	2.01	2.09	2.06
300	2.17	2.10	2.12	2.10	2.16	2.13
350	—	2.17	2.16	2.17	2.24	2.19

An approximate theoretical discussion of the transient phenomena in the system of circuits Fig. 1 is given in the appendix. From this it follows that the transient voltage depends only upon the transformer inductance L, and on e_0 and i_0, but is independent of the resistance r in the transformer circuit. This affords a method of checking the absence of oscillations or other disturbances. The internal resistance of the transformer is $r' = 0.355$ ohm. Inserting a much larger resistance, $r'' = 25.7$ ohms, in series with the transformer circuit, should greatly decrease any oscillation in this circuit, if it existed, but should have no effect if the transient voltage is a single impulse, in accordance with the discussion in the appendix. All the tests were made with and without this additional resistance r'', and the agreement of the results of both sets of tests shows the absence of oscillations.

III. RESULTS OF TESTS

Tests were made with needles, and with spheres of 3.8 cm. diameter, in air and in dry white paraffine oil. For the latter, the spark gap was arranged vertically, and surrounded by a glass vessel filled with oil.

TABLE III

Transient voltages—Dielectric strength of air

Voltage		Amperes primary supply i_0 =						
Primary volts e_0	Secondary kilovolts e	0.25	0.50	1.0	2.0	3.0	4.0	(∞)
Needles		Striking Distance in cm.						
50	15	0.41	0.75	0.98	1.10	—	1.22	1.26
100	30	0.48	0.88	1.47	1.89	—	2.31	2.73
150	45	0.50	0.97	1.77	2.44	2.68	3.14	4 45
200	60	0.515	1.02	1.95	2.88	3.32	3.88	6.83
250	75	0.52	1.05	2.06	3.22	—	4.50	9.80
300	90	0.525	1.06	2.13	3.45	4.05	5.02	13.0
350	105	0.53	1.07	2.19	3.60	4.46	5.39	16.3
Without resistance.........		1	1	3	2	1	1	—
With resistance............		1	1	2	1	0	1	—
Spheres								
50	15	0.075	0.18	0.29	0.36	0.38	0.40	0.43
100	30	0.093	0.235	0.47	0.66	0.73	0.78	0.95
150	45	0.106	0.265	0.57	0.90	1.02	1.16	1.54
200	60	0.11	0.285	0.65	1.07	1.27	1.49	2.19
250	75	0.11	0.30	0.69	1.19	1.40	1.70	2.86
300	90	0.11	0.31	0.715	1.29	1.50	1.87	—
350	105	0.11	0.32	0.73	1.35	1.56	1.94	—
Without resistance.........		2	2	3	2	1	1	—
With resistance............		1	1	2	1	0	1	—

The results are given in Table III and Figs. 3 and 4 for air, and in Table IV and Figs. 5 and 6 for oil. In these tables also are given the number of sets of tests, with the resistance r'', and without it, which have been averaged as discussed above.

TABLE IV
Transient voltages—Dielectric strength of paraffine oil

Voltage		Amperes primary supply i_0 =				
Primary volts e_0	Secondary kilovolts e	0.50	1.0	2.0	4.0	(∞)
Needles		Striking Distances in cm.				
50	15	0	0	0	0	0.03
100	30	0	0	0.016	0.054	0.17
150	45	0	0.025	0.064	0.21	0.49
200	60	0	0.036	0.155	0.40	0.98
250	75	0	0.049	0.235	0.54	—
300	90	0	0.055	0.28	0.64	—
350	105	0	0.061	0.30	0.71	—
Without resistance.......		1	2	1	1	—
With resistance..........		1	2	1	1	—
Spheres						
50	15	0.026	0.042	0.050	0.066	0.07
100	30	0.033	0.061	0.071	0.098	0.16
150	45	0.036	0.071	0.087	0.121	0.27
200	60	0.037	0.078	0.099	0.133	0.375
250	75	0.037	0.083	0.107	0.144	0.48
300	90	0.037	0.088	0.114	0.157	—
350	105	0.037	0.092	0.120	0.163	—
Without resistance.......		2	4	2	2	—
With resistance..........		2	4	2	2	—

For comparison, tests were made with 60-cycle alternating voltages and are given in Table V and Fig. 7, for needles and spheres, in air and in oil.

In these tests, the primary of the transformer was shunted by a constant non-inductive resistance of 30 ohms, to avoid any change of wave-shape of the terminal voltage of the transformer when varying it by a series resistance. The constancy of the transformer ratio was checked by using another like transformer as a step-down transformer. For needle points in air, the observed striking distances were identical, within the errors of observation, with those given in the Standardization Rules of the A.I.E.E.

TABLE V

Alternating-current 60-cycle voltages—Dielectric strength

Kilovolts e maximum $= \sqrt{2} \times$ effective voltage	Striking distance in air-cm.		Striking distance in paraffin oil—cm.	
	Needles A. I. E. E.	Spheres	Needles	Spheres
5	0.40	0.125	—	0.02
10	0.81	0.27	—	0.045
15	1.26	0.43	0.03	0.07
20	1.72	0.59	0.06	0.10
25	2.22	0.76	0.11	0.13
30	2.73	0.95	0.17	0.16
35	3.27	1.14	0.27	0.20
40	3.82	1.34	0.37	0.235
45	4.45	1.54	0.49	0.27
50	5.19	1.75	0.63	0.305
55	5.98	1.96	0.80	0.34
60	6.83	2.19	0.98	0.375
65	7.75	2.41	—	0.41
70	8.70	2.63	—	0.445
75	9.80	2.86	—	0.48

In the last columns of Table III and IV, and in Figs. 3 to 6, have been added the striking distances for maximum alternating voltage, that is $\sqrt{2}$ times effective voltage, as taken from Table V and Fig. 7.

It is interesting to note in Table V and Fig. 7 the great difference in the shape of the curves of striking distances, with 60-cycle alternating voltage, in oil and in air. In oil, up to 29 kilovolts maximum, the striking distance between needle points is less than between 3.8 cm. spheres. Below 15 kilovolts, no striking distance between needle points under oil could be observed at all; the striking distance apparently was so small that the needle points could not be adjusted for a sufficiently small gap. When approaching the disruptive voltage, mechanical motion of the oil and, occasionally, the production of gas bubbles was observed, and also a noticeable time lag, so that three to five seconds had to be allowed at every voltage point before further raising the voltage; otherwise the disruptive voltage could be considerably exceeded. It seems that electrostatic disruption in oil is a very complex phenomenon, involving mechanical motions and chemical dissociation. The oil had to be carefully dried and filtered, otherwise the results become very erratic.

In Figs. 3 and 4, the striking distances with transient voltages, between needles and 3.8-cm. spheres in air, each curve corresponds to a definite current input into the transformer, that is, a definite energy value. The energy is the lower, the smaller the current and the curve for unlimited energy input, as given by a steadily applied alternating voltage, is marked by ∞.

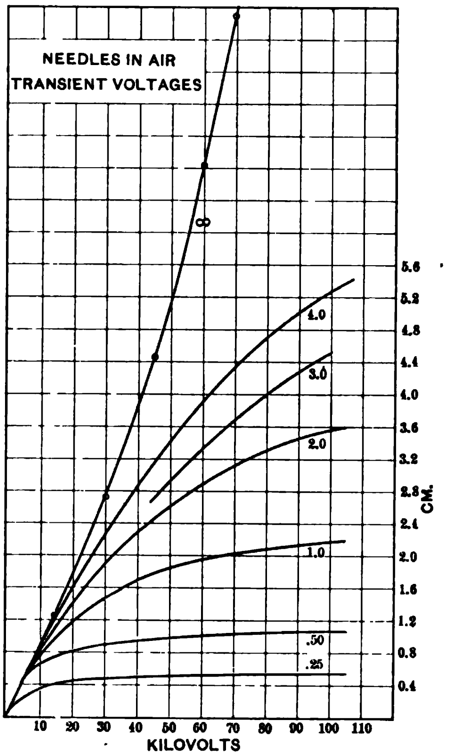

FIG. 3

It seems from this that the curves of striking distances with transient voltages start from the curve of unlimited energy (∞) at low voltages, but drop below this curve the earlier and the more rapidly, the smaller is the amount of available energy.

In Fig. 3, for an energy input into the transformer represented by $i_0 = 0.25$ or 0.5 ampere, the striking distance is, at 15 kilovolts, very much lower than at unlimited energy. At $i_0 = 1.0$ and 2.0 amperes it is still appreciably lower, while for $i_0 = 4.0$ amperes, it is practically the same at 15 kilovolts as with unlimited energy, but drops below at higher voltages.

All these curves of constant-energy striking distance seem, for higher voltages, to approach the horizontal direction; that is, a finite limit of striking distance. For the small amount of energy available with $i_0 = 0.25$ and $i_0 = 0.5$ ampere, this final limit of striking distance seems to have been practically reached within the range of the tests, and has been fairly well approached at $i_0 = 1.0$ ampere. For $i_0 = 2.0$ amperes or more, however, the curve of striking distance is still markedly rising at 105 kilovolts.

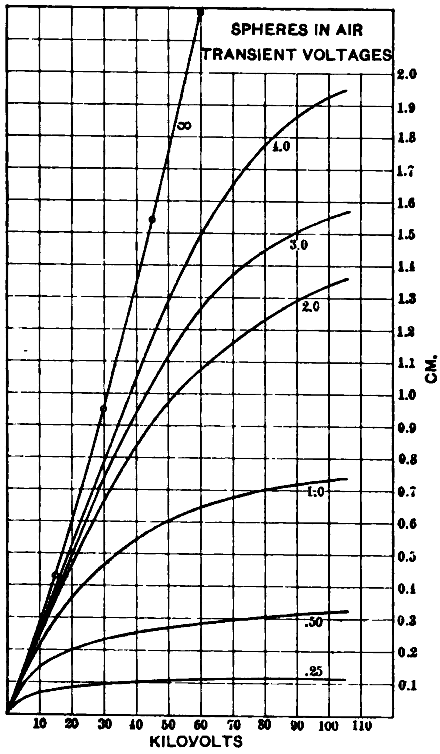

FIG. 4

With transient voltages, the striking distance seems to approach a finite limit with increasing voltage, and this limit is the higher, the greater is the available energy, which is behind the voltage. For sufficiently high voltage, the striking distance at limited energy becomes independent of the voltage, and merely a function of the energy back of the voltage. Thus between needle points in air, for the energy represented by $i_0 = 0.25$ ampere, 50 kilovolts gives practically the same striking distance as 100 kilovolts—a little over one-half cm., At the higher energy given by $i_0 = 0.5$ ampere, 50 kilovolts still gives nearly the same striking distance as 100 kilovolts, but the striking distance is about twice as great as at the lower energy given by $i_0 = 0.25$ amperes. At 25 kilovolts, $i_0 = 0.25$ ampere gives nearly the same striking distance as at 100 kilovolts, but $i_0 = 0.5$ ampere already gives a lower striking distance at 25 than at 100 kilovolts.

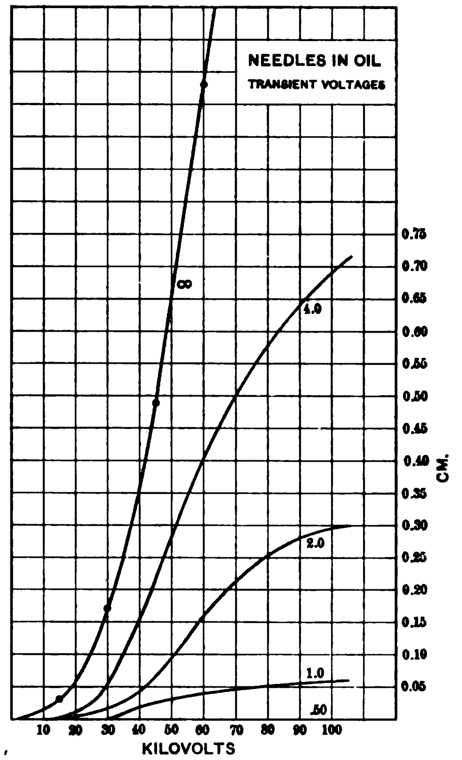

FIG. 5

Hence the usual curve of striking distance, derived by tests with unlimited energy, does not apply at all when the voltage lasts so short time that the energy back of the voltage is limited. At 100 kilovolts, the striking distance between needle points in air is about 15 cm. with unlimited energy, but only 0.52 cm., or about one-thirtieth as much, with the limited power of $i_0 = 0.25$ ampere; and even at $i_0 = 1$ ampere, the striking distance is still less than 2.2 cm., or one-seventh as much as given by unlimited energy at the same voltage of 100 kilovolts.

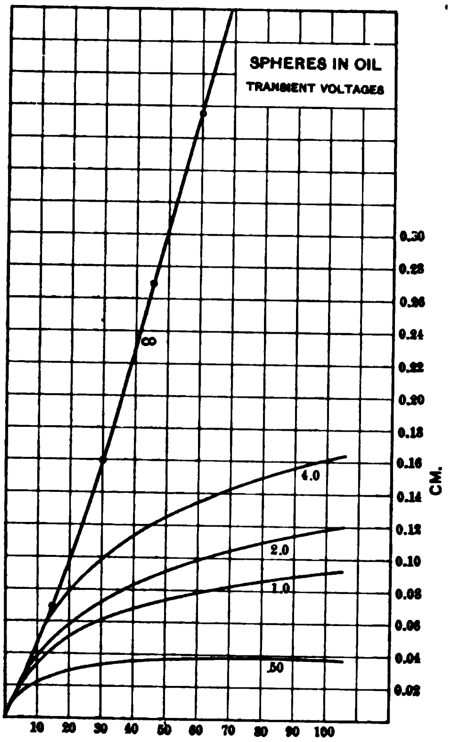

FIG. 6

At transient voltages of very limited energy, the striking distance becomes a function of the energy, and not of the voltage, and increases with increasing energy, but not with increasing voltage.

Between spheres in air, the effect of limited energy back of the voltage in decreasing the striking distance is similar to that between needle points, but is greater with low values, and slightly less with higher values of energy. That is, with the same available energy, if the energy is very small, the striking distance between spheres at transient voltage is a smaller fraction of the striking distance of unlimited energy, than it is with needle points. This is shown by Table VI, which gives the striking distances of transient voltages as fractions of the striking distances with unlimited energy, for needle points and for 3.8-cm. spheres in air.

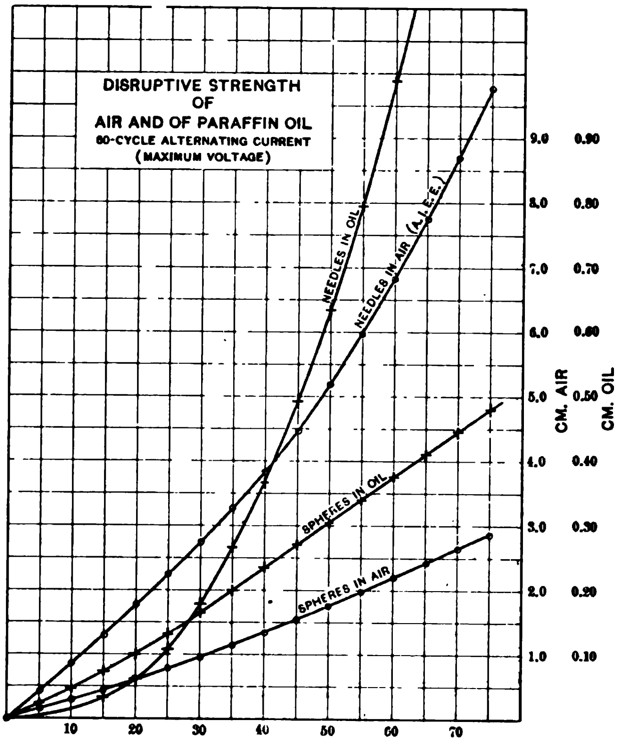

FIG. 7

Thus, if a needle gap and a sphere gap are set to discharge at the same alternating voltage, at transient voltages the discharges would always pass over the needle gap if the energy is very small, and usually over the sphere gap if the energy is large.

TABLE VI

Transient-voltage striking distances in air, as fractions of unlimited-energy striking distances

Voltage kilovolts e	$i_0 = 0.25$	0.50	1.0	2.0	4.0
Needles in air:					
15	$\frac{d}{\infty} = 0.325$	0.595	0.777	0.873	0.970
30	0.176	0.323	0.538	0.693	0.845
45	0.112	0.218	0.398	0.500	0.707
60	0.706	0.150	0.286	0.422	0.567
75	0.053	0.107	0.210	0.329	0.460
90	0.040	0.082	0.164	0.266	0.387
105	0.033	0.066	0.134	0.221	0.331
Spheres in air					
15	0.174	0.418	0.675	0.837	0.930
30	0.098	0.247	0.495	0.695	0.823
45	0.069	0.172	0.370	0.585	0.754
60	0.050	0.130	0.297	0.488	0.680
75	0.038	0.105	0.242	0.416	0.595
Spheres in oil:					
15		0.372	0.60	0.715	0.940
30	—	0.207	0.382	0.445	0.613
45	—	0.134	0.263	0.322	0.448
60	—	0.099	0.208	0.264	0.355
75	—	0.077	0.173	0.223	0.300

With spheres in oil, the behavior at transient voltages is similar as with spheres in air, as seen from Table VI, except that the decrease of striking distance with limited energy is very much greater with oil than with air, and at the lowest value of energy, that given by $i_0 = 0.25$ ampere, no discharges at all could be observed; that is, the energy apparently was not sufficient to break down even the smallest oil film.

This means that the "time lag of disruptive strength" of oil is much greater than that of air, and an oil gap requires a greater amount of energy, to be punctured, than an air gap set for the same alternating voltage (*i.e.*, voltage of unlimited energy.)

Thus a sphere gap of 0.6 cm. in air, and a sphere gap of 0.1 cm. in oil, discharge at the same voltage of 20 kilovolts, if unlimited power is back of the voltage. With a single impulse of transient voltage, limited in energy to that given by $i_0 = 2.0$ amperes, the air gap discharges at 27 kilovolts, while the oil gap requires

62 kilovolts. To discharge at 30 kilovolts, the energy given by $i_0 = 4.0$ amperes is required for the oil gap, while the air gap requires only the energy given by about 1.75 amperes; that is, much less energy. It therefore follows, that an air gap, set for such distance as to protect oil insulation against voltages of unlimited energy, also protects against transient voltages; but inversely, an oil gap, even if set to discharge at an alternating voltage much lower than that which air insulation would safely stand, would not protect against transient voltages if of sufficiently limited power.

To some extent, similar relations exist between the needle gap and sphere gap in air. As seen from Table VI, for low values of energy, an air needle gap would protect a sphere gap against transient voltages, but not inversely; while for higher values of energy, a sphere gap would protect a needle gap against transient voltage, but not inversely. The differences for higher values of transient energy are relatively small compared with those for lower values, and in general, therefore, it seems that the needle gap in air is safer than the sphere gap in protecting against transient voltages. Thus spark gap terminals are preferably corrugated or knurled.

Very different and strange are the curves of striking distance of transient voltages, with needle points in oil, as shown in Fig. 5. The lower energy values, corresponding to $i_0 = 0.25$ and $i_0 = 0.5$ ampere, give no appreciable striking distance at all, even above 100 kilovolts. At $i_0 = 1.0$ ampere, no appreciable striking distance exists at 30 kilovolts, but the lowest voltage at which an appreciable though very small (0.025 cm.) striking distance is observed, is at 45 kilovolts. Even at the highest energy values used in the test, 15 kilovolts give no striking distance. With needle points in oil, the transient voltage curve does not approach the alternating voltage curve ∞ at low voltage (as seems to be the case in Figs. 3, 4 and 6). It has an incurve at low voltage like the alternating curve ∞, but at higher voltages, the higher the voltage the lower the energy. Such needle points in oil seem to require the highest amount of energy; that is, they give the greatest time lag of discharge, far greater than spheres in oil. At 60 kilovolts, the striking distance between needle points in oil is, at $i_0 = 1.0$ ampere, less than 1/27 of what it is with unlimited energy, while with spheres in oil it is about one-fifth, and with needles as well as spheres in air, approximately three-tenths.

There appears thus an essential difference in the relation between needle points and spheres as discharge terminals in oil and in air, and the difference is of the same general character for transient voltages as for alternating voltages. This difference is somewhat similar in its nature to the difference between brittle and ductile bodies in their action against mechanical forces.

IV. STRIKING DISTANCES WITH INFINITE TRANSIENT VOLTAGES

The striking distances of transient voltages of constant energy seem, with increasing voltage, to approach a constant value, as seen in Figs. 3 to 6. An attempt was therefore made to find a mathematical expression for this upper range of the curve, at which the striking distance begins to become independent of the voltage and a function of the energy. The two simplest curves, which respresent asymptotic approach to a straight line, are the exponential and the hyperbola. The shape of the curves in Figs. 3 to 6 is different from the characteristic of the exponential, and an equilateral hyperbola was thus tried.

Assuming that d_0 = the striking distance, reached at infinite transient voltage, and the approach to this value is hyperbolic at higher voltages. This would give the curve

$$e\,(d_0 - d) = c^2 \qquad (1)$$

where d is the striking distance at transient voltage e, and c is a constant.

If now e_1 and e_2 are two voltage values, and d_1 and d_2 their corresponding striking distances, we get, by substitution in equation (1)

$$e_1\,(d_0 - d_1) = c^2$$

$$e_2\,(d_0 - d_2) = c^2$$

and from this, by eliminating c^2

$$d_0 = \frac{e_2\,d_2 - e_1\,d_1}{e_2 - e_1} \qquad (2)$$

By this equation (2), from any two points of a curve a value of d_0 can be calculated, and if the values of d_0, calculated from the different pairs of points of the same curve of striking distances agree, this would show an agreement of the observed curve with an equilateral hyperbola.

This calculation was made by using the observations from 45 to 105 kilovolts, and the results are given in Table VII.

TABLE VII
Striking distances d_0 at infinite transient voltage

$$e\,(d_0 - d) = c^2;\ d_0 = \frac{e_2 d_2 - e_1 d_1}{e_2 - e_1}$$

		e_1 = 45	45	75	90	kilovolts
	i_0	e_2 = 60	75	90	105	kilovolts
Needles in air:	0.25	0.56	0.54	0.55	0.56	avg. d_0 = 0.55
	0.5	1.17	1.17	1.11	1.13	1.14
	1.0	2.49	2.50	2.48	2.55	2.51
	2.0	(4.20)	4.58	4.60	4.50	4.56
	4.0	(6.10	6.98)	7.42	7.61	7.5
Spheres in air:						
	0.25	—	—	—	—	Avg. d_0 = 0.11
	0.5	0.345	0.36	0.36	0.38	0.36
	1.0	(0.89)	0.85	0.84	0.82	0.84
	2.0	(1.58)	1.67	1.79	1.71	1.72
	4.0	2.48	2.54	2.72	2.36	2.52
Needles in oil:						
	1.0	(0.067)	0.11	0.085	0.096	Avg. d_0 = 0.09
	2.0	0.43	0.555	0.505	0.42	0.46
	4.0	(0.97)	1.1	1.14	1.13	1.13
Spheres in oil:						
	0.5	—	—	—	—	Avg. d_0 = 0.037
	1.0	(0.909)	0.103	0.113	0.116	0.111
	2.0	(0.135)	0.139	0.149	0.156	0.148
	4.0	(0.169)	0.188	0.222	0.199	0.203

Four values of d_0, corresponding to successive sections of the empirical curve, are given, and as seen from Table VII, these four successive values of d_0 agree with each other very well, especially in air; that is, they show no regular deviation from the averages, which are also given in Table VII. A marked deviation from the average is found only for the lower voltage sections of the curves of high energy; that is, those parts at which the curve is fairly close to that of unlimited energy, and was to be expected in this

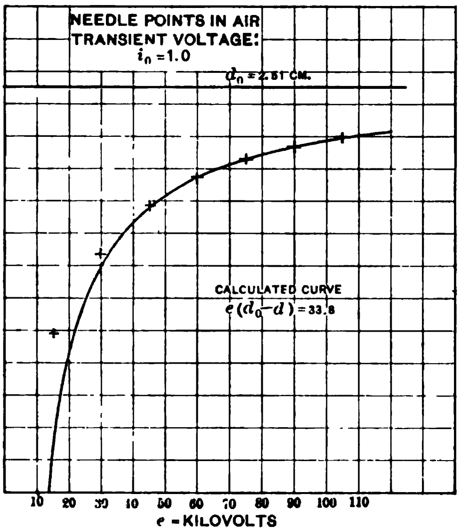
NEEDLE POINTS IN AIR
TRANSIENT VOLTAGE:
i_0 = 1.0
d_0 = 2.51 CM.
CALCULATED CURVE
$e(d_0 - d) = 33.8$
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
d = CM.
10
20
30
40
50
60
70
80
90
100
110
e = KILOVOLTS

FIG. 8

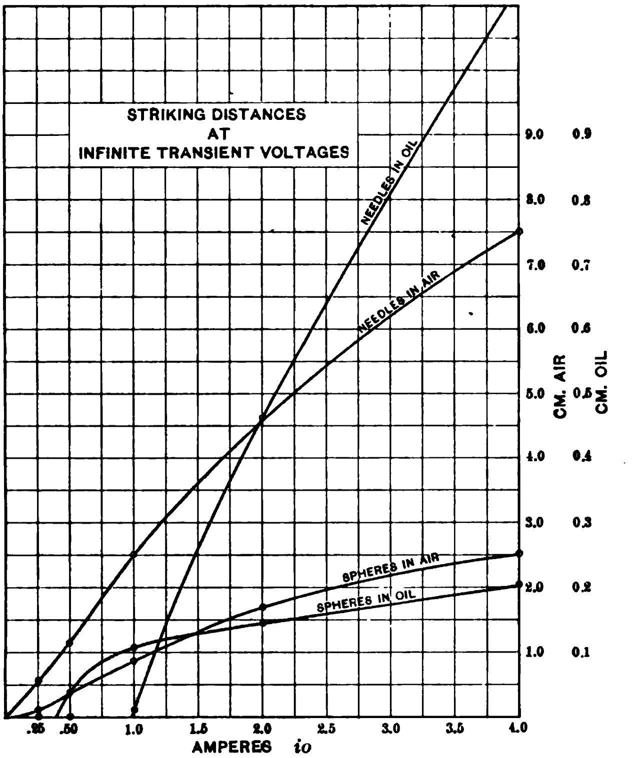
STRIKING DISTANCES
AT
INFINITE TRANSIENT VOLTAGES
NEEDLES IN OIL
NEEDLES IN AIR
SPHERES IN AIR
SPHERES IN OIL
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
CM. AIR
CM. OIL
.25
.50
1.0
1.5
2.0
2.5
3.0
3.5
4.0
AMPERES i_0

FIG. 9

case. In averaging, these values have been omitted and are given in brackets in Table VII.

It seems, from Table VII, that the agreement of the striking distance curve of transient voltages with the equilateral hyperbola, is more than a mere coincidence, and seems to be based on some physical law. Especially close is the agreement with the air curves, while the oil curves are more irregular, as was to be expected from the complex nature of the phenomena occurring in oil, as discussed above.

As illustrating this, there is plotted in Fig. 8 the equilateral hyperbola calculated for needle points in air, the energy being $i_0 = 1.0$ ampere, and the observed values are marked by crosses. As seen, from 45 kilovolts upwards, the agreement is practically perfect.

The striking distances d_0 at infinite transient voltage, as a function of the current i_0, which supplies the available energy, are plotted in Fig. 9, the curves for air being plotted to 10 times the scale of the curves for oil, as in Fig. 7.

Since the energy available at the spark gap is not a simple function of the current input into the transformer, but related thereto by the magnetization curve of the transformer, no simple expression can be expected to represent the curves of Fig. 9.

V. ENERGY OF THE DISCHARGE

An attempt was made to estimate the energy of the discharge from the excitation curve of the transformer. This excitation curve is given in Table VIII, and plotted in Fig. 10, with the maximum values of the exciting current as abscissæ, and the maximum values of the 60-cycle alternating voltage as ordinates.

Up to $i = 1.0$ ampere, the values of Table VIII are derived by alternating current, since in this range, below saturation, the ratio of maximum to effective value of the exciting current is very closely $\sqrt{2}$. The higher values are determined by ballistic test with continuous current, in the following manner: The transformer is shunted by a constant non-inductive resistance, and a milliammeter is included in this shunt. The throw of the milliammeter needle is observed when impressing upon the transformer various values of direct current. First, a series of readings was taken with the non-inductive shunt so adjusted as to give good deflection within the range in which the excitation curve of the transformer had been determined by alternating current, and plotted in Fig. 11 as the calibration curve of the

TABLE VIII

Excitation of transformer and energy

60 Cycles

i	e	$\Sigma i \Delta e = s$	i	e	$\Sigma i \Delta e = s$	i	e	$\Sigma i \Delta e = s$
0.05	2.1	0.052	0.75	119.6	54.2	1.9	233	189.4
0.1	4.7	0.247	0.8	130.1	62.4	2.0	237	197.2
0.15	7.9	0.647	0.85	140.6	71.1	2.2	245	214.0
0.2	12.2	1.397	0.9	151.0	80.2	2.4	253	232.4
0.25	18.3	2.767	0.95	161.5	89.9	2.6	260	249.9
0.3	26.4	4.99	1.0	171.8	100.0	2.8	267	268.8
0.35	36.2	8.18	1.1	185.0	121.0	3.0	273	286.2
0.4	46.2	11.93	1.2	195.0	132.5	3.2	279	304.8
0.45	56.5	16.50	1.3	203.0	142.5	3.4	284	321.3
0.5	66.9	21.24	1.4	210.0	152.0	3.6	289	338.8
0.55	77.4	26.8	1.5	216.0	160.7	3.8	294	357.3
0.6	88.0	32.9	1.6	221.0	168.4	4.0	299	376.8
0.65	98.5	39.4	1.7	225.0	175.0			
0.7	109.1	46.6	1.8	229.0	182.0			

TABLE VIII

Correction for residual magnetism

i	e	$\Sigma i \Delta e = s$	e	$\Sigma i \Delta e = s$	e	$\Sigma i \Delta e = s$	e	$\Sigma i \Delta e = s$
$i_0 =$		0.25		0.5		1.0		$\geqq 2.0$
0.0	-8.0	0.0	-40	0	-124	0	-168	0
0.05	-4.2	0.095	-26	0.35	- 68	1.40	-104	1.60
0.1	0	0.410	-14	1.25	- 41	3.42	- 58	5.05
0.15	+5.8	1.135	- 4	2.50	- 20	6.04	-26	9.05
0.2	11.5	2.135	+ 7	4.42	- 4	8.84	- 6	12.55
0.25	18.3	3.675	17	6.57	+10	11.99	+10	16.15
0.3			26.4	9.15	23	15.57	23	19.73
0.35			etc.		34	19.15	34	23.31
0.4					46.2	23.73	46.2	27.89
					etc.		etc.	
s, by above table =		2.767		4.99		11.93		11.93
Difference =		0.908		4.16		11.8		15.96

TABLE IX
Energy of magnetization

i_0 = (amperes) =	0.25	0.5	1.0	2.0	3.0	4.0
$s = \Sigma i \Delta e$ =	2.767	21.24	100.0	197.2	286.2	376.8
Correction for residual magnetism =	0.908	4.16	11.8	15.96	15.96	15.96
Per cent =	32.8	19.6	11.8	8.1	5.6	4.2
Total s =	3.675	25.4	111.8	213.2	302.2	392.8
Energy, in ioules:						
$W = \frac{s}{2\pi f} = \frac{s}{377} =$	0.00975	0.0676	0.298	0.566	0.803	1.044
=	0.01	0.068	0.30	0.566	0.80	1.04

(f = 60 cycles.)

ballistic test. Then the non-inductive resistance was adjusted to bring the deflection for the range from 1.0 ampere to 4.0 amperes, on the curve Fig. 11, and from this curve, from the known

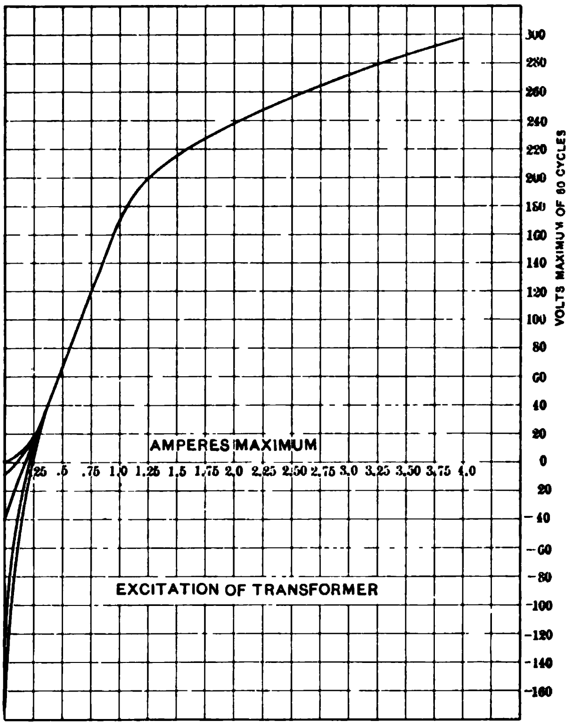

FIG. 10

voltage at 1.0 ampere, the voltages corresponding to higher currents were calculated.

By energizing the transformer in the same direction as before, and in the reverse direction, the residual magnetism was determined, and thereby the correction of the energy for residual magnetism estimated.

The energy input into the transformer was calculated from the area between the excitation curve Fig. 10 and the vertical axis, as

$$W = \frac{\Sigma i \triangle e}{2 \pi f}$$

where $\triangle e$ is the difference between two successive voltage values, i the average current corresponding to $\triangle e$, and thus $\Sigma i \triangle e$ the desired area. $f = 60$ cycles.

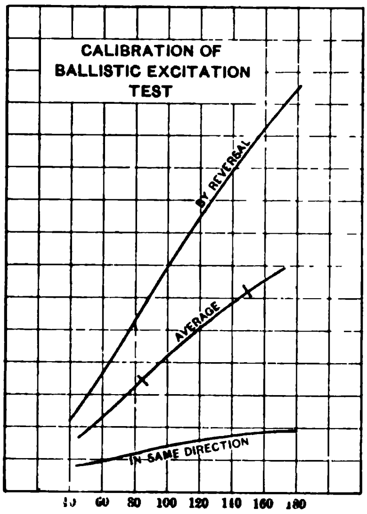

FIG. 11

This calculation is given in Tables VIII and IX, together with an approximate correction for residual magnetism.

It is interesting to note, that the energy values used in the tests, varied from a minimum of 0.01 joule (or watt-seconds) to a little over 1 joule. It must be considered, however, that this represents the total energy input into the transformer. These energy values, therefore are the upper limit of the energy which is sufficient to break down the spark gap, and considered in this manner, it is remarkable to see how very small an amount of energy is sufficient to produce disruptive effects.

Comparing the striking distances at infinite transient voltage (that is, at voltages which are so high, that the striking distance has become independent of the voltage, and a function of the energy only), as given in Table VII, with the corresponding values of energy, in Table IX, would give the striking distance as a function of the energy. The data are not sufficient to determine with any degree of exactness the dependence of the striking distance on the energy, since the energy values represent the total energy, and not that available at the spark gap. By comparing, however, the curves of striking distance for oil, and those for air, with the same terminals, relative values of the disruptive energy of oil and of air can be derived.

The striking distances between 3.8-cm. spheres in air can be represented approximately by

$$W = 0.3\, d_0^{1.5}$$

and those between the same spheres in oil by:

$$W = 10\, d_0^{1.5}$$

where d_0 = striking distance at infinite transient voltage, in cm., and W = energy in joules used for producing the transient voltage.

From this it would follow that an air gap requires only 3 per cent of the energy required by the same oil gap, to start a discharge; or inversely, that it takes 33 times as much energy to electrostatically disrupt oil as its takes with air.

The curves for air and oil calculated from above equation are given in Fig. 12a and b with the striking distance between spheres d_0 as abscissæ, and the energy W was ordinates. The observed values are marked by crosses, but as seen, the agreement is not very close.

The striking distance curve with transient voltages between needle points in oil is so different in shape from that in air that it does not appear probable that both can be expressed by the same equation, as required for comparing the disruptive energy of air and oil. The striking distance curve between needle points in oil, seems to reach the zero value ($d_0 = 0$) at a finite value of energy ($W_0 = 0.235$ joule), and if this is the case, it would mean, that with needle points in oil, about one quarter joule is required to start the discharge, irrespective of distance and voltage, and only the remainder of the energy is available for disrupting the path of the discharge. This however requires further investigation.

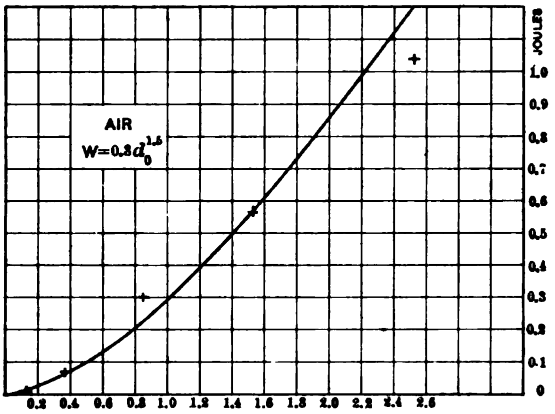

Fig. 12A

The striking distance curve with infinite transient voltages between needle points in air can be expressed approximately by the equation

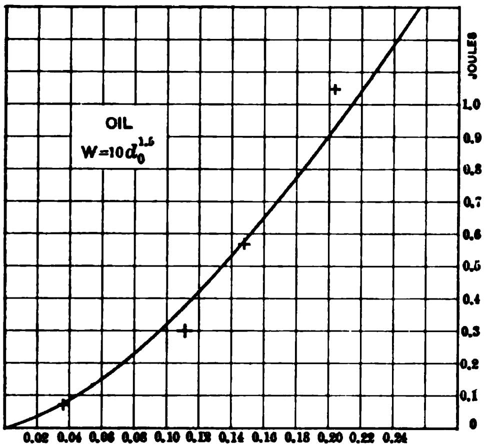

Fig. 12B

$$W = 0.063\, d_0^{1.5}$$

and that between needle points in oil, by the equation

$$W = 0.235 + 0.72\,d_0$$

From this it would also follow, that a spark gap between 3.8-cm. spheres in air requires about 5 times as much energy as a spark gap of the same length in air between needle points.

In table X are given the ratios of the striking distances $\left(\frac{\text{distance in oil}}{\text{distance in air}}\right)$ for needle points and for 3.8-cm. spheres.

As seen, with needle points the ratio increases with increasing transient voltage, and also increases with increasing energy. With spheres, the ratio first decreases, and then increases again, and seems to reach a minimum for some intermediate values of voltage and of energy.

TABLE X

Ratio of striking distances $= \frac{\text{distance in oil}}{\text{distance in air}}$

e kilovolts	amperes = 0.25 joules = 0.01	0.50 0.068	1.0 0.30	2.0 0.566	4.0 1.04	8 8
Needles						
15	0	0	0	0	0	0.0238
30	0	0	0	0.0085	0.0234	0.0623
45	0	0	0.0141	0.0262	0.067	0.110
60	0	0	0.0185	0.0538	0.103	0.144
75	0	0	0.0238	0.0730	0.120	—
90	0	0	0.0258	0.0812	0.128	—
105	0	0	0.0278	0.0833	0.132	—
∞	0	0	0.0358	0.101	0.151	—
Spheres						
15	0	0.144	0.145	0.139	0.165	0.163
30	0	0.141	0.130	0.108	0.126	0.168
45	0	0.136	0.125	0.097	0.104	0.182
60	0	0.130	0.120	0.093	0.089	0.172
75	0	0.123	0.120	0.090	0.085	0.168
90	0	0.119	0.124	0.088	0.084	—
105	0	0.116	0.126	0.089	0.084	—
∞	0	0.103	0.132	0.086	0.081	—

VI. CONCLUSIONS

The disruptive discharge through a dielectric requires not merely a sufficiently high voltage, but requires a definite minimum amount of energy.

The disruptive discharge does not occur instantly with the application of voltage, but a finite though usually very small time elapses after the application of voltage, before the discharge occurs. During this time the disruptive energy is supplied to the dielectric. This time may be called the " time lag of the discharge ".

The disruptive energy of oil seems to be about 30 times greater than that of air, and that of solid dielectrics probably is still greater. An oil gap thus requires a greater time before it discharges than an air gap, but even an air gap does not discharge instantly. An air gap thus can protect an oil gap against momentary voltages, but not inversely.

With limited available energy, the striking distance increases slower with increasing voltages, and drops below the striking distance with unlimited energy; and ultimately the striking distance becomes entirely independent of the voltage, and merely a function of the energy.

At constant energy, with increasing voltage, the striking distance seems to approach constancy in a hyperbolic curve.

The voltage at which the striking distance has become practically independent of the voltage, is the lower, the more limited is the amount of available energy.

From the available data, the following approximate empirical equations for the energy W, in joules, used for a disruptive discharge over a distance d_0, in cm., are derived:

Needle points in air	$W=0.063\,d_0^{1.5}$
3.8-cm. spheres in air	$W=0.3\,d_0^{1.5}$
Needle points in dry white paraffine oil	$W=0.235+0.72\,d$
3.8-cm. spheres in dry white paraffine oil	$W=10\,d^{1.5}$

The investigation of the disruptive effects with transient voltages, *i.e.*, limited energy, is of theoretical interest, as it may lead to a clearer understanding of the nature of the disruptive discharge. It also is of industrial importance, as most of the abnormal voltage phenomena occurring in electric circuits are transient, *i.e.*, of limited energy, and an effective control and protection of electric systems therefore will require a knowledge of the action of transient voltages as well as permanent voltages. Very little however is known on the disruptive effect of transient voltages, and further extensive investigations on this subject are therefore desirable.

APPENDIX

APPROXIMATE EQUATIONS OF TEST CIRCUIT

Let $r = r' + r''$ = total resistance of transformer circuit, including lamp resistances, etc., and L = inductance.

Let e_0' = voltage impressed upon this circuit, with initial value e_0.
i = current in this circuit, with final value i_0
e = voltage induced in the transformer.

From Fig. 1 we have

$$e_2 = e_0' + r_2\, i_2 \tag{1}$$

$$e_0' = e + r\, i \tag{2}$$

$$e_0' = r_3\, (i_2 - i) \tag{3}$$

$$e = L \frac{d\, i}{d\, t} \tag{4}$$

Eliminating e_0', e, i_2, and substituting

$$R^2 = r\, r_2 + r\, r_3 + r_2\, r_3 \tag{5}$$

gives

$$L \frac{d\, i}{d\, t} + \frac{R^2}{r + r_2}\, i - \frac{r_3}{r_2 + r_3}\, e_2 = 0$$

and since, at the moment of starting, $t = 0$

$$i = 0, \text{ hence } \quad e_0 = \frac{r_3}{r_2 + r_3}\, e_2 \tag{6}$$

the equation becomes

$$L \frac{d\, i}{d\, t} + \frac{R^2}{r + r_3}\, i - e_0 = 0 \tag{7}$$

This is integrated by

$$i = A\, \varepsilon^{-at} + B \tag{8}$$

Substituting (8) in (7) gives

$$a = \frac{R^2}{(r+r_3)\ L} \tag{9}$$

$$B = \frac{e_0\ (r+r_3)}{R^2} \tag{10}$$

Since for $t = 0$, $i = 0$, we have, by substituting (9) and (10) in (8)

$$A = -B = -\frac{e_0\ (r+r_3)}{R^2} \tag{11}$$

Since for $t = \infty$, $i = i_0$, we have, by substituting in (8)

$$B = i_0 \tag{12}$$

hence, from (11) and (9)

$$A = -i_0 \tag{13}$$

$$a = \frac{e_0}{i_0 L} \tag{14}$$

thus

$$i = i_0 \left\{ 1 - \varepsilon^{-\frac{e_0}{i_0 L} t} \right\} \tag{15}$$

and from (4)

$$e = e_0\, \varepsilon^{-\frac{e_0}{i_0 L} t} \tag{16}$$

hence, for $t = 0$

$$e = e_0 \tag{17}$$

that is, the ratio of transformation holds for the initial transient voltage.

The time integral of voltage is

$$E = \int_0^\infty e\,dt$$

$$= i_0 L \tag{18}$$

and the equivalent duration of the transient voltage

$$t_0 = \frac{E}{e_0} = \frac{i_0 L}{e_0} \tag{19}$$

As seen, all resistances, r, r_2, r_3 are eliminated except insofar as they are contained in e_0, the initial voltage, and i_0, the final current.

The above equations are approximate only, since they assume e_2 and L as constants.

The values of t_0 are, for

$i_0 =$	0.25	0.50	1.0	2.0	3.0	4.0	amperes.
$L =$	0.194	0.354	0.455	0.314	0.242	0.198	henry
$e_0 =$ 50	$t_0 =$ 0.97	3.54	9.10	12.6	14.5	15.8	milli-secs.
100	0.48	1.77	4.55	6.3	7.2	7.9	" "
150	0.32	1.18	3.03	4.2	4.8	5.3	" "
200	0.24	0.88	2.27	3.15	3.6	3.95	" "
250	0.19	0.71	1.82	2.5	2.9	3.2	" "
300	0.16	0.59	1.52	2.1	2.4	2.6	" "
350	0.14	0.51	1.30	1.8	2.1	2.3	" "

that is, a time varying from 0.00014 to 0.0158 seconds

From the table of effective duration t_0 of the high voltage impulses, given at the end of the appendix, we can derive approximate values of the striking distances as function of the time of the application of constant voltage, by substituting the values of transient striking distances, given in Tables III and IV, into the Table X at the end of the appendix.

This gives the Table XII, which is plotted in Figs. 13 to 16. As seen, the curves have a curious double bend. This however

TABLE XII

Striking Distances with Transient Voltages

(From Tables III, IV and X)

	kv.									
	15	$t=$	0.97	3.54	9.10	12.6	14.5	15.8	$\times 10^{-3}$	∞
Air: Needles......		$d=$	0.41	0.75	0.98	1.10	—	1.22		1.26
Spheres......			0.075	0.18	0.29	0.36	0.38	0.40		0.43
Oil: Needles......				0	0	0		0		0.03
Spheres......				0.026	0.042	0.050		0.066		0.07
	30	$t=$	0.48	1.77	4.55	6.3	7.2	7.9		∞
Air: Needles......		$d=$	0.48	0.88	1.47	1.89	—	2.31		2.73
Spheres......			0.093	0.235	0.47	0.66	0.73	0.78		0.95
Oil: Needles......				0	0	0.016		0.054		0.17
Spheres......				0.033	0.061	0.071		0.098		0.16
	45	$t=$	0.32	1.18	3.03	4.2	4.8	5.3		∞
Air: Needles......		$d=$	0.50	0.97	1.77	2.44	2.68	3.14		4.45
Spheres......			0.106	0.265	0.57	0.90	1.02	1.16		1.54
Oil: Needles......				0	0.024	0.064		0.21		0.48
Spheres......				0.036	0.071	0.087		0.121		0.27
	60	$t=$	0.24	0.88	2.27	3.15	3.6	3.95		∞
Air: Needles......		$d=$	0.515	1.02	1.95	2.88	3.32	3.88		6.83
Spheres......			0.11	0.285	0.65	1.07	1.24	1.49		2.19
Oil: Needles......				0	0.036	0.155		0.40		0.98
Spheres......				0.037	0.078	0.099		0.133		0.375
	75	$t=$	0.19	0.71	1.82	2.5	2.9	3.2		∞
Air: Needles......		$d=$	0.52	1.05	2.06	3.22		4.5		9.8
Spheres......			0.11	0.30	0.69	1.19	1.40	1.70		2.86
Oil: Needles......				0	0.049	0.235		0.54		
Spheres......				0.037	0.083	0.107		0.144		0.48
	90	$t=$	0.16	0.59	1.52	2.1	2.4	2.6		∞
Air: Needles......		$d=$	0.525	1.06	2.13	3.45	4.05	5.02		13.0
Spheres......			0.11	0.31	0.715	1.29	1.50	1.87		
Oil: Needles......				0	0.055	0.28		0.64		
Spheres......				0.037	0.088	0.114		0.157		
	105	$t=$	0.14	0.51	1.30	1.8	2.1	2.3		∞
Air: Needles......		$d=$	0.53	1.07	2.19	3.60	4.46	5.39		16.3
Spheres.....			0.11	0.32	0.73	1.35	1.56	1.94		
Oil: Needles......				0	0.061	0.30		0.71		
Spheres......				0.037	0.092	0.120		0.163		

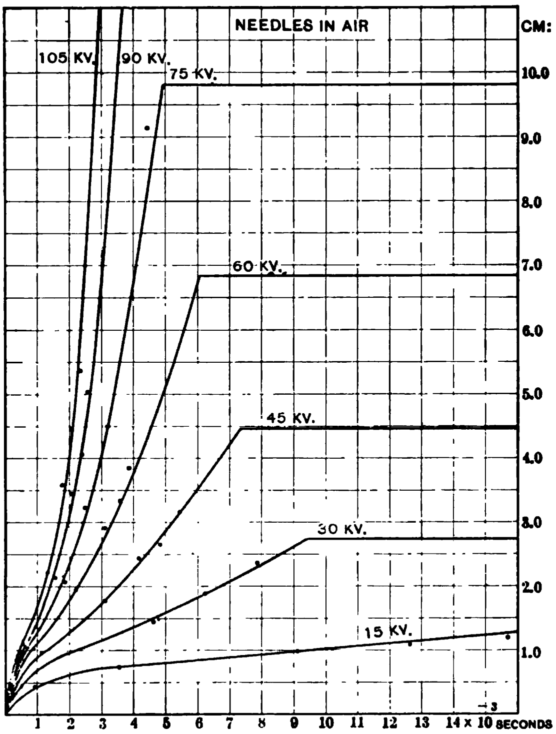
NEEDLES IN AIR
CM:
105 KV.
90 KV.
75 KV.
60 KV.
45 KV.
30 KV.
15 KV.
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 x 10^{-3} SECONDS

FIG. 13

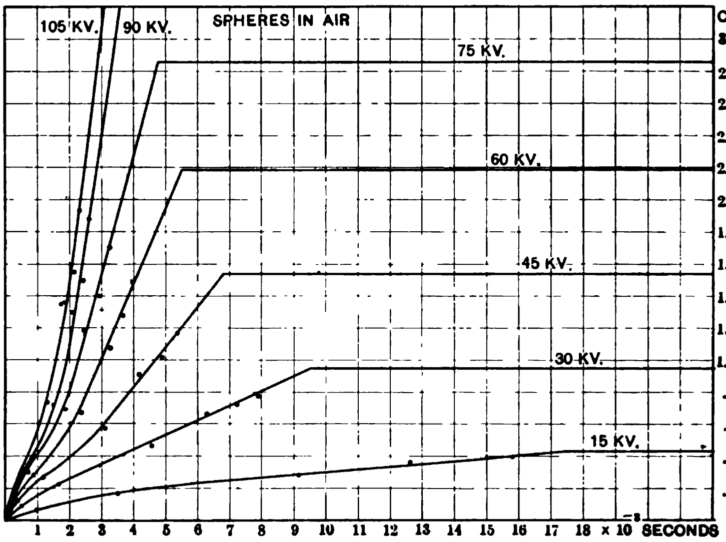
SPHERES IN AIR
CM.
105 KV.
90 KV.
75 KV.
60 KV.
45 KV.
30 KV.
15 KV.
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 x 10^{-3} SECONDS

FIG. 14

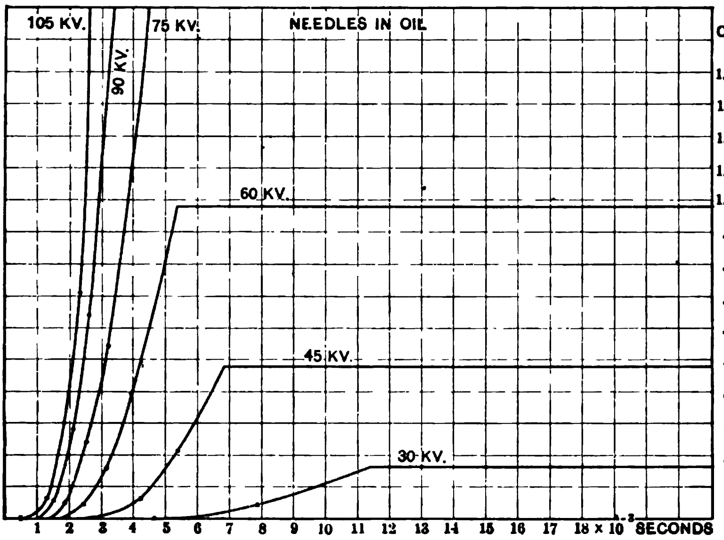
105 KV.
90 KV.
75 KV.
NEEDLES IN OIL
60 KV.
45 KV.
30 KV.
CM.
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18 × 10⁻³ SECONDS

FIG. 15

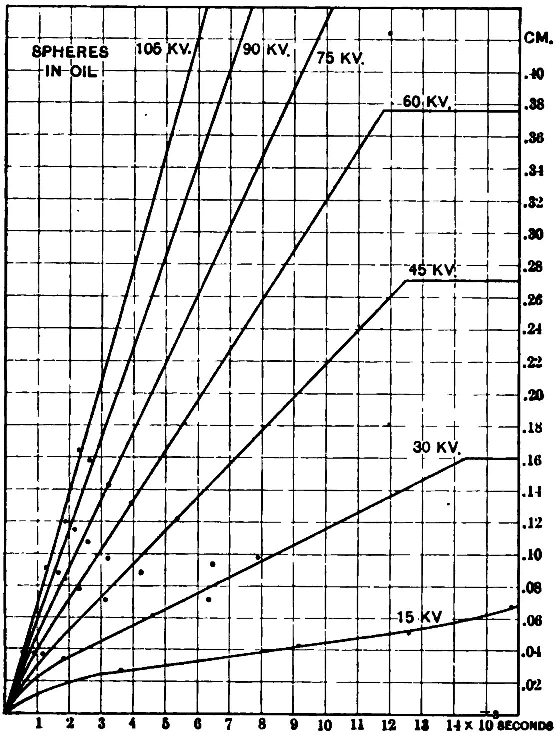
SPHERES IN OIL
105 KV.
90 KV.
75 KV.
60 KV.
45 KV.
30 KV.
15 KV
CM.
.40
.38
.36
.34
.32
.30
.28
.26
.24
.22
.20
.18
.16
.14
.12
.10
.08
.06
.04
.02
1
2
3
4
5
6
7
8
9
10
11
12
13
14 × 10⁻³ SECONDS

FIG. 16

TABLE XIII
Minimum Time of Standard Striking Distance

e Kv.		Air		Oil			Avg.	Calc.
		Needles	Spheres	Needles	Spheres			
							$\times10^{-3}$	
15	$t_0 =$	16.8	17.5		17	$\times10^{-3}$	17.1	17.2
30		9.5	9.5	11.3	(14.4)		10.1	9.9
45		7.4	6.8	6.9	(12.4)		7.0	7.2
60		5.9	5.5	5.3	(11.7)		5.6	5.7
75		4.9	4.8		(11.2)		4.85	4.75
90		(4.4)					(4.4)	4.1
105		(4.2)					(4.2)	3.6

$$t_0 = \frac{37.8}{e^{.8}}; \quad (e^2 t_0)^2 = \frac{74\times10^6}{t_0^3}$$

may be apparent only, and due to the constant error inherent in the method of test. Producing these twisted curves, until they strike the horizontal line of constant voltage striking distance, gives the minimum time required for the application of voltage, to reach full striking distance. However, in most cases the transient striking distance curves in Figs. 13 to 16 do not extend to high enough values to get their point of intersection with the horizontal line of constant voltage with any degree of accuracy. Estimating these points of intersection, gives the values recorded in Table XIII and plotted in Fig. 17, which can approximately be expressed by the equation:

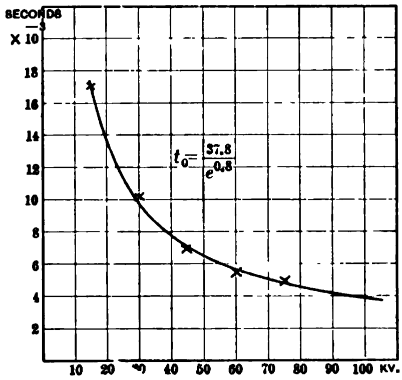

FIG. 17

$$e^{0.8}\, t_0 = 37.8$$

These values however are very uncertain, as stated above, and further investigation of these phenomena is very desirable.

A paper presented at the 27th Annual Convention of the American Institute of Electrical Engineers, Jefferson, N. H., June 29, 1910.

THE ELECTRIC STRENGTH OF AIR

BY J. B. WHITEHEAD

Air is the commonest and most widely used of insulators. Its insulating characteristics are remarkably good; it has low specific inductive capacity, very low conductivity, and an electric strength or resistance to rupture which until recently has met all the demands of the electrical engineer. As a result of the increase in values of transmission voltage, however, and of improvements in high-voltage apparatus and line insulators, the electric strength of air has become a limiting factor in the long distance transmission of power.

Values of the electric strength of insulating materials are usually given in volts or kilovolts per centimeter. In the case of air, and probably in that of all other insulating substances, it is not possible to state a fixed value for the electric strength for standard conditions of temperature and pressure. The shape, size and separation of the terminals have an important influence on the electric strength as calculated from the break-down voltage. For example, the apparent electric strength of air in kilovolts per centimeter varies between 5.5 and 12 for needle points at distances between 75 cm. and 1 cm., and approaches 100 for corona formation at the surface of very small wires. Similarly there are discrepancies among the values derived from experiments with spheres of different diameter at various distances of separation, as well as with other forms of discharge terminals. The explanation of these discrepancies has not yet been satisfactorily given. It will ultimately be found however to involve some or all of the following facts:

The air between two terminals may be partly ruptured without a resulting discharge; such a partial rupture is always a cause of copious ionization; this ionization is a separation of the ultimate particles of the air into positive and negative charges or gaseous ions which render the air highly conducting. Besides these there is a further peculiarity of the structure of the air in the neighborhood of conductors which results in a marked and regular dependence of the electric intensity causing ionization, on the radius of curvature of the electrode; this fact is particularly interesting in that the phenomenon occurs under a variation of dimensions 10^5 times as great as the mean free paths of the molecule and free electron in the atmosphere, and is thus apparently not directly connected with these quantities.

An example of the influence of these facts is the spark between needle points. The high value of potential gradient at the points causes break-down in their neighborhood, resulting in ionization, conductivity, and consequent change of shape of the effective terminal from a point to a sphere or other solid shape. The sphere enlarges until the intensity at or near its surface, decreasing with increasing radius, falls to a value which cannot further ionize the air, and there is then equilibrium without discharge. For spheres of a certain size and range of separation ionization is followed by an increase in electric intensity, and in this case is immediately followed by disruptive discharge.

Alexander Russell,* in a most valuable paper, has considered various types and sizes of terminal in which there can be no initial ionization without resulting discharge. He shows from the results of various investigators that if the terminals are chosen for these conditions, a constant value of about 39 kilovolts per centimeter is found for the electric strength of air. He also draws some interesting comparisons between his own results with spheres and those of Steinmetz with needle points, showing that they are in fair agreement when the facts of ionization as above described are considered. Russell's conclusions lead to very uniform results for the particular cases he examines, and by an extension of his reasoning it would appear that if we could determine the voltage of initial ionization or break-down for a given pair of terminals, and could calculate the corresponding potential gradient, we should arrive at the same value of the electric strength of air for all shapes and sizes of terminals. This is not the case however.

As is well known, the surface electric intensity at which

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* A bibliography of the principal articles referred to is given at the end of the paper.

cylindrical wires begin to discharge increases markedly with decreasing diameter of wires. For wires of diameter one cm. and larger, the critical surface intensity is constant at about 40 kilovolts per cm., and this corresponds to the value found by Russell, and also to the value at which secondary ionization sets in, as determined by Thomson and others working with vacuum tubes. For wires smaller than one cm. the critical intensity increases, reaching the value 80 for a diameter 0.1 cm. The ionization theory offers no obvious explanation at this point, nor does Russell discuss the fact that the surface electric intensity for wires smaller than one cm. diameter may be raised far above 39 kilovolts per cm. without any evidence of break-down or ionization of the air. In fact it should be noted that Russell's constant value of 39 kilovolts per cm. depends on the assumption, not yet justified except by his conclusions, of a constant value of " lost volts " at the surface of separation between terminal and air. The apparent variation of the electric strength of air with the diameter of wire is a most promising problem for the experimental physicist. The suggestion by several writers that the air has greater strength near the wire than at a distance is only an unscientific statement of the fact. Undoubtedly the electric strength of the air will ultimately be found to be constant. The influences which for small wires reduce the actual intensity below the apparent value, and make necessary Russell's assumption, will be discovered and the correction factor for any type of terminal will then be available. Some further discussion in this connection will be found at the end of the paper.

The apparent values of critical surface intensity for cylindrical wires as determined by different observers differ considerably. The principal workers in this field have been Steinmetz, Scott, Ryan, H. B. Smith, Mershon and Watson. With the exception of the last named an account of the work of each has been presented to the Institute. Steinmetz, Ryan and Watson worked within the laboratory; Scott, Smith, Mershon and Watson on aerial lines. Watson worked with continuous potentials only. If all the observations be expressed in terms of critical surface intensity there is a marked difference in the results. Omitting those of Mershon the others show differences as great as 10 per cent for wires in the neighborhood of 0.3 cm. diameter, while the results of Mershon fall 33 per cent below the lowest of the others. Ryan and Watson have studied the influence of atmospheric pressure, Ryan that of temperature, and Mershon notes a decided influence of water vapor in the air, Ryan's investigation in this direction being inconclusive. Two general methods of observing the point of initial break-down have been used; the visual appearance of corona, and the break, more or less sharp, in the curve connecting voltage and line current or line power. The first method introduces a considerable possibility of personal error. The second method necessitates the elimination of leakage, charging current, and transformer losses, which are often many times larger than the quantity sought, and its accuracy is open to some question.

PRESENT INVESTIGATION

The primary aims of the present investigation have been the development of an accurate method of determining the electric strength of air in the neighborhood of round wires; the application of the method to clean smooth wires of various materials of diameter less than one cm.; and a study of the influence of moisture on the electric strength of air near smooth and rough wires. In addition, some interesting properties of the visual corona are described.

The Method. The new method developed permits a determination of the critical intensity or electric strength of air in the neighborhood of round wires to an accuracy within 0.5 per cent. It also permits accurate control of the temperature and moisture content of the air under observation. It makes use of the fact that electrical rupture is invariably accompanied by ionization, and that extremely minute traces of ionization may be detected by the gold leaf electroscope, one of the most sensitive instruments at our disposal.

The wire is stretched along the axis of an outer metallic cylinder, and the voltage applied between them. Air is drawn from the neighborhood of the wire under investigation and over a suitable discharge terminal connected to the gold leaf system of the electroscope *G*, Fig. 1. As soon as the ionization accompanying electrical break down occurs the electroscope discharges.

Near each end of the outer cylinder a series of small holes is drilled permitting air to be drawn through the cylinder. The electroscope terminal is placed close to the openings by which the air leaves. The electroscope retains its charge until the critical voltage is reached and then discharges rapidly. A diagram of the apparatus and auxiliaries is shown in Fig. 1. *A* is the wire accurately centered in the outer cylinder; it is supported under tension by dry threads well beyond the ends of the cylinder which are closed by the wood and glass caps *B B*. Air is drawn through the cylinder by an exhaust fan, entering at *C* and leaving at *D*; the velocity of the air is measured at *F*. Any degree of moisture is obtained by bubbling the air through water at various temperatures, and the driest state by drawing through a large column of calcium chloride. The temperature of the air was controlled by passing it through a large coil of lead pipe immersed in a tank filled with ice or water of any desired temperature. The moisture content of the air was determined by reading its temperature and also the temperature of the dew point, as indicated by a polished brass mirror at *E*; water of any temperature could be passed through the solid back of this mirror, the temperature being read from a thermometer with its bulb immersed in mercury. The temperature of the air was read at each end of the tube, and by means of the coil described was varied between 6 and 40 deg. cent. The dew point could in this way be read to 0.5 deg. cent. and values of relative humidity from 0.1 up to saturation were obtained by the methods described.

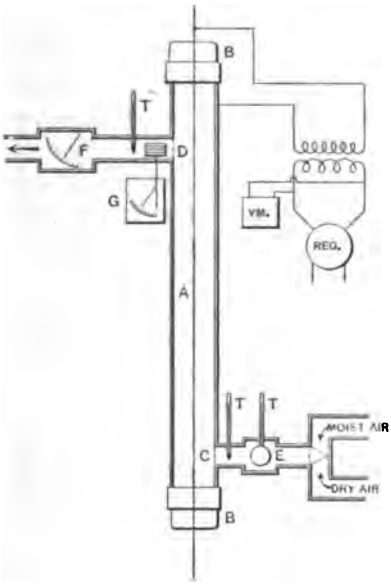

FIG. 1.—Arrangement of apparatus

The voltage was obtained from a 3-kw., 60-cycle transformer, 100 to 25,000 volts, the high tension winding being in four sections. The primary voltage was read on a Weston dynamometer voltmeter, standardized for this work, and was controlled by an induction regulator; for close adjustments a small amount of resistance, of negligible influence on the wave form, was inserted. The ratio of turns of the transformer as obtained from the manufacturer is 1 to 250.18 and this value is used for determining the secondary voltage. The charging current of the wire and cylinders is negligible, and no evidence of leakage current could be detected on an ammeter in the high-voltage circuit, reading to less than one tenth the normal full-load transformer current. The resistance of the primary winding affected the secondary voltage as read above by less than 0.1 per cent.

Accuracy of the Method. The electroscope was provided with a scale viewed through a telescope. Its discharge terminal was a cylindrical cage of copper wire placed within 0.5 cm. of the wall of the main outer cylinder. The reading taken was the time in seconds, as determined by a stop-watch, required for the gold leaf to pass over a fixed interval on the scale. The normal time for free leak over this interval was of the order of magnitude of a day. The eye could readily detect motion of the leaf corresponding to 250 seconds. In the experiments on clean wires an increase in the primary voltage of one per cent at the critical value was generally sufficient to reduce the time of discharge from that corresponding to its normal rate of leak, *i.e.*, thousands of seconds, to two or three seconds. These figures indicate how sharply marked is the critical voltage, and how sensitive the electroscope.

In taking observations, the electroscope is charged and a slow current of air drawn through the apparatus. With eye on the electroscope leaf the voltage is gradually raised to a value at which the electroscope just begins to discharge as detected by the eye, and its rate of leak is then measured. The voltage is increased by small steps, corresponding rates of leak being taken several times for each value. The temperature and pressure were also noted. The time for discharge drops from practically an infinite value to very low values (from two to four seconds) within a very small change of voltage. Several of the many sets of observations are given in Table III and elsewhere, and reference is made to curve 2 in Fig. 7 for the sharpness with which break-down begins. The curves are plotted between time to discharge as ordinates, and kilovolts as abscissæ.

Tests and Experiments

The first experiments described are an investigation of the influence of the velocity of the air through the apparatus. The corrections for temperature and pressure variation are then discussed. Then follow the observations on wires of various sizes, and materials under various conditions as to surface and moisture.

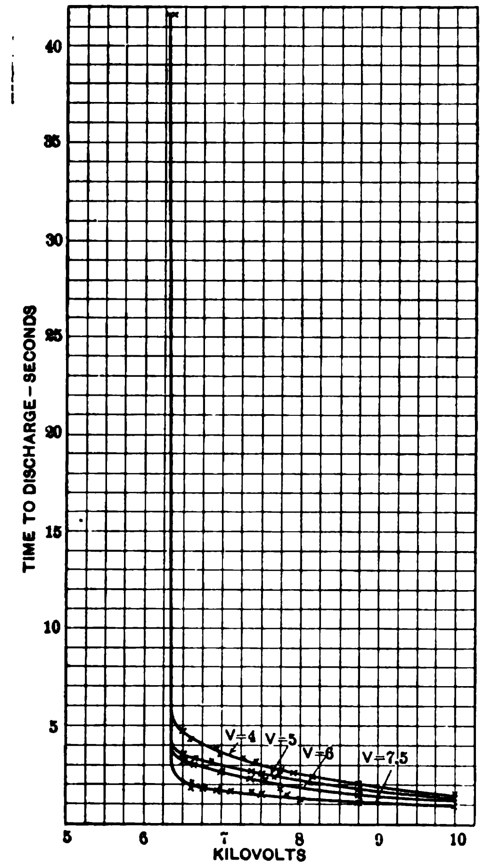

Fig. 2.—Influence of air velocity on rate of discharge

Effect of Air Velocity. A series of observations is given in Table I showing that the method as described is, within wide limits, independent of the velocity with which the air is drawn through the apparatus. A series of curves plotted from another set of observations is shown in Fig. 2. The point of initial break-down is not affected by the velocity, but the rate at which ions reach the electroscope is. In the observations from which the curves are plotted, the electroscope was some distance from the discharging wire, permitting diffusion and recombination of the ions. The curves from the values in Table I are all superposed, since in this case the electroscope was very close to the discharging wire, and even at no motion of air in the tube the diffusion or projection of the ions from the discharging wire is of sufficient volume to discharge the electroscope so rapidly as to mask any effect of the increase by velocity.

TABLE I. CRITICAL VOLTAGE INDEPENDENT OF VELOCITY OF AIR

Velocity of air, feet per minute									
0		98		162		252		371	
Primary volts	Seconds to discharge	Primary volts	Seconds to discharge	Primary volts	Seconds to discharge	Primary volts	Seconds to discharge	Primary volts	Seconds to discharge
60.5	300	60.5	400	60.5	425	60.2	400	60.7	500
61	5	61.6	2.7	60.7	18	60.8	9	61.2	3
61.8	2.8	62.5	1	61	4.5	61.2	2.2	62	1
62.1	2	61.2	2.2	61.5	1.8	62	1.2	—	—
63.5	0.8	60.6	300	62.5	1	63	0.6	—	—

As seen, the point of initial breakdown is independent of the velocity. The action of the electroscope was found to be more pronounced when a moderate velocity is used; also a continuous draft is necessary for renewing the air, and maintaining constant conditions of temperature and moisture. Throughout the experiments a velocity of 150 ft. per min. was generally used, and the electroscope placed as close as possible to the outlet from the cylinder forming the outer terminal.

Influence of Temperature.—By means of the heating and cooling apparatus already described, the series of observations, given in Table II, were taken on polished copper wire 0.276 cm. diameter at temperatures between 6 and 41 deg. cent., Fig. 3 shows the corresponding curve corrected to 760 mm. pressure.

TABLE II. INFLUENCE OF TEMPERATURE ON CRITICAL VOLTAGE

Mean temperature, cent....	7.4	11.0	16.4	20.0	20.5	27.9	41.0
Primary volts observed....	71.6	70.7	70.5	69.1	70.2	69.0	66.8
Barometric pressure.......	763.0	755.8	764.0	755.8	765.5	765.5	765.5
Primary volts corrected to 760 mm................	71.4	71.0	70.1	69.5	69.8	68.4	66.3

In these experiments the temperature of the air was read at the points of entering and leaving, the cylinder being covered with heat-insulating materials so as to maintain the temperature as constant as possible. The difference in temperature between the entering and leaving air was a maximum at four degrees at the highest temperature, and the mean values are given in the table. This test was undertaken to ascertain the correction factor for temperature to be applied in the later investigations. The results are not offered as being the most accurate attainable, and a more exact determination of the influence of temperature is planned for a separate investigation. The results are amply accurate for the purpose of correction, and indicate that at 760 mm. pressure there is a drop or rise of 0.22 per cent in the critical voltage for each degree centigrade rise or fall from 21 deg. cent. Ryan has investigated the influence of temperature on the voltage at which the corona becomes visible, and his results at atmospheric pressure indicate the value 0.27 per cent per centigrade degree above or below 21 deg. cent. In the present experiments, critical voltages are reduced to 21 deg. cent. by means of the factor 0.22 per cent per degree.

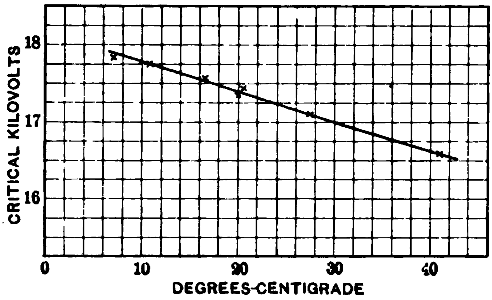

FIG. 3.—Influence of temperature -0.276 cm. wire in 6.35-cm. tube

Influence of Pressure. The variations in atmospheric pressure introduce considerably less disturbance than those of temperature. The minimum and maximum pressures encountered in these experiments were 750 mm. and 772 mm. Ryan and Watson have investigated the influence of pressure, but their results are not in good agreement. In these experiments, critical voltages are reduced to 760 mm. pressure by Ryan's factor. The values of this factor vary from 0.985 for 750 mm. to 1.009 at 766 mm. My observations within the narrow range stated above are in fair agreement with these values, being 1.88 per cent variation, as against 1.53 per cent by use of Ryan's expression. As most of the observations were taken at pressures differing little from 760 mm., and necessitating corrections of only a few tenths of a per cent, no separate investigation of pressure influence was undertaken.

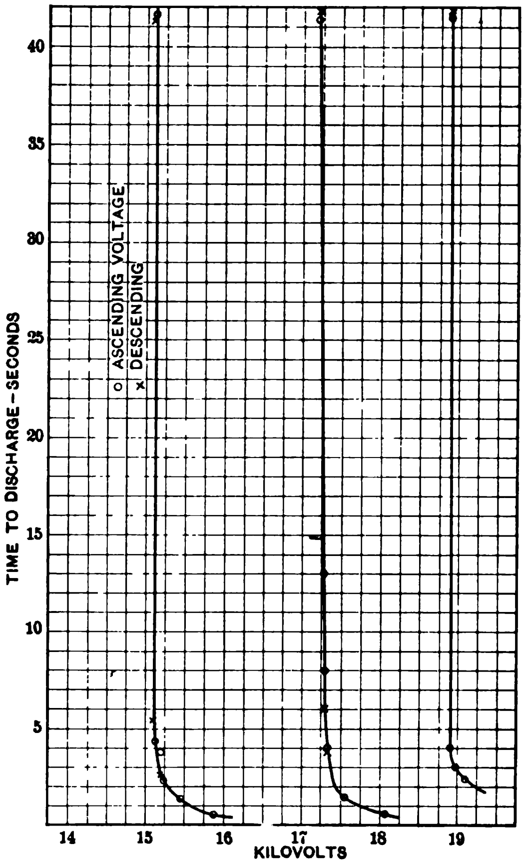

FIG. 4.—Typical curves showing critical voltage for wires of 0.205, 0.276 and 0.347 cm. diameter in 6.35-cm. tube

OBSERVATIONS ON CLEAN SOLID WIRES

A great many observations were made on copper, aluminum and steel wires of diameters between 0.089 cm. and 0.5 cm. centered in tubes of 4.9 cm., 6.35 cm. and 9.82 cm. internal diameter, and 100 cm. length. The steel wires were taken from rods of tool steel; they were perfectly straight and readily polished and handled without danger of kinks. The copper and aluminum wires were heated by electric current to dull red and at the same time subjected to tension; they were then carefully polished and placed in the outer tube without bending or contact with other objects. The two larger tubes were placed in the vertical position and the wire held under tension in accurately centered insulating bushings on the ends. The air was strained through cotton wool and a cambric screen at the entrance to the tube. On raising the voltage the charged electroscope is unaffected until the critical voltage is reached when a sharply marked rapid rate of leak sets in. In Table III several sets of observations on wires of 0.205 cm. and 0.276 cm. are given; Fig. 4 gives two curves plotted from the figures of the table as well as the curve for 0.347 cm. wire. From these it may be seen that at the critical point an increase of one per cent in the voltage is sufficient to cause the electroscope to discharge in three or four seconds although it was unaffected at the lower value. With increasing values of voltage, the electroscope discharges still more rapidly, although owing to its sensibility a point is soon reached when the discharge is so rapid that its time cannot be read. The visible corona ap-

TABLE III. POLISHED COPPER WIRES IN 6.35-CM. BRASS OUTER TUBE

0.205 cm. diam.		0.276 cm. diam.		0.276 cm. diam.	
Primary volts	Time to discharge seconds	Primary volts	Time to discharge seconds	Primary volts	Time to discharge seconds
60	∞	69	∞	68.5	∞
60.3–5	just begins	69.5–6	25	68.8	just begins
60.6	4.2	70.3	2.4 3.4 2.8 2.4	69.3	3.8 4.2
60.8	3.8 3.8 3.6	71	1.6 1.6 1.4	69.2	8 1.3 8
60.9	2.2 2.2 2.2	73.2	0.8	70	1.4 1.4 1.4 1.4
61.8	1.4 1.4	71	1.4 1.4 1.4	72.2	0.6 0.6
62.5	1 1 1	69.7–8	9.2 10	69.3	3.8
63.5	0.6	69	∞	69.2	6
61	2.2 2.4	69.2	just begins	68.7	∞
60.5	5.4	0		0	
60.2	∞	69		68.5	∞
60.3	just begins	69.6–8	9.2	68.9	just begins
				69.2	7 6
		70.3	2 2	70.1	1.4 1.4
Temperature 19 deg. cent. Barometer 764 mm. Dew point 5 deg. cent. March 4		Temperature 19.5 deg. Barometer 761 mm. Dew point 4 deg. Feb. 15 Corrected critical volts 68.8		Temperature 21 deg. Barometer 762 mm. Dew point -2.5 deg. Feb. 18 Corrected critical volts 68.7	

pears faintly at the beginning of the break in the curve and brightens rapidly with increasing voltage. Recalling Ryan's observations that corona and power loss begin together, this shows that there is no ionization before power loss sets in. The nature of the power loss has been the subject of much speculation, and the above fact is one leading to my conclusion that a part if not all of the loss is in the process of ionization, *i e.*, the separation of the two opposite charges on the molecules of the gas. The shape of the curve beyond the critical point depends on the air velocity, distance to the electroscope, size of its terminal etc., and it offers a means of studying the shape of the loss curve

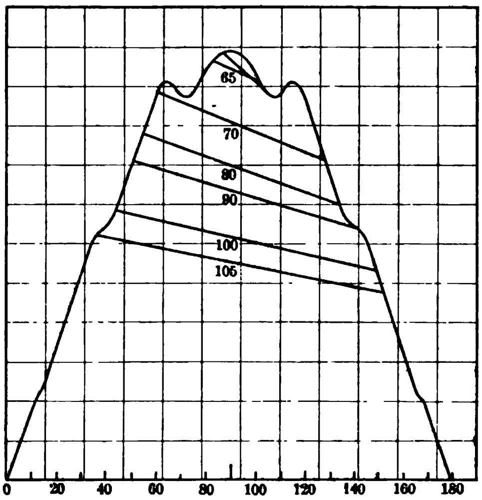

FIG. 5.—Region on voltage wave occupied by corona at various voltages

for voltage above the critical value. The investigation has not as yet been extended in this direction.

A further fact of interest in connection with these curves is that for decreasing voltage the curve is retraced, and ionization or break-down ceases at the same voltage at which it began. There is thus no apparent after-effect of foregoing ionization. This fact may be also observed by opening the transformer circuit when the electroscope is discharging; it stops instantaneously even when its initial rate is extremely rapid, *i e.*, when ionization is copious. This indicates that the life of a free ion is extremely short, and also in view of the low air velocities used that the ions reach the electroscope by their own velocity in the electric field, rather than by any aid of the air draft. This conclusion is in accord with the independence of critical voltage and air velocity. Some further evidence in this direction is given in the description of experiments with the corona.

Table III indicates the nature of the observations taken on many variations of size and material of wire and outer tube, under various atmospheric conditions. The results on a given size of wire at different times and in different tubes are in excellent agreement when the corrections for temperature and pressure are applied. This is indicated in Table III and also in Table IV in which the results of this portion of the work are condensed. In Table IV the observed values of critical primary volts have been corrected to 21 deg. cent. and 760 mm. pressure by the factors already described. The critical value is that at which the discharge of the electroscope begins. This point is very sharply marked, and under steady circuit conditions could be read to 0.2 primary volts. On the curves of Fig. 4 it corresponds to the beginning of the steep descent of the vertical limb. The maximum electric intensity at the surface of the wire corresponding to the critical primary voltage is calculated from the primary reading by the expression

$$\frac{d\,V}{d\,x} = \frac{V}{x \log \frac{b}{a}}$$

in which V is the maximum value of potential difference between wire of radius a, and tube of inner radius b; x is the distance from the center of the wire to the point for which the calculation of intensity is made, and thus for the surface of the wire $x = a$. To obtain V, the primary voltage is multiplied by the ratio of transformation, and the ratio of maximum to effective value of e.m.f. of the 60-cycle circuit used throughout the experiments. An oscillogram of this electromotive force wave was taken, and from careful measurements of the ordinates Fig. 5 is a good reproduction. By the summation of the squares or ordinates sufficiently close together to take account of the irregularities, the ratio of maximum to effective value was found to be 1.45 for one-half wave and 1.455 for a whole wave; the value 1.452 has been used in calculating the values in the last column of Table IV.

In Fig. 6 the results given in Table IV are plotted between diameter of wire and maximum critical surface intensity. With the exception of two points, at diameters 0.276 and 0.325 cm., the curve is fairly smooth. The former point is off only 0.8 per cent and the latter for an aluminum wire about one per cent. Aluminum is very difficult to polish, the finest abrasives leaving streaks and a dull surface; this is sufficient to cause the observed lowering of critical voltage.

TABLE IV. RELATION BETWEEN DIAMETER AND CRITICAL SURFACE INTENSITY

Diam. cm.	Material of wire	Diam. of tube cm.	Material of tube	Critical primary volts corrected	Ratio	Maximum critical surface intensity
0.089	Copper	4.9	Brass	74.5	125.09	77,100
0.122	"	"	"	44.0	250.18	70,950
"	"	"	"	87.8	125.09	70,800
0.156	"	"	"	97.0	"	65,880
"	"	"	"	97.0	"	65,880
0.205	"	"	"	109.5	"	61,350
"	"	"	"	55.0	250.18	61,500
"	"	6.35	"	60.5	"	62,080
"	"	"	"	60.2	"	61,780
"	"	"	"	(8) 59.9	"	61,680
0.254	Aluminum	"	"	65.9	"	58,750
0.276	Copper	"	"	68.9	"	58,080
"	"	"	"	68.8	"	
"	"	"	"	68.5	"	
"	"	"	"	69.0	"	
"	"	"	"	(8) 68.9	"	58,080
"	"	9.52	Steel	77.3	"	57,650
0.325	Aluminum	6.35	Brass	72.8	"	55,000
0.347	Copper	6.35	"	75.13	"	54,500
0.3405	"	9.52	Steel	85.7	"	55,100
0.399	Steel	"	"	92.5	"	53,050
0.475	"	"	"	100.6	"	51,400

This curve is of interest when compared with that of Watson for continuous potentials; the curves coincide for the smallest diameters, but Watson's is lower by 6 per cent at 4 mm. If, as he states, the temperature was constant at 17 deg. cent in Watson's experiments, this suggests that a higher value of alternating potential is necessary for break-down, and that a time element is involved; an elevation of temperature however would account for a part of this difference. Ryan's values at which the corona appears are also plotted for comparison. In the present work frequent observations of corona were made, and its appearance invariably coincided very closely with the critical voltage as indicated by the electroscope read by an independent observer.

OBSERVATIONS ON DIRTY WIRE

Throughout the experiments on clean wires it was found that the least dust, dirt, or other inequality of surface was accompanied by a lowering of the critical voltage. On viewing such

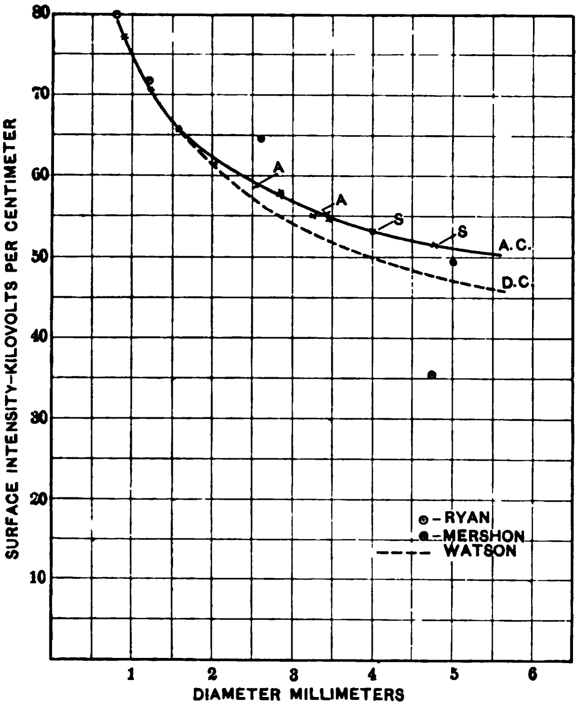

FIG. 6.—Relation of critical intensity and diameter

a wire through the end of the tube a discharging point could usually be detected. On raising the voltage, other points appear on a dirty wire, and the amount of lowering of critical voltage depends on the size and number of surface irregularities and their location with reference to the electroscope. Thus for copper wire 0.122 cm. in diameter taken from a fairly clean coil and not polished, the drop in critical voltage below that for clean wire was only one per cent. On the other hand, a 0.277-cm. polished copper wire, giving a critical surface intensity of 56,500 volts per cm., was heated by current until it took on a flaky coat of oxide. Its critical intensity was reduced to 37,850, or by 33 per cent. Repeated observations (see Table VI) show this point to be very constant and sharply marked. On comparing the discharge curves for clean and dirty wires (see Fig. 7), however, it will be seen that the break in the curve is less sharply marked for the dirty wire and the bend more gradual. This indicates a lesser supply of ions, but a supply amply sufficient to cause a rapid discharge of the sensitive electroscope. It is thus apparent that the figure 37,850 has no significance, only representing the value at which the first surface irregularities begin to dis-

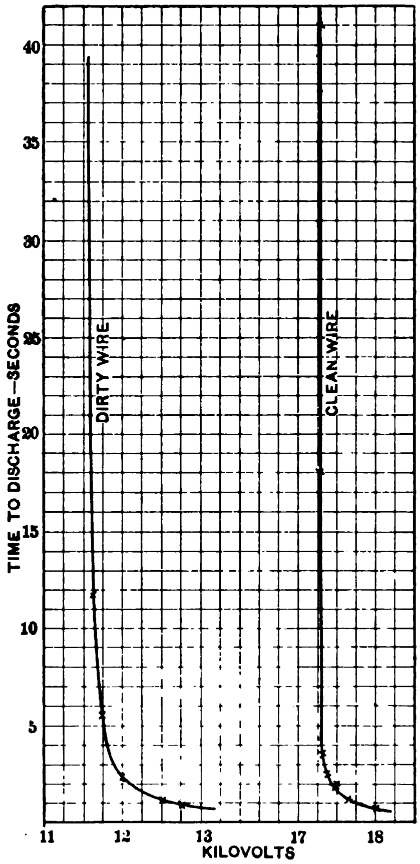

Fig. 7.—Discharge curves—clean and dirty wires 0.276-cm. wires in 6.35-cm. tube

charge. These discharges represent energy loss, and in sufficient quantity may cause the voltage at which appreciable loss begins, to fall far below the value for clean wires.

INFLUENCE OF MOISTURE

The method of securing any degree of moisture content of the air has been described. The continuous draft of air through the apparatus, with temperature and moisture instruments close to entrance and exits, ensures a constancy of conditions not possible with the closed cylinders used by Ryan and Watson. Moist air was also obtained by drawing it upward through a dense spray, and by taking it from outside the building on rainy days. The invariable conclusion from many experiments is that moisture in the air has no influence on the surface intensity at which ionization and loss begin. Several sets of observations are given in Table V. The observed and corrected primary voltages are given and also the conditions of temperature, pressure, and moisture content. A range of relative humidity from 0.1 to 0.9 was covered. The " vapor product " as defined by Mershon is also given in the last column, and ranges from 0.008 to 0.83; this quantity is the product of the relative humidity by the vapor pressure in inches of mercury.

Mershon, working on aerial wires, concludes that moisture lowers the critical voltage by about 16 per cent for a range of vapor product 0 to 0.6. Since his wires were exposed to weather they were subject to some degree of surface imperfection. Since such imperfections are an aid to condensation of moisture it was thought that a lowering influence of moisture might be possible in this way. A series of tests with moist air was therefore made on the dirty wire already described. The results as given in Table VI indicate that in the case of dirty wire also, the moisture content of the air has no influence on the value of voltage at which ionization and loss begin. A possible influence of the velocity of the air through the apparatus in checking condensation was also investigated by drawing moist air through for some time, testing for critical voltage, then stopping the air draft and testing, etc. In no case was it possible to detect any influence of the moisture content on the critical voltage.

It is difficult to imagine any other conditions of Mershon's experiments which might explain an influence of moisture. His wires were suspended by paraffined cords over which the loss was only one or two per cent, and consequently all losses save those in the atmosphere itself were practically eliminated. Floating particles and mist depositing on the lines would lower the critical voltage but with given surface conditions, the experiments described above indicate an entire absence of any influence of moisture. Mershon also finds that the rate of loss beyond the critical voltage increases with the vapor product. Here also no obvious explanation offers itself. The curves of the present

TABLE V. CRITICAL VOLTAGE—MOISTURE CONTENT—CLEAN WIRES

Primary volts at which discharge begins	Temperature of entering air deg. cent	Temperature of dew point deg. cent	Barometer mm.	Primary volts corrected 21 deg. and 760 mm.	Relative humidity	Vapor product
0.206 cm. diameter						
60.3–5 60.3	20	-4	764.5	59.96	0.194	0.025
60.5	19	5	764	59.93	0.4	0.102
60.2 60.1	21	8	764.5	59.9	0.433	0.136
60 60.1	23	16.5	764	60.07	0.65	0.38
59.9 60	24.8	18	764	60.21	0.68	0.41
59.2	27	23	763.5	59.71	0.82	0.624
59	28	25	763.5	59.62	0.9	0.833
60.5	20	0	763.5	60.07	0.264	0.047
0.276 cm. diameter						
68.8	21	-10	761.5	68.7	0.108	0.008
68.8 68.9	21	-2.5	761.5	68.75	0.208	0.031
68.8 69	20.4	1.5	761.8	68.8	0.293	0.060
68.8	24	8.5	762.8	69.2	0.374	0.122
68.8	25	13	762.8	69.2	0.47	0.204
68.5 68.8	26	16	763	69.1	0.546	0.292
69	21.6	15	763	68.9	0.66	0.33
68–69	23.4	18	763	68.7	0.72	0.43
68.5–69	20	17	760	68.7	0.86	0.504
0.347 cm. diameter						
75.3	19.6	3	760	75.0	0.33	0.072
75.2	19.8	8	760	75.0	0.46	0.147
75.1–75.5	22	12.5	760	75.4	0.54	0.23

experiments between discharge rate of electroscope and voltage show that either the number or the velocity of the free ions about the wire is lessened in moist air, and this means a less loss. This result is in conformity with those of many other experiments. It has long been known for instance that the conductivity of air is lessened by moisture; also that the velocity of ions is less in moist air than in dry air. Steinmetz notes an increase of electric strength of air by the presence of fog and steam. Zeleny has shown that between dryness and saturation the voltage of initial discharge between a point and a plane is constant for negative potentials, and varies by less than 1.5 per cent for positive potentials. He also shows that the currents of discharge are both lowered with increasing moisture content.

TABLE VI. CRITICAL VOLTAGE—MOISTURE CONTENT—DIRTY WIRE 0.297 CM. DIAMETER

Primary volts at which discharge begins	Temperature of entering air deg. cent	Temperature of dew point deg. cent	Primary volts corrected 21 deg. and 760 mm.	Relative humidity	Vapor product
46.5 47	19	0.5	46.2 46.7	0.282	0.05
46.5 47	19	6	46.2 46.7	0.428	0.11
46 46.2	20	9	45.8 46	0.49	0.16
46 46.5	21	12.5	45.9 46.4	0.58	0.24
45.5 46	25	18	45.8 46.3	0.65	0.39
45.5	26	19	45.9	0.65	0.41

When the critical voltages observed by Mershon are reduced to electric intensities at the surface of the wires they are found to be well below these of Ryan, Watson, and the values given in this paper. For example, the loss from a 0.472-cm. wire, according to Mershon, begins at a surface intensity 35,000 volts per cm., see Fig. 6; the value found in the present experiments for the same size wire is 51,000. This difference of 30 per cent can only be accounted for in three ways: (1) The method of taking the critical point from the loss curves. (2) Dirt and irregularities on the wires. (3) Break-down of the air near the strings at a lower value than that necessary on a free wire. Examination of the curves show that the critical point is taken close to the sharp upward break of the curves, and the method offer small chances of too low a choice of critical value. Dirt and irregularities will lower the critical voltage, but require extreme conditions for as great a lowering as 40 per cent, as is indicated by the experiments already described. With the larger wires used by Mershon, it does not seem possible that this degree of surface irregularity could result from any deposit from the air. The third possibility mentioned seems to have been eliminated by the tests to which the cords were subjected before using.

In view of these discrepancies, one naturally turns to Mershon's method of measuring the loss as a possible source of error. This method involves the elimination, by means of a differential wattmeter, of transformer losses aggregating several times the value of the loss to be measured. The method is elegant in conception, but in view of the small losses to be measured, it is to be regretted that its accuracy could not be tested further than described. Since Mershon's observations appear to have been taken in all seasons, it may be stated that a range of temperature of 35 deg. cent. and of pressure of 25 mm. of mercury, and an error of 5 per cent in the critical point as taken from the curves, would give a range of critical voltage as wide as that attributed by him to moisture.

EXPERIMENTS ON CORONAE

One of the most striking phenomena in the experiments already described is the extreme sharpness with which the critical voltage appears. The sharp stoppage of the electroscope discharge on interrupting the alternating voltage, and the coincidence of discharge curves for ascending and descending voltage, in the present investigation, indicate that any after-effect of the ionization due to corona must be of duration less than one-half a period. Ryan showed in beautiful manner how the appearance of corona was accompanied by a hump on the charging current curve in the neighborhood of the maximum of the voltage wave, thus suggesting a periodic character. In order to investigate these phenomena further the following stroboscopic device was used. A 0.156-cm. polished copper wire was stretched along the axis of an outer cylinder of 10.5 cm. internal diameter, and voltage applied between them. The wire was viewed longitudinally through six slits, each 4.7 mm. wide, in a disk driven by a six-pole synchronous motor; the slits were on a circle of 27 cm. radius. The position of the eye was fixed by an eyepiece on a screen movable about the motor axis; this screen had a small radial slit 0.5 cm. wide, under the eye piece and opposite the circle of slits in the revolving disk. The angular position of this slit was read on a circular scale. The eyepiece therefore moves through 56 cm. in covering the interval corresponding to one period of the alternating circuit. On viewing the corona with this apparatus, it is at once found that there are certain regions where it cannot be seen and others where it is readily visible, thus showing its periodic character. Further the points of separation of dark and bright regions are sharply marked, so that it is possible to determine quite accurately over how great a proportion of a period the corona exists. A set of observations for various voltages, above the critical value, are given in Table VII. The first column gives the voltage on the transformer primary; the second column, the scale reading at which the corona becomes visible advancing the eye piece from the dark region towards the bright, and in a direction contrary to that of the motion of the disk. The observation therefore is of the angular position at which the corona ends. The readings of two independent settings of the eyepiece are given for each voltage to indicate the accuracy. The position corresponding to zero value of electromotive force was obtained by an instantaneous contact device and voltmeter connected across the transformer primary. The third column gives the average readings reduced to electrical

TABLE VII. LOCATION OF CORONA ON VOLTAGE WAVE

Primary volts	Corona appears			Corona disappears			
	Degrees of scale	Electrical degrees		Degrees of scale	Electrical degrees		Starting Intensity
		Reading	Corrected		Reading	Corrected	
105	10.4 10.8	31.8	27.1	50 50	150	143.5	66,500
100	12.5 12.7	37.8	33.1	48 47.2	142.8	136.3	68.300
90	14.6 15.4	45	40.2	45.4 45.4	136.2	129.7	74,200
80	16.6 17.4	51	46.3	43.8 44.2	132	125.5	70,000
70	19 19.2	57.3	52.6	42 42	126	119.5	70,500
65	27.6 27.8	83.1	78.4	34.6 34.2	103.2	96.7	70,600
65	26.5 27	80.2	75.5	33 33.2	99.3	92.8	—

degrees, and the fourth column these values corrected for the width of the slit and referred to the zero value of electromotive force determined as described above. The succeeding columns give the corresponding readings of angular position at which the corona can no longer be seen. This observation is therefore the angular position at which corona begins on the rising side of the electromotive force wave.

The results in Table VII indicate that the corona corresponding to a given voltage will persist on the decreasing side of the wave to a value below that at which it starts on the side of rising voltage. After the intensity drops below the value at which ionization begins the foregoing plentiful ionization is able to preserve luminosity for an appreciable interval. This interval is seen to be extremely short and of the order of magnitude of one or two thousandths of a second. In fact the settings for vanishing point of corona on the side of decreasing voltage are somewhat less sharply marked indicating that the corona fades off more gradually than it starts. The readings for 65 volts primary taken on different days show some discrepancy. The corona is very faint at this voltage close to the peak of the electromotive force wave and therefore very sensitive to reading error and voltage variation. In this region, also, the accuracy of setting is somewhat impaired by the presence of the three peaks of the electromotive force wave.

The wave form as measured from the oscillogram is plotted in Fig. 5, and the ordinates at which the corona starts and ceases for the several values of primary voltage are indicated; the voltage is rising on the left side of the curve. The ordinates corresponding to the angles given in Table VII indicate voltage values which by obvious calculation permit the evaluation of the figures for surface intensity at which the coronæ begin. These values are given in the last column of Table VII. They are in fairly good agreement, considering the method by which they are obtained with the accurate figure for this wire 65,800 as determined with the electroscope. It is altogether probable that this latter figure is the real value at which the corona starts on the rising side of the wave, and if it be taken as a basis the lag of the point at which corona vanishes would be somewhat lessened from the values indicated in Fig. 5.

Positive and Negative Coronæ. The arrangement of apparatus as described above superimposes the coronæ corresponding to the positive and negative halves of the electromotive force cycle.

By closing alternate slits in the revolving disk it is possible to view the positive and negative coronæ independently. Several sets of readings were made for each half wave of the angle at which corona begins and ends. The readings for the two half waves were made on the same portion of the scale by reversing the field of the synchronous motor. The points of beginning and ending of corona were found to be independent of the polarity of the wire. There was very little difference to be detected in the appearance of the two coronæ; if there is any difference it is a somewhat greater brightness and sharper definition of one.

The extreme sharpness with which the corona appears was well illustrated in the stroboscopic experiment in various ways. For example, when viewing the corona near the position at which it is cut out, very small voltage fluctuations are reflected as flickers in the corona. By setting the eyepiece very near to the position of eclipse, a regular pulsation of the corona was generally visible, and was traced to a slight hunting of the motor, thus causing a vibration of the eclipsing edge of the hole in the disk about its true synchronous position. A further evidence of sensibility could be seen by adjusting the voltage so that the critical value was in the region of the three peaks on the crest of the wave, as shown in Fig. 5. It was then possible by moving the eyepiece to pick out the several peaks separated by the dark intervals corresponding to the depressions.

Diameter of Corona. It has been suggested by Steinmetz and others that the diameter of the corona is such as to reduce the electric intensity at its boundary to the constant value of the electric strength of air, *i.e.*, about 40 kilovolts per cm. Jona states that the diameter of the corona for a given arrangement of conductors is independent of the size of the wire and depends only on the voltage. Also that the diameter is such as to reduce the electric gradient at its boundary below the electric strength of air. The same suggestion has been made by Russell in several places.

The measurement of the diameter of the corona is very difficult. Jona's figures and conclusions are apparently based solely on eye estimates of the diameter. Photographic methods fail, since the phenomenon is accompanied by much invisible ultraviolet radiation. A preliminary attempt looking to the development of a method for measuring the diameter of the visible corona is described below; it has yielded results which are sufficiently concordant to make them worthy of recording here. The experiments are being carried further in this most interesting direction.

A slit was cut in the wall of the outer 15.2-cm. cylinder and at right angles to the axis. A 0.156-cm. wire stretched along the axis develops a well defined corona for voltages above 18,000. A screen one cm. wide was placed transversely across the slit and close to the wall of the outer cylinder. The screen was moved up and down to positions in which its upper and lower edges cut off the corresponding edges of the corona, the eye being at a pin hole at the horizontal level of the wire and at a distance from the wire 6.15 times that of the screen from the wire. It is necessary in these experiments that the eye be thoroughly rested and accustomed to the darkness. In making the final setting of the point at which the screen completely obscures the corona edge, direct scrutiny is not possible owing to the blind property of the fovea of the eye, and use must be made of the adjacent regions of the retina. In this way any number of quite consistent readings may be taken. The screen was carried on a cathetometer which could be read to a hundredth of a millimeter. The results at effective voltages 28,000 and 24,000 are given in Table VIII. They show that the maximum deviations from the average values of observed diameter are of the order 10 per cent to 15 per cent. This must be regarded as fair, in view of the small diameters measured, and offers good promise for further investigation in this direction.

TABLE VIII. DIAMETER OF CORONA, 0.156 CM WIRE IN 15.2-cm.CYLINDER

28,000 volts				24,000 volts			
Top	Bottom	Difference	Diameter corrected	Top	Bottom	Difference	Diameter corrected
11.065	10.45	0.615	0.462	10.335	11.065	0.73	0.324
11.03	10.43	0.60	0.48	10.375	11.035	0.66	0.408
11.02	10.41	0.61	0.468	10.335	11.06	0.725	0.33
11	10.41	0.59	0.492	10.355	11.06	0.705	0.354
11	10.41	0.59	0.492	10.375	11.06	0.685	0.379
11.035	10.375	0.66	0.408				
Average diameter.......			0.468	Average diameter.....			0.36

As corrected for the width of the screen and the angle at the eye, the diameters of the coronæ at 28,000 and 24,000 volts are

0.46 cm. and 0.36 cm. respectively. The values of electric intensity at the edge of the coronæ, calculated on the assumption that the conductor is enlarged to these diameters, *i.e.*, that the corona has no resistance, are 50,250 and 51,700 volts per cm. respectively. The values of intensity at which the corona forms on solid wires of diameters 0.46 and 0.36 cm. are 51,500 and 54,000.

While it is hazardous to draw conclusions from work as yet so incomplete the above figures for a solid wire and a corona assumed to be perfectly conducting are in such close agreement as to at least suggest: First, that the edge of the corona marks the limit of ionization or rupture; and second, that the corona has high conductivity, the greater part of the potential difference, and hence loss, occurring beyond its boundary. On this assumption the loss would be due to the forced passage under the electric gradient of molecular ions through the air. It is to be noted however that these figures do not indicate that the intensity at the edge of the corona is 40,000 volts per cm., the suggested constant electric strength of air, but that it is higher and its value related to the corona diameter in the same way that the critical surface intensity for a solid wire is related to the diameter of the wire.

Discussion and Conclusions

It is evident from the facts and experiments which have been described above that the laws under which the corona appears are not yet definitely fixed. There are a good many consistent facts, however, which permit us to speculate as to the nature of the corona. The most conspicuous of these facts is that the break-down of the air which is invariably accompanied by a more or less visible corona is attended by copious ionization. Our present knowledge of ionization of gases reveals three possible sources of ions or charged particles: (*a*) the ions may be drawn from the substance of the wire or terminal itself under the electric intensity; (*b*) the molecule of the gas may be disrupted by a separation of its two component charges by the intensity of electric field in which it finds itself; (*c*) a molecule of a gas may be ionized or separated into its component charges as a result of a collision between itself and another molecule or charged particle.

Regarding the possibility of drawing free charges from the metal of the terminals, we have the experimental evidence that the generation of ions in the neighborhood of wires is independent of the material of the wires and we should expect different figures for different materials if initial ionization started in this way. Further it has been calculated that the electric intensity necessary to draw electrons from metal is of a very much higher value than that at which corona begins. With reference to the second possible source (*b*), it has also been shown that the intensity necessary to separate the component charges of a molecule is higher considerably than the intensity at which corona begins at atmospheric pressure.

There is considerable evidence that the third source of ionization mentioned above, *i.e.*, ionization by collision, or secondary ionization as it is called, is that which leads to the starting of corona. There are always a certain number of free electrons or negative charges and of ions of molecular size present in the air at atmospheric pressure. These free charges have their origin in the frequent collisions between molecules and are extremely few in number. A single charge does not have a long independent existence but when it combines with a molecule of opposite charge its place is taken by other charges, so that the average condition is that of a constant number of free charged particles. These charged particles account for the conductivity of the air which may be observed by sensitive instruments. It is the value of this low conductivity which leads to our knowledge as to the number of free charges present.

Now the electron, or corpuscle, the smallest negative charge of which we have knowledge, requires an intensity in the neighborhood of 170,000 volts per cm. in order to give it a velocity sufficiently great to break up a molecule with which it collides. The corpuscle attached to a molecule, however, has a larger mass and consequently if it can acquire sufficient velocity it can the more readily break up a molecule with which it collides. These are the agents which are active in secondary ionization, which has been investigated by many physicists, notably J. J. Thomson, Townsend and von Schweidler. The values at which this class of ionization sets in as determined by physicists working with continuous potentials and generally in vacuum tubes, is between thirty and forty thousand volts per cm. This figure is in very good accord with the value at which corona sets in for wires above one cm. in diameter. The influence of temperature and pressure is also the same in each class of phenomena. It may be stated then with some positiveness that secondary ionization is the cause of the initial break-down of the air and formation of corona.

It is evident that in the formation of the corona very short time intervals are involved, for it begins in the close neighborhood of the maximum value of the intensity wave, and, within the comparatively narrow limits already investigated, is independent of the frequency. It begins and ends at approximately the same value on the wave of intensity when the maximum intensity is above the critical value. If we try to picture the phenomenon of the starting of break down we may reason somewhat as follows: In an alternating electric field the free ions of molecular size vibrate with increasing amplitude as the voltage arises. The velocity is greatest at the maximum value of voltage if as is probable we presuppose some retarding force. If, however, the ion meets nothing its amplitude will be greatest at the end of a half wave. We may suppose that there are always some ions which collide with molecules when their velocity is a maximum. When with increasing voltage this maximum velocity is sufficient to ionize the molecule with which the ion collides secondary ionization sets in liberating more free ions which themselves become ionizing agents and a cumulative effect sets in at once resulting in a general state of ionization.

The intensity (40,000 volts per cm.) at which secondary ionization sets in around large wires corresponds with the value deduced by Russell for the discharge intensity between terminals of various shapes about which there can be no preceding ionization. In cases where there is antecedent ionization the effective terminal enlarges until the intensity at its surface falls to the ionizing value as is indicated by the experiments on the diameter of the corona described above. The value 38 to 40 kilovolts per cm. satisfies many of the cases of discharge which arise and thus offers itself as the long sought constant value of electric strength of air.

There is one important case, however, which is not yet harmonized with this value, namely the case in which the radius of curvature of the terminal is small, the most conspicuous instance being the range of diameter of round wires of less than one cm. In these cases the apparent intensity at which ionization begins is much higher than 40,000 volts per cm. The value of intensity may be carried to 80,000 for small wires and there is not the slightest trace of ionization. To state that the air has a different strength near the wire than at a distance is only another way of stating the fact and dodges the question. As the diameter is decreased it becomes comparable with the space separation of the free ions. There is considerable evidence that under normal conditions there are about 1000 of these ions per cubic cm. of air. This would give them an average distance of separation of about 1 mm. Thus as the ions vibrate near the wire surface they must be brought much nearer together in the case of a small wire. Hence there will be larger forces of repulsion brought into play retarding or limiting the amplitude of vibration and thus necessitating higher values of intensity to overcome these forces.

These are questions for solution by the experimental physicist but the field is at present practically untouched. The application of alternating electromotive forces to the problems of the ionization of gases has been absolutely neglected. Corona formation and the laws which regulate it are of the first importance for electrical engineers since corona is to be prevented both as a source of loss and an enemy of insulation. The field is replete with fascinating problems. Their solution however involves the use of methods and apparatus generally not familiar to the physicist. Hence it is to be hoped that this most interesting field will be entered more generally by experimental engineers.

The experiments described in this paper were carried out at the Johns Hopkins University. The author wishes to acknowledge the valuable assistance of Dr. C. F. Lorenz and Mr. P. G. Agnew.

SUMMARY OF RESULTS

The conclusions from the experiments of this paper may be briefly summarized as follows:

1. A method is described which permits the determination of the electric strength of air near round wires within 0.5 per cent.
2. Values of the electric strength of air near clean smooth wires of diameters between 0.08 cm. and 0.5 cm. have been determined.
3. Temperature and pressure cause the greatest variations in the electric strength of air near a given wire.
4. At 760 mm. pressure there is a drop or rise of 0.22 per cent in the electric strength of air per centigrade degree rise or fall from 21 deg. cent.
5. Water vapor or moisture has no influence on the electric strength of air. Increasing moisture content probably lessens the loss above the critical voltage.
6. There is no loss through air until the critical voltage accompanied by ionization and corona is reached.

7. The electric strength of air is independent of the material of the wire or terminal.

8. The critical voltage may be markedly lowered by dirt and surface impurities. This lowering may be as great as 33 per cent.

9. The corona is periodic but ceases at a somewhat lower value on the voltage wave than that at which it begins.

10. The corona has high conductivity and most of the loss takes place beyond it.

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DIELECTRIC STRENGTH OF OIL

BY H. W. TOBEY

A large part of the apparatus comprising the equipment of electric power transmitting systems depends, for its safe and successful operation, on oil. This fact continues to grow in importance from year to year as the size of the units in which it is used increases, the operating voltages become higher, and the conditions more severe.

Not only must this material be of such consistency that it will circulate freely and so carry heat from the sources where it is generated to external cooling surfaces, but it must be free from any impurities which would injure the insulation or active material of which the apparatus is built; and above all, it must withstand voltage stresses without interruption, year in and year out. Failure to meet these conditions, sooner or later, means failure of the apparatus with which it is used.

It is the purpose of the present paper to outline some of the more important characteristics of oil which fulfil these conditions with special reference to dielectric strength. These characteristics are exemplified throughout by curves and data which have been collected from the results of extensive tests and investigations carried on during a number of years.

NATURE OF INSULATING OILS

The oils now most commonly used for insulating purposes are obtained from crude petroleum by " fractional " distillation this being entirely distinct from the method known as " cracking " distillation, used for obtaining the greatest yield for burning oils. Fractional distillation is carried on in such a way as to yield a sweet, unburned residual oil, while distillates of higher boiling points, after being subjected to various other manipulations become what may be called insulating oils. The process is carried on in such a manner as to preserve the hydrocarbons in their natural form. It is probable that they are composed chiefly of bodies having the general formula $C_n H_{2n+2}$, though without doubt they contain also bodies made up of $C_n H_{2n}$.

This brief description gives an idea of the method used in obtaining insulating oils, together with their composition. The characteristics, such as flashing and burning points, viscosity, etc., depend, of course, upon the limits worked to during the process of distillation and refining. The following data, however, indicates what may be expected from a medium and from a light grade oil.

	Medium	Light
Flashing temperature	180° to 190° cent	130° to 140° cent
Burning temperature	205 to 215	140 to 150
Cold test	-10 to -15	-15 to -20
Specific gravity at 13.5 deg. cent	0.865 to 0.870	0.845 to 0.850
Viscosity at 40 deg. cent (Saybolt test)	100 to 110 sec.	40 to 50 sec.
Acid, alkali, sulphur, moisture	None	None

When free from moisture both have the same dielectric strength (45,000 to 50,000 volts, sine wave, between ½ in. discs placed 2/10 in. apart.)

The two most noticeable differences are in the fire and viscosity tests. The medium grade has a flashing temperature about 50 deg. above that of the lighter oil and a burning temperature about 60 deg. above. As to viscosity, a given quantity of the medium grade oil requires about two-and-one-half times as long to pass through a given orifice as does the light grade, conditions as to temperature, etc., of course, being the same.

It is usually customary for reasons of design to use the medium grade in apparatus such as self-cooled transformers, for example, in which the temperature of the oil at the top, due to overloads, etc., may reach fairly high values, the lighter grade being employed in apparatus such as water-cooled transformers, for instance, where the temperature may be more readily controlled. By this means the maximum possible temperature of the oil will in either case, be well below the flash and burning points. Under these conditions, too, it would require a long time for any external source of heat, such as a fire in the building, to raise the temperature to a point such that the oil would take fire and burn. Combustion would not be supported until the temperature had been raised above the burning point.

FACTORS WHICH CAUSE VARIATION OF DIELECTRIC STRENGTH

In taking up the question of dielectric strength and the factors which cause it to vary, it will be well, in order to avoid possible confusion, first to mention the considerations upon which all remarks and tests contained in the paper are based.

The voltage under which the oil breaks down, while under electric stress, depends upon the maximum value of the electromotive force, not upon the square-root-of-mean-square value. This is a long established fact. If, however, the shape of the electromotive force wave is not distorted during test, the ratio between maximum and square-root-of-mean-square values remains constant, and the latter may be used as a basis for measurements. This applies to all voltage values mentioned in the paper. The ratio between these two values, however, differs with every wave-shape, therefore, if the voltage is to be determined in the usual way from voltmeter readings, it is absolutely essential to have the shape of the e.m.f. wave well defined in order to correctly interpret the results. Moreover, the shape should remain the same throughout all tests and for all voltages. This condition existed during the tests mentioned in the paper. Square-root-of-mean-square values are recorded throughout.

All tests referred to here, were carried on under as nearly uniform conditions as possible. Sine-wave generators furnished the energy. Voltage variation was obtained by field control, in connection with series multiple windings on the low tension side of the testing transformer. No series resistance was used in the controlling system.

According to the A. I. E. E. standard for determining striking distances in air, a non-inductive resistance of one-half ohm per volt should be placed in series with each terminal of the spark-gap to prevent surges which might occur at the time of breakdown. It was suggested that the same precaution might be advisable in connection with the tests between various shaped terminals in oil. This was therefore carefully tried out with a disk and needle point. These terminals give a straight line curve up to a comparatively high voltage and therefore furnish a ready means of checking. Two sets of readings were taken, with increasing distances and for voltages up to 180,000. In one set, a water resistance adjustable to one-half ohm per volt was placed in series with each terminal, while in the other set, the transformer leads were connected directly to the terminals without intervening resistance. The results were identical. All other tests were therefore made without series resistance.

As far as possible, tests were made of uniform duration, low voltage first being applied and increased gradually until breakdown occurred, this usually requiring from five to twenty-five seconds depending on the magnitude of the voltage. In this way the question of time was largely eliminated, although it is probable that the insulating qualities of oil do not change materially under continued stress. This cannot be said to hold true, though, during short intervals, fractions of a second, for example, for in such cases time has an important bearing on the result.

For the sake of uniformity, the same frequency was used throughout, although it is believed that the variations in breakdown values are comparatively small over the range of present commercial frequencies.

The difficulties in carrying on an investigation of this kind are great, owing to the number of variables which may creep into the work. Even with apparently identical conditions, it is sometimes difficult to duplicate results. An enormous number of tests were therefore necessary in order to obtain reliable figures. Every point used in plotting the curves reproduced in the paper, is the result, not of one test, but of a great many, from which an average was taken.

SHAPE OF TERMINALS

The disruptive strength of oil depends to a large extent on the shape of terminals between which it is tested. For the sake of comparison, assume a uniform grade of oil which is clean and free from moisture. The voltage necessary to break through a given distance between two spheres is less than between two disks. That required to disrupt the oil between needle points is less than between two spheres, etc.

The reason for this is at once apparent from diagrams, Figs. 1 to 5. By referring to these and to the curves, Fig. 6, it will be seen that the shapes of terminals which cause the lowest breakdown values, are those which allow the greatest concentration of electric stress at one or both terminals. In other words, the terminal is surrounded by a zone of oil across which the stress is greater than in the next succeeding zone. The oil in the former is strained beyond its strength and breaks down. As soon as this occurs the stress is transferred to the next zone and this breaks, and so on across the entire gap. In actual practice, of course, these ruptures occur in such rapid succession that they are virtually simultaneous.

When the distribution of flux is perfectly uniform, as for example, between large disks placed near together, the average and maximum densities are the same. This no longer holds where the field is distorted, for in this case the stress across one section of the gap, as already indicated, may be very much greater than across the remainder. The distances between terminals may have been exactly the same, yet the second gap will break down at lower voltage because the oil in one section of it was strained beyond its breakdown point. This condition is illustrated in the diagrams, Fig. 1 to 5, which were drawn by first plotting the

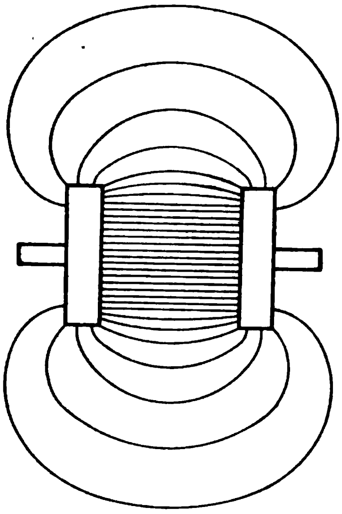

FIG. 1—Electrostatic field between disks

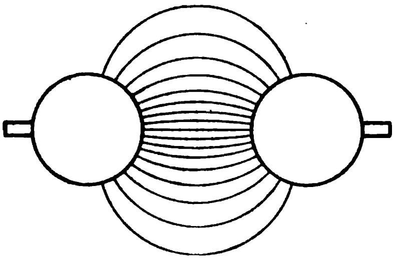

FIG. 2—Electrostatic field between spheres

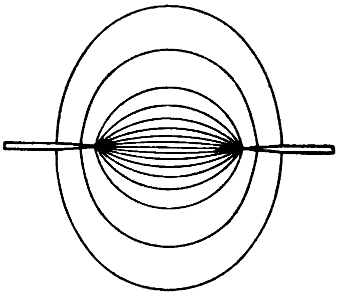

FIG. 3—Electrostatic field between needle points

equipotential lines and afterwards filling in the lines of force, the latter of course being normal to the former at every intersection. The accuracy of the lines was checked in a somewhat novel manner, as follows:

It is well known that the laws governing the distribution of magnetic fields of force are in many respects the same as those governing electrostatic fields. Iron terminals were therefore produced, resembling those shown in Figs, 1 to 5. These were placed, two at a time, on a plane of paper over the poles of an electro-magnet, and iron filings sprinkled onto the paper. The arrangement of the filings both as to direction and concentration, gave a very clear conception of the distribution of an electrostatic field of force between similar terminals in oil.

Again, referring to the curves, Fig. 6, attention should be called to the fact that the size of each pair of terminals was the same throughout the range of voltage covered. This means that the distribution of the lines of force in the electrostatic field changed slightly with each setting. In order to determine definitely therefore, the effect of shape of terminal on the breakdown strength of oil for a definite distribution of flux, it would be necessary to use many different sizes so that the dimensions of the terminals would bear a definite relation to the length of gap. The only curve which would not be affected, would be the one referred to needle points. The distribution of the lines of force in this case would be the same for all distances, unless perhaps the rounded shape of the points would have an effect at extremely small distances, small fractions of an inch, for example.

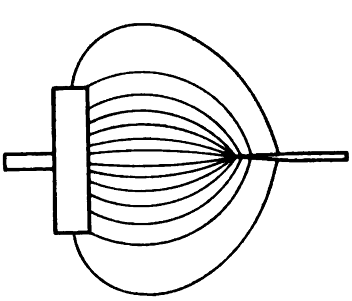

FIG. 4—Electrostatic field between disk and needle points

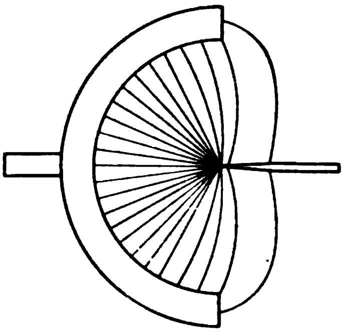

FIG. 5—Electrostatic field between hollow hemisphere and needle points

OIL TESTING APPARATUS

The two standards now most commonly used for oil testing are composed of pairs of terminals of definite shape, arranged in a suitable receptacle for holding the oil.

In one of these, the testing terminals consist of ½ in. diameter brass balls fastened to 3/16-in. rods. These are placed vertically in a glass tube and arranged so that they may be adjusted for different distances, 0.15-in. usually being considered standard. Average dry oil should not break down at less than 30,000 volts.*

The other of the two mentioned standards is composed of two ½-in. brass disks, mounted on ⅜-in. rods and arranged horizontally in a receptacle for holding the oil. The disks may be adjusted for different distances although, 2/10-in. has been adopted as standard. Dry oil should not break down in this at less than 45,000 to 50,000 volts, with a sine-wave e.m.f.

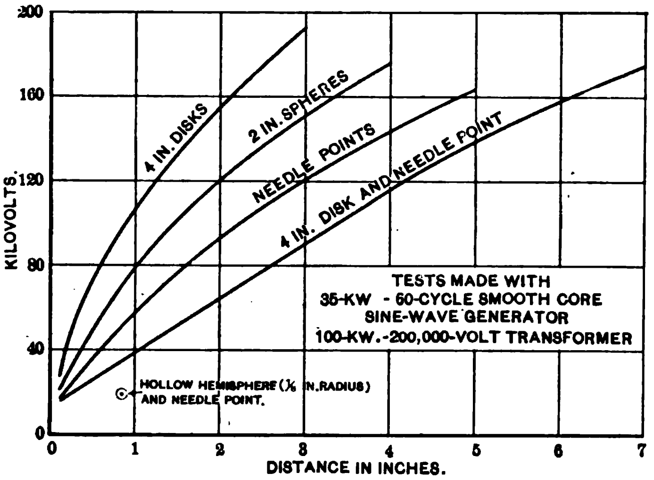

FIG 6—Disruptive voltage of dry oil measured between variously shaped terminals

The disk form of gap was employed in making the various tests mentioned in the paper. It was preferred because of its uniform electrostatic field, and also on account of the fairly large amount of oil which would be subjected to test.

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* Articles by C. E. Skinner, on "Transformer Oil," *Electric Journal*, May, 1904; and by S. M. Kintner on "The Testing of Transformer Oil," *Electric Journal*, October, 1906.

Particles of moisture or other impurities could be detected over a considerable area.

EFFECT OF TEMPERATURE

The dielectric strength of oil does not vary greatly with moderate changes in temperature. One sample tested, for example, stood an average of 52,000 volts at 60 deg. cent. before breaking, and 45,500 or only 10 per cent less, at 20 deg. cent., while at slightly above zero its value had dropped only to 44,000 volts.

Upon congealing, however, as the temperature drops below the freezing point of the oil, the dielectric strength increases with great rapidity, in some cases reaching a value 60 to 80 per cent higher than that just before the freezing point was passed. In the example just referred to, the dielectric strength rose to approximately 77,000 volts, or an increase above 44,000 of 75 per cent.

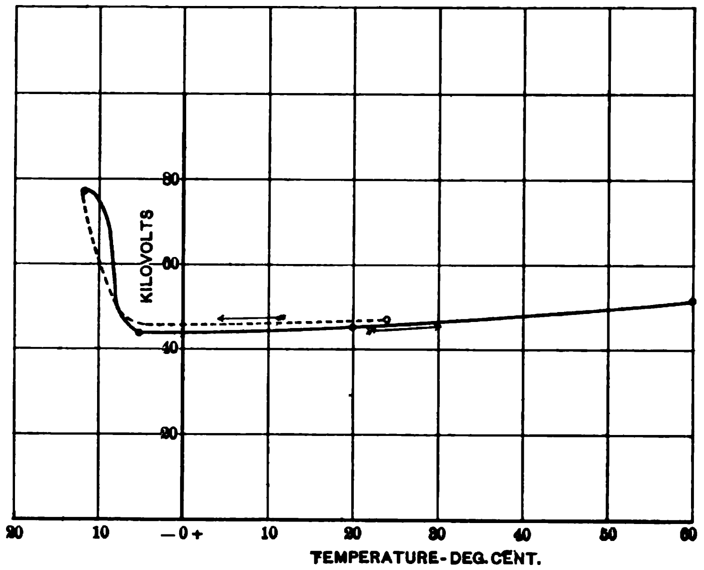

FIG. 7—Effect of temperature on dielectric strength

On heating, the strength drops to the value it had just before freezing, although it is usually necessary to raise the temperature considerably above the freezing point before this occurs. In other words, changes in strength lag behind changes in temperature. Continued heating will finally restore the dielectric strength to its initial value. The accompanying curve, Fig. 7, indicates the cycles through which these changes take place. This may be considered typical for one kind of oil. The values for other kinds are quite likely to vary considerably from those shown by this curve, but the manner in which the changes occur are much the same.

It should be explained that the solid part of the curve was plotted from actual test values, also the beginning and end of the dotted portion. The path followed by the dotted part indicates what may be expected to occur during the first part of the cycle. (As no refrigerating machine was available, it was necessary to make the tests last winter, and but a limited number of points could be obtained.)

EFFECT OF MOISTURE

Oil, as far as dielectric strength is concerned is extremely sensitive to moisture. As already stated, even the slightest amount is detrimental. It is therefore, of the greatest importance not only to remove every trace before putting the oil into service, but also to maintain this condition of dryness under continued operation.

The accompanying curves, Figs. 8 and 9, still further emphasize these facts, indicating, as they do, the reduction in dielectric strength for gradually increasing percentages of moisture. The first was plotted from results of tests on a medium grade and the second from tests on a light grade oil.

It is often difficult to determine how moisture can be taken up by oil contained in apparatus having fairly tight covers, yet this frequently happens, nevertheless. Some of the moisture may settle to the bottom, where it can be gotten rid of by simply drawing off a limited quantity of oil. A certain percentage on the other hand, will be retained and kept in circulation. The percentage which may be safely allowed naturally depends to some extent on the voltage of the apparatus, but that this amount must be extremely small is apparent from the curves just mentioned. Even 3/100 of one per cent, reduces the dielectric strength to three-quarters. (This means but five or six drops of water per quart of oil.) With the addition of 1/100 of one per cent of moisture, the strength is reduced to one-half.

It is evident from the above that the importance of dry oil cannot be over estimated. The apparatus into which it is to be placed, including the interior surface of the tanks, should be thoroughly dried, and not only should the oil be tested for dielectric strength before it is put into service, but at stated periods afterwards, as well. Oil found below the desired value should be dried or replaced with new.

As to the various methods which have been used for detecting moisture, the following may be mentioned:

A quantity of oil may be placed in a tank and allowed to settle for a week or ten days, at the end of which time a sample may be taken from the bottom with a glass tube, or a thief. If much water is present, the eye will readily detect it.

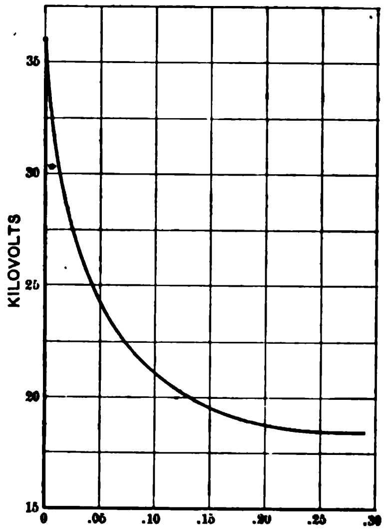

Fig. 8—Influence of moisture on dielectric strength of oil of medium viscosity

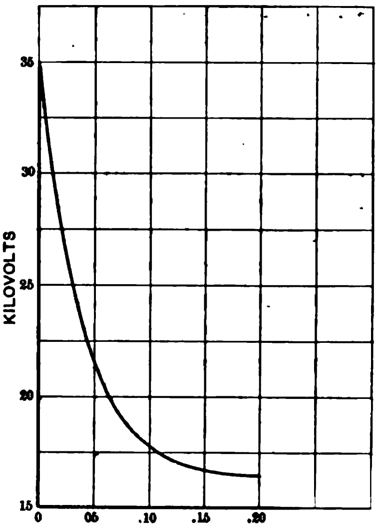

Fig. 9—Influence of moisture on dielectric strength of light oil

A piece of cold glass plate may be held over a sample and the latter heated to the boiling point of water. Any moisture driven off will be condensed on the plate.

Anhydrous copper sulphate is sometimes used, a small quantity being shaken with the oil to be tested. If it contains moisture in any considerable quantity, a slightly blueish color will result.

Still another method is to thrust a red hot nail or piece of wire into a sample of oil. A crackling noise will be heard if moisture is present. If dry, there will simply be a puff of smoke.

A similar test can be made by placing a sample of oil in a small porcelain dish, and heating it over a flame. If moisture is present a sharp crackling noise will result, much the same as with the hot nail or wire just referred to.

Of all the methods which have been used, however, the dielectric strength test is the most satisfactory and reliable. Moreover, it is extremely sensitive so that even the smallest percentage of moisture may be detected.

This last method is the only one which can be recommended as being absolutely sure. The one mentioned just before this, *i. e.*, heating the oil in a porcelain dish is the next most reliable, but even this is not certain. (A number of tests were made on various samples to determine the accuracy of this method, and not more than 60 per cent of the results were correct. It may be of value, occasionally, however, when no high voltage testing outfit is available). The hot wire method would come in the same class.

The other tests mentioned are only of service when large quantities of moisture are present. Otherwise, they are not reliable.

METHODS OF DRYING AND FILTERING OIL

In view of the importance of dry oil, many methods for removing moisture have been devised. Some of these are suitable for laboratory only, and are not practical for commercial purposes. Others are quite satisfactory for use in the shop and testing department, but on account of the expensive apparatus required, cannot well be employed for installation work or in connection with any but the largest power plants. Still other methods have been tried out and then laid aside, either on account of cost of operation or length of time required for treatment. As a result, there are but few methods which are of much service commercially. It may be well, however, to mention all, some briefly, others at greater length, depending upon their importance. The following will be considered.

Drying by means of:

(1) Chemicals,
(2) Heat,
(3) Heat and vacuum,
(4) Heat and air,
(5) Settling,
(6) Centrifugal separators,
(7) Paper filters,
(8) Miscellaneous.

It should be noted here that the first five methods mentioned above, are suitable only for removing moisture, and do not remove dirt or other foreign matter. The next two in the list purify as well as dry. Sometimes one method, sometimes a combination of several methods have been used successfully.

Chemicals. Of the various chemicals used for dehydrating oil, calcium chloride has given the most satisfactory results, although calcium oxide, (unslacked lime) is also used extensively and gives good results. Calcium carbide and metallic sodium, as well as other agents have been tried with varying degrees of success.

The accompanying curves, Fig. 10, indicate the comparative rates at which these materials remove moisture from oil. It will be noted that calcium chloride required seventy hours; metallic sodium 115; calcium oxide 165; and calcium carbide 260 hours, to bring the oil from a dielectric strength of 7,000 volts up to 30,000. (Tests made between ½-in. disks placed 2/10-in. apart.)

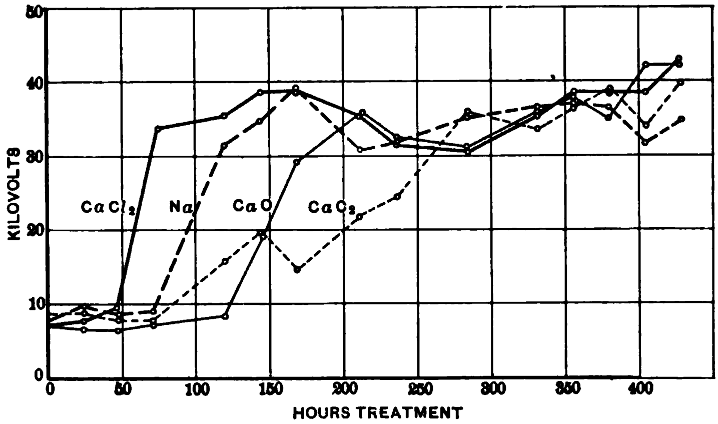

FIG. 10—Effectiveness of oil drying material
Calcium chloride, $CaCl_2$; Metallic sodium, Na; Unslaked lime, Ca O; Calcium carbide, CaC_2

The tests were made first by mixing a small amount of water with a quantity of oil, separating into four parts and adding respectively the four drying agents; six per cent by weight in each case. The drying materials were chemically pure, and in order to expose the same surface to the oil, they were broken up into about ¼-in. lumps. The samples were thoroughly shaken and allowed to stand 24 hours after which they were tested.

The process of shaking, allowing to stand, testing, etc., was repeated every 24 hours, until the oil had returned to its initial dielectric strength.

Calcium chloride required the least time of all.

Metallic sodium came next in order of time. Its use, however, is considered dangerous, inasmuch as it unites with water to form hydrogen and caustic soda, and if a large quantity of water is present the reaction might cause sufficient heat to ignite the hydrogen. Moreover, the caustic soda formed dissolves in oil and tends to soften insulating materials, such as varnish or gum compounds.

Calcium oxide required still longer time to absorb the moisture as was also the case with calcium carbide. The latter also has the disadvantage that it gives off a highly inflammable gas, acetylene, when it comes in contact with water.

Continuing the subject of calcium chloride as a dryer, it may be of interest to mention the results of several tests made to determine the best method of utilizing such material for removing moisture from oil in transformer tanks, when the natural circulation of the oil alone is relied upon for bringing all portions in contact with the calcium.

Three tests were made, the oil in each instance being placed in a fairly large sized tank, and maintained at a temperature of about 80 deg. cent. by means of a wire-coil rheostat at the bottom. One per cent of water was added to the oil and thoroughly mixed with it for each of the three trials. In the first trial no calcium chloride was used, the test being made to determine the length of time required to bring the oil back to a given dielectric strength by settling only. In the second trial, a quantity of calcium chloride was placed at the bottom of the tank, and for the third trial the chloride was placed in a perforated metal tube, suspended in the tank midway between the top and the bottom.

At the beginning of each trial, the oil measured approximately 7,000 volts, (tested between ½-in. disks, placed 2/10-in. apart.) The runs were continued until the oil at the top of the tank reached a strength of 50,000 volts, (that at the middle measured 45,000 volts, or over.) Ten days were required in the first instance, four in the second and two in the third. The most effec tive method used therefore, was that in which the chloride was suspended in the center of the tank. Whenever this method is used, however, care must be taken to provide a suitable receptacle for collecting the water and wet chloride, and yet allow free contact between the fresh chloride and the oil.

A method which gives still better results as regard time required, is one which provides for the forcing of oil through a receptacle containing calcium chloride or calcium oxide, (unslacked lime.) The quantity of oil which can be dried per hour is thus greatly increased. It is usual in connection with this treatment, to complete the process by forcing the oil through dry sand. This removes all traces of dirt and foreign material and prevents any particles of lime which may be held in suspension, from passing through into the receiving reservoir. Bone black or Fuller's earth are sometimes used in connection with this process, in case it is desired to remove coloring matter from the oil as well as other impurities.*

Heat. Heat is frequently employed for removing moisture. It is sometimes applied to the outside of the receptacle containing the oil, and in other cases is introduced by means of steam coils or an electric heater. The last mentioned arrangement is preferable, and is usually more convenient. In all cases the temperature maintained is about 105 deg., or, in other words, slightly above the boiling point of water.

This process at best is slow. It must be watched with great care, and there is always the danger of injuring the oil from over-heating. Long continued overheating will cause a deposit to be thrown down and is also liable to change the nature of the oil by driving off some of the lighter hydrocarbons.

Heat and Vacuum. The danger of the overheating mentioned above may be practically overcome by removing the air pressure from the drying receptacle and employing heat as before. The reason for this is that water boils at much lower temperature in vacuum than ordinary air pressure. Thus, in a 27-in. vacuum, boiling occurs at 46 deg.; in a 28-in. vacuum at 38 deg., and in a 29-in vacuum at 25 deg. cent., etc.

This process may be still further facilitated by allowing dry air to bubble slowly through the oil. The air may be readily freed from moisture by first passing it through some dehydrating substance, such as calcium chloride or unslacked lime.

Heat and Air. Perfectly dry air has also been used to advantage. This may be forced through numerous openings at the bottom of the tank and allowed to bubble up to the surface.

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* Article by S. M. Kintner, "The Treating of Transformer Oil," *Electric Journal*, October, 1906.

The oil in the containing tank may, or may not, be heated, although heating naturally facilitates the operation. The air may be dried by passing it through calcium chloride or other drying agents.

Instead of using air alone, the air and vacuum process may be employed, as outlined at the end of the preceding paragraph.

Settling. When oil contains a large quantity of water it may be gotten rid of almost entirely by allowing it to stand for some time undisturbed. The water as well as some of the impurities gradually settle to the bottom, leaving a dry oil to be drawn off from the top. The process usually requires a number of days, and herein lies the greatest difficulty in its use.

Centrifugal Separation. The different specific gravities of oil and water make it possible to separate the two by centrifugal action. It is extremely difficult to remove all of the moisture by this means, but it serves a good purpose in taking out a considerable portion of it when the oil is extremely damp. The remainder, however, may be removed by means of a filter within the upper part of the machine, so that virtually both steps in the process take place at the same time. The operation may be accomplished by a standard cream separator like the De Laval. The damp oil is fed into the top and passes down into the center of the rapidly revolving element. The centrifugal action forces the water, which is the heavier of the two, toward the outer casing, where it may be drawn off like skim milk. The oil, like the cream, passes into a central chamber and then up through sheets of filtering material into a receiving reservoir, from which it may be drawn off for use. During the first part of the operation, all but about one-tenth of one per cent of moisture may be removed, while the small amount remaining, is taken out by the filter.

Damp oil has in this way been raised in dielectric strength to a value of between 40,000 and 45,000 volts, (measured between ½-in. discs, placed 2/10-in. apart.)

With a medium sized machine it is possible to dry and clarify from 50 to 60 gallons per hour, provided the oil is not in too poor condition to start with.

Paper Filters. It has been known for some time that ordinary filter paper, such as is used in chemical laboratories will allow oil to pass slowly through it, but will not allow water to pass. This principle has recently been employed on a larger scale in what is known as an oil dryer and purifier. This piece of apparatus consists of a press for holding the paper, a pressure pump and an operating motor, together with necessary piping, valves, gauges, etc.

The most interesting part of the outfit is made up of a number of alternate grids, and chambers arranged in such a way that square sheets of blotting paper may be placed between them and the entire device bolted together. By means of suitable channels the oil from the pressure pump is led into the chambers, forced through the blotting paper and finally discharged into the receiving tank. The blotting paper allows the oil to pass, but retains all moisture and impurities thus raising the dielectric strength to values as high as 60,000 to 70,000 volts, (measured between ½-in. disks, placed 2/10-in. apart.)

With a moderate sized press, 600 gallons of medium grade oil may be treated per hour, and twice this amount of light oil, it merely being necessary to replace the blotting paper occasionally, once every half-hour to an hour is sufficient with oil in fair condition.

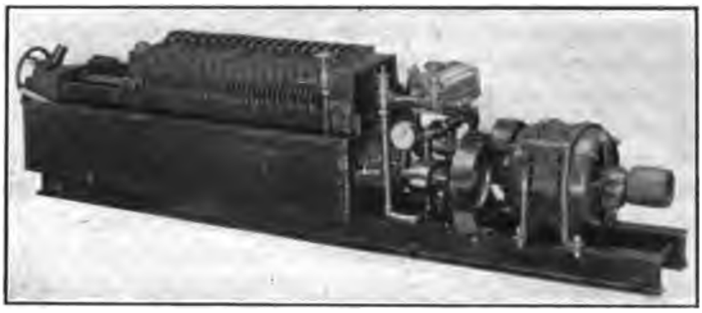

FIG. 11—Oil drier and purifier

Not only can such an outfit be used for first drying and purifying oil before it is introduced into high voltage transformers, but it may also be employed from time to time while the transformers are in operation. In such cases the oil is taken from the bottom of the transformer tank, forced through the filter press and back into the transformer at the top of the tank, this process, of course, being continued until the oil reaches the desired dielectric strength.

The general construction of the outfit is shown in Fig. 11.

Miscellaneous Methods. Capillary action has been made use of to some extent in freeing moisture from oil, also electrostatic force. Sponges have been tried and found to give fairly good results. The expense however is prohibitive, as only the very best grade of sponges are at all suitable. For removing impurities sand gives excellent results. Cheesecloth is also frequently used.

PRESENCE OF SULPHUR AND PARAFFINE

While the presence of free sulphur has an effect on the dielectric strength of oil, the greatest danger lies in the fact that even in minute quantities it vigorously attacks the copper.

In time, conductors have been known to be completely severed on account of sulphur alone. It may be detected very readily by dipping a small polished wire into the oil, which has previously been heated, and allowing it to remain until it becomes black. The time required for this to occur may be judged from the following table, which is made up from results of tests on oil heated to 85 deg. cent.

Per cent sulphur	Time required to blacken copper wire
1/10 of 1 per cent	2 to 3 minutes
1/100 of 1 per cent	30 minutes
1/1000 of 1 per cent	15 to 20 hours
1/10000 of 1 per cent	Uncertain

In some oils small amounts of sulphur exist in very strong chemical combination. These however, have not been proved to be deleterious, probably because the combination is so strong that it is difficult to break it up.

As to paraffine, there must be freedom from solid material of this kind in solution; otherwise, particularly in water-cooled apparatus, it might be frozen out of solution and result in clogging of the oil ducts.

INSULATION RESISTANCE AS AN INDICATION OF DIELECTRIC STRENGTH

It has sometimes been thought that insulation resistance of oil is an indication of its dielectric strength. The accompanying curve Fig. 12 will show that this is by no means always the case, unless temperature is also taken into consideration. It indicates what is experienced every day in heating transformers. With increase in temperature the insulation resistance falls very rapidly, while the dielectric strength of the oil gradually increases until conditions become constant.

If moisture is present, in a transformer, for example, the insulation resistance may drop to a very low value when the oil is heated, and then rise for a time as the last traces of moisture are driven off.

It is only safe to assume that everything is dry when the insulation resistance becomes constant and remains so for several hours. Even this final value, though, may be far below that obtained when the oil was cold.

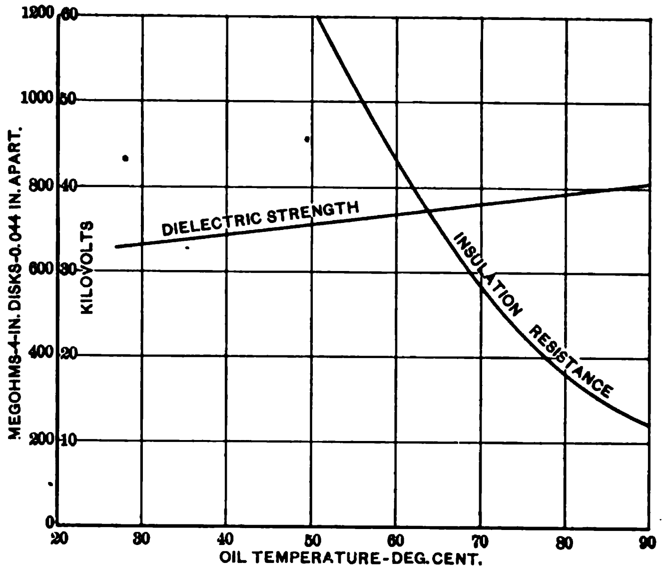

FIG. 12—Variation of dielectric strength and insulation resistance with temperature

SUMMARY

Having first laid down the conditions which an insulating material must fulfil in order to give satisfactory results, we have shown that oil best meets these provided it is used within definite limits. The limits have been found only after making a careful study of the more important characteristics, and it has only been by a systematic investigation of the chemical and physical properties that oil has gradually been made to attain its present state of superiority. It fulfils the ideal conditions so well that it is almost universally used in spite of the fact that it requires unusual care in its treatment and handling.

It is hoped that the paper will aid in giving a clearer understanding of the various properties, not only that such treatment and handling may be made comparatively simple, but also to assist in the selection of oil and its use.

In closing, the writer wishes to acknowledge the valuable assistance received from Dr. C. P. Steinmetz, Mr. A. B. Hendricks, Jr., and Mr. J. A. Capp, all of whom have taken an active interest in the tests, experimental work and study of the results.

DISCUSSION ON "DISRUPTIVE STRENGTH WITH TRANSIENT VOLTAGES", "THE ELECTRIC STRENGTH OF AIR" AND "DIELECTRIC STRENGTH OF OIL". JEFFERSON, N. H., JUNE 29, 1910.

D. B. Rushmore: Mr. Whitehead in his paper says something which is perhaps more true than many people realize: "As a result of the increase in values of transmission voltage, however, and of improvements in high voltage apparatus and line insulators, the electric strength of air has become a limiting factor in the long distance transmission of power." It is only of a very recent period that this has been true. It is, however, of great interest and import. In the somewhat old problem of transmitting power, one obstacle after another has been overcome until at present we are confronted with the effect of the insulating properties of air, and what action will be taken with regard to overcoming the obstacles presented by it is a question of much importance at the present time. Until very recently, line insulators were the limiting feature, and at 60,000 volts the standard form of insulator was operating near its limitations. With the new suspension insulators, however, the line can be insulated far beyond the point at which the dielectric strength of air will stand. The question of altitude in transmission lines is also becoming important, because of the lower dielectric strength of air at the higher altitudes. The physical phenomena which take place when corona has formed are extremely interesting, and a considerable number of points arise in connection with it. For instance, it is not quite clear without fuller understanding, why corona should cease to be formed by the lower voltages than that at which it begins.

The phenomena described in the paper are those which are of immediate interest to many members of the Institute. To take an example, a line which was to operate at 60,000 volts had the design of the insulators carefully worked out so that they would always flash over before puncturing. A number of times, however, lightning punctured these insulators and the dielectric time-lag of air was used to explain the occurrence. Also many operating engineers are familiar with the slight blackening of the bright copper wires in their stations, due to the effect of corona formation.

The problem of how best to perform experiments of this kind is a difficult one. We all like to see the conditions surrounding such investigations as nearly as possible like those under which the application of the results will be made, such as the interesting work carried on by Mr. Mershon some years ago on outside commercial lines. It is, however, extremely difficult to obtain exact data in this way, and it would seem that the basis for our engineering recommendations must to a large extent be the result of experiments carried on in the Laboratory.

The relation of power or energy to breakdown or ionization is not clear, and the effect of frequency on such dielectric failure still remains a subject for discussion. The point most deserving of attention is that the future progress of the art depends very largely on the results of the study of the properties of dielectrics. The characteristics of this class of material bring about the limiting features in high voltage power transmission.

V. Karapetoff: Those familiar with the history of the theory of elasticity and of the mechanical strength of materials will find it quite similar to the history of practical electro-statics. During the early stages of the development of civil engineering the engineers who needed to know the strength of columns, bridges, etc., tested them in their actual complicated shapes. The result, therefore, did not characterize the materials, but only certain objects of definite dimensions made out of these materials. Knowing the strength of a column or of a beam of a certain size, it was not possible to predict the strength of a column or of a beam of a different cross-section and of a different length. Then, gradually, a theory of resistance of materials was developed and formulae established into which the elastic coefficient of a material, the dimensions of an object made out of this material, and the given forces entered as independent factors. The next stage in the theory was to combine various stresses and to combine the resultant strains. In most structures and parts of machines there is usually more than one set of stresses (for instance a normal stress and a shear), and unfortunately stresses are combined according to a different law than the resulting strains. Finally the fact became clear that it is the resulting *strain* and not the stress that limits the safe load of a piece of material—I am speaking of mechanical strength now—no matter by what combination of stresses the strain is produced. As the last step, the theory was extended to include the action of *dynamic* loads or what we call in electrical engineering *transient* loads. In bridges, in reciprocating engines, and in the many other cases loads are not steady, they are intermittent; kinetic energy and inertia enter therefore as disturbing factors.

A similar development took place in applied electrostatics. Our predecessors started with a theory of charges acting at a distance. Naturally, with such a wrong assumption, not much progress was made, because the phenomena take place in the dielectric and not on metallic surfaces.

After Faraday and Maxwell had cleared the way for a correct interpretation of electrostatic phenomena, and after it had become necessary for engineers to take into account the dielectric strength of materials, a new impetus was given to electrostatic experiments. But as in the case of early experiments on columns, beams, etc., " practical " electrical engineers still use electrodes of all kinds of fancy shapes, from which the dielectric strength of dielectrics proper cannot be conveniently calculated. Knowing, for instance, the striking distance between two pointed electrodes, it is impossible to calculate the striking distance between electrodes of a different shape, or to determine the critical voltage with the same electrodes at a different distance. The question is, however, being gradually put on a more rational basis; it is at present clearly understood by physicists and by many engineers that the striking distance per centimeter of air-gap between needle points really does not mean much, as regards the dielectric strength of air. Experiments must be preferably made on large (practically infinite) parallel plates, in which case the stress in the dielectric is the same at all points. Or, else, electrodes must be used of such a shape that the true strains (critical dielectric flux density) can be calculated from the striking distance. Concentric cylinders are convenient for the purpose.

I wish to refer to the sketches Figs. 1, 2 and 3 of Mr. Tobey's paper, which illustrate my point. The sketches show the difference between a uniform dielectric field in the case of parallel plates, and non-uniform fields in the case of sharp points on spheres.

In a non-uniform electrostatic field it is necessary to consider the actual stresses from point to point, because the air is not broken down simultaneously at all points. It is possible to break down certain portions of the air nearest to the electrodes, to ionize it, to make it a conductor, without producing a jump-spark. The air so ionized becomes a part of the electrode, so that the break-down finally occurs between new shapes of electrodes. This leads to the consideration of the quantity usually called the electrostatic capacity between two electrodes, but which ought to be more properly called the *permittance of the dielectric*. By using proper values of permittance and " permittivity " of the dielectric, calculations of the dielectric strength of insulation are put on the same scientific bases as calculations of conductors of non-cylindrical shapes.

At present we are not yet advanced far enough to be able to calculate the distribution of electrostatic stresses in all cases, but in the simplest cases, for instance, such as is presented by Dr. Whitehead, or in the case of two spheres, it is possible to calculate the actual stresses and their distribution. It is not the average strength of the air, considered as a mass, that interests the engineer, but the *weakest point* at which the air breaks down. The safety of insulation must be considered with regard to this weakest point, the same as the civil engineer figures out the factor of safety of the weakest part in his bridge. And fortunately the electrical problem is simpler than the corresponding problem in the theory of elasticity, because there we have two kinds of stresses, normal stress and shear, while in dielectrics there is but one kind of stress. I do not know what kind it is; perhaps it is some kind of shear between positive and negative electricity; at any rate we have to consider only one kind of stress.

Now we come to the last stage, the same as civil engineers had to face, namely, the effect of dynamic loads, of transient voltages. The paper by Mr. Hayden and Dr. Steinmetz represents the results of a pioneer investigation in this field. Let us consider their experiments in the light of a mechanical analogy, that of an elastic rod or a column suddenly subjected to a normal stress by a released weight. Is it correct to say that the weight is instantly balanced to its full extent by elastic forces in the rod? To me such an assumption contradicts the laws of mechanics of elastic bodies.

In order to produce an elastic reaction a strain or a deformation must first occur in the rod. The rod can resist only (1) as the result of such a strain (elasticity), or (2) by opposing an acceleration of its parts (inertia). In the case under consideration there is no initial strain in the rod, and in order to produce it parts of the rod must be accelerated layer by layer. At the very first instant the load is balanced by a very high acceleration of a very small part of the mass of the rod adjacent to it; then the next layers are accelerated so that we get the effect of a travelling compression wave. Only after a certain displacement has taken place the load is balanced in part or in full by the elastic forces. Hence this paradox that with a very short application of the weight, that corresponds to our transient voltage, the column or the rod can seemingly support without being destroyed a heavier load than with a load applied gradually. Is it not more logical to suppose that the molecular strain, the *actual strain* at which the material breaks down, is the same in both cases? Only in the case of a transient application a part of the load is balanced by the acceleration of the mass and has no time to produce elastic stresses, before the load is removed.

It seems to me that the results obtained by Mr. Hayden and Dr. Steinmetz must be interpreted in the same light. I cannot conceive how a voltage of say 100 kilovolts can be applied suddenly to a neutral dielectric, that is to say to a dielectric which is not strained. The action must be equal to the reaction, and a dielectric which is not strained can produce no electrostatic reaction. It can react only electromagnetically, by means of displacement currents in it, or in the other parts of the circuit. I am willing to grant that the voltage calculated by the authors was actually induced in the high-tension windings of the transformer, but it does not follow from this that at the very instant of the closure of the primary switch this full voltage acted across the air-gap, producing *static* stresses in the dielectric. The electromagnetic inertia effects are predominant at the first instant.

The slope of the voltage wave is very steep at the first instant; therefore, even a very small magnetic leakage between the two windings of the transformer, a leakage negligible with ordinary frequencies, must have produced an enormous counter-electromotive force. I am inclined to think that at the first instant the voltage between the electrodes was practically equal to zero. The unstrained dielectric acted as a short-circuit, and the applied voltage was balanced by the reactance counter e.m.f. We must remember that the rush of current at the first instant is tremendous, in order to produce the required displacement in the dielectric. There could have been also a considerable magnetic field in the dielectric proper. We have in reality a much more complicated phenomenon, *electromagnetic* as well as *electrostatic*, than it appears on the surface. It is hardly scientific to say that we simply have 100 kilovolts momentarily applied to air or oil, and that momentarily these dielectrics can support more than with a steady application of the voltage.

We must be particularly careful now, when we just begin to understand the full meaning of these phenomena, not to describe them in a " short-hand " way, but to specify carefully the actual physical relations. Without this precaution, busy practitioners are only too prone to misunderstand the results, and to apply them in cases for which they were not intended at all.

Percy H. Thomas: Professor Whitehead's paper suggests many questions that I presume he is not in position to answer as yet, but there are a few points which I think would clear up some matters.

Professor Whitehead has apparently made a very desirable advance in having devised a method for the study of corona and allied phenomena in which he can eliminate all variables which he does not control. His tests, being laboratory tests, and made under somewhat limited conditions, do not tell us everything about corona, but apparently he has succeeded in controlling all the variables actually present in his tests, so that he can absolutely reproduce his results on different days and under quite different circumstances. With such a result realized, it is possible to add another known variable, and get its effect, and so on step by step.

I ask Dr. Whitehead if he will tell us something concerning the electrical conditions at the ends of his tube.

I would ask Dr. Whitehead if it is possible that the peculiar action of small wires in giving the apparently high dielectric strength for air could be due to the fact that near the surface of the small wire the strain is changing rapidly. That is, the volume of air that is subjected to the maximum stress is very much more limited than where the wire is larger; the potential gradient being much sharper in the case of the small rods.

I would ask whether the air which passes through the tube coming from the wire at the time of the formation of corona is ionized in the sense that there are positive and negative charges therein equally balanced, or whether it comes away with a predominant positive or with a predominant negative charge, and if so, which? Also whether he has tried any other gases than air.

Another point, in the visual observation of the corona through oscillographs, has he observed both positive and negative waves, direction being taken with reference to the test wire—that is, were observations made with the positive potential on the inner wire or the negative potential on the inner wire, or with both? If so did any difference appear?

One other question—I would ask how the actual arc, that is, the complete break down, follows after the ionization first begins, that is how wide a range of voltage, for example, exists between the point where you can first observe a rapid dropping of the electroscope, and formation of the actual arc.

A. E. Kennelly In regard to one particular point in these very interesting papers, Dr. Whitehead emphasizes the fact the electric intensity at which disruption appears is greater for small wires than for large wires. A suggestion for the reason of this remarkable phenomenon may be offered tentatively. We know, referring to the properties of the magnetic field for a moment, that a small magnetically polarized iron particle, or iron filing, is not acted upon by any magnetic force of translation—any bodily moving force—when subjected to a uniform magnetic field, or a magnetic flux distribution acting in parallel straight lines. There are forces of rotation, couples, or torques, but no forces of translation. When, however, the magnetic field is not uniform but divergent, the iron filings are subjected to translatory forces as well as couples, and are pulled bodily towards the denser parts of the field. This effect may roughly be described by saying that the magnetic pull, in the denser part of the field, on the attracted pole, is less than the opposing push, in the weaker part, of the field on the repelled pole. In fact, we know that the pull of a divergent field $\mathcal{H}$ upon a spherical iron particle or spherical iron filing depends upon the product $\mathcal{H} \cdot \frac{d\,\mathcal{H}}{d\,s}$, where $\frac{d\,\mathcal{H}}{d\,s}$ is the greatest space rate of change of the field.

Now returning to the electric field, if we may assume that a molecule of gas subjected to an electric field is polarized thereby, then the molecule will be subjected to a couple or aligning force; but if the electric field is uniform, there will be no pull, or force of translation, on the molecule. If, however, the field is convergent, a force of translation will exist as well as the couple, and the molecule will be pulled towards the denser part of the field. In the case of an electrified round wire, the field will be radially divergent from its surface, and the divergence will be numerically greater, the smaller the wire's diameter. We should, therefore, expect air-molecules to be drawn in towards the surface of the wire, and to crowd together near that surface, just as though the atmospheric pressure were locally increased in this vicinity. If such a local increase of air-density occurred around and near the surface of a wire, the electric intensity required to produce disruption should be increased, as it increases with the atmospheric pressure, and the increase should be greater the smaller the wire. I tried the experiment recently, with Dr. G. W. Pierce, since reading Dr. Whitehead's paper, of electrifying a two-millimeter wire running down the axis of a glass tube and observing whether the pressure of the air, within the tube as a whole, became thereby altered with respect to the pressure of the air outside the tube. We were unable to detect any such effect. Consequently, although the effect above suggested might occur, and might yet be masked in this experiment by opposing actions, yet it must be admitted that thus far, the suggestion is not supported experimentally.

W. H. Pratt: There is one suggestion which comes to me in connection with the second paper, which has read. The results quoted with moist air are apparently in disagreement with certain other measurements which have been made. May it not be that moist air, as we find it in the open, at times contains electric nucleii due to the partial re-evaporation of condensations that have occurred around these electric nucleii, and hence the moist air, at such times, is really somewhat conducting, whereas in the experiments that were outlined, the moisture was added to the air in such a way that it certainly would not be expected to be conducting.

E. E. F. Creighton: Two of the big problems in the transmission and distribution of electrical energy are the lightning protection of the transmission circuit and the suppression of troubles from internal surges of electrical energy. The dielectric spark lag and the spark energy enter into both problems and most vitally in the latter. Speaking of internal surges only, it has been noted here and there all over the country that transformers and generators would fail at some internal part of the winding. On any particular system these failures are rather infrequent, but the aggregate is considerable. Some time ago this problem of internal surges was confused by the presence of end turn effects. Modern designers have eliminated the end turn failures by heavily reinforced insulation. This leaves the problem of caring for internal surges distinct and prominent. The conditions of cost are not such that a designer may place everywhere in the windings, as he does on the end turning, an insulation that will stand a test pressure of 6,000 to 20,000 volts when the dynamic voltage normally present is only ten to twenty volts. The amount of energy in these internal surges is usually small. The excellence of a design taking these factors into consideration would never be casually apparent, yet they would be vital. With these practical features in view, the theoretical and experimental studies made by the authors assume a great importance. Careful measurements are the life of further progress. A simple method of test is given which can be extended easily to further studies.

The speaker has had occasion to study a particular feature of the dielectric spark lag of protective apparatus, with the object in view of getting rid of it. We were surprised to find lags extending to several seconds. To the speaker's knowledge this long lag has never been observed before. These data have a strong bearing on the subject of the paper. Among several other things, the dielectric spark lag depends on the excess voltage above the voltage which would cause a spark to pass if applied for a long time, theoretically for an infinite time. For brevity, call this, excess voltage the super-spark potential.

As would naturally be expected, the relation between the super-spark potential and the time, is hyperbolic. For very great superspark potentials the time interval before the spark passes becomes only a few milliseconds, or may even go down into the microseconds.

In the curve herewith reproduced the measurements were taken by the simple method of the oscillograph. Direct current potential was applied to a gap and the time interval measured between the application of the potential and the beginning of the current in the spark. The points of slight super-spark potential deviate very little from hyperbolic curve—in this particular case $x\ (y-23) = 1780$. (See Fig. 1). But the points at considerable super-spark potential are somewhat variable, showing an erratic behavior not understood at present. At only 35-volt super-spark potential, the lag is 200 milli-seconds. At 250-volt super-spark potential, it is 20 milliseconds. At 300-volt super-spark potential it is 6 milliseconds.

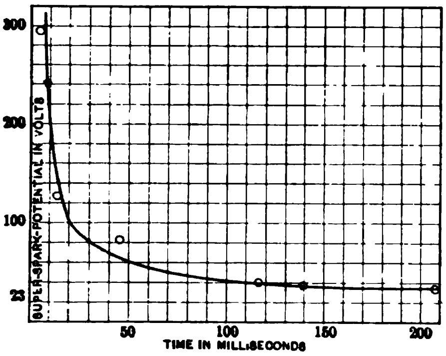

FIG. 1.—Super-spark potential curve. The points are taken by measurement and the curve is the hyperbola $x\ (y-23) = 1780$

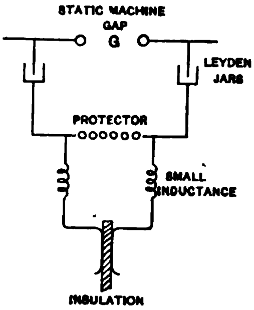

FIG. 2

The asymtote to the curve is 23 volts above the spark potential at an infinite time of application. This may have been due to difference in conditions of tests as this value was taken some time previous to the other readings.

The dielectric-spark-lag was demonstrated by another test using alternating potential. The spark-potential for continuous application was less than the peak value of the alternating potential, yet under these conditions it was not possible to spark across the gap. Successive alternations apparently deionized the gap. At any rate the time of application of super-spark-potential was not sufficient to cause a spark and the successive impulses were not cumulative.

The obnoxious effect of the spark lag on the operation of lightning arresters was noticed first, years ago, in taking equivalent needle-gaps and other direct measurements of the value of lightning arresters.

The gap at *G* of a static machine requires a certain pressure to spark. (Fig. 2). This determines the value of pressure that will appear at the protector. At the terminals of the protector is attached the insulation to be protected. Between the protector or lightning arrester and the insulation a small amount of inductance is placed to imitate circuit conditions. When the pressure at *G* was as high as 100,000 volts, the insulation was not injured as the spark took place quickly at the protector. When, however, the electric pressure at the gap (*G*) was relatively small, in one case about 3,000 volts, the insulation was punctured. The greater time lag of the protector allowed the charge to pass beyond into the insulation and although the spark sometimes took place in the protector, it occurred too late to give protection.

In regard to Dr. Whitehead's paper, I wish to say that in the study of the dielectric spark-gap, we came across the same thing that he has studied in what he has named dirty wires, or the oxidation of the wire. We had ionization taking place on wires which allowed a spark to pass at less than fifty per cent of the normal spark potential, and I felt that it could not be explained by any roughness of the surface. It seemed evident from the tests we made, that the ionization was due to the oxide on the surface, in some inexplicable manner. In other words, the oxide apparently causes a considerable degree of auto-ionization. After we removed the oxide it disappeared, although the surface was equally rough. The tests were made in hydrogen vapor, and consequently the oxide on the copper was reduced by the passage of an arc over the surface. These results are suggestions although the phenomenon may be different from the effect of duty copper wires in air.

J. C. Lincoln: There is one question I would ask Dr. Whitehead. In the diagram of his apparatus, he shows a wire in the medium which is controllable, and I take it from the diagram that there is passed through the medium an alternating voltage, and therefore that the ionization, such as there would be, would tend to produce positive and negative ions in the tube, and in that way the ions are passed across the indicating instrument and some kind of an indication is given. Apparently either the negative or the positive ions are in preponderance, and I would like to know which did preponderate.

Charles F. Scott: I want to say a word in appreciation of the three papers which have been presented, and the work they represent, and the valuable part which these papers will play in the progress of the art.

In going into a new field like this high voltage field, there is good deal of pioneer work to be done of two kinds—work in the laboratory and work in the field, theoretical work and practical work. Very often these alternate. First we take one kind of step and then the other. Dr. Whitehead enumerated several papers which have been presented to the Institute, which are preliminary to his, and form a series. In running over these papers, I note the first one is on the dielectric strength of air by Dr. Steinmetz, a laboratory paper; next is the Telluride test by Mr. Mershon, which was a field test; next is the paper by Professor Ryan, a laboratory test; next follows a Mershon paper, giving field tests, and now the Whitehead paper, a laboratory paper follows. The next thing on the regular schedule would be to have another paper from Mershon.

Harris J. Ryan: Dr. Whitehead's paper is a most valuable contribution to the subject.

The writer agrees with the author that " secondary ionization is the cause of initial breakdown and formation of corona." For out-door conditions he prefers the terms " native " ionization to " antecedent " ionization as used in the paper. He differs from the author in the conclusion that native ionization enlarges the effective terminal until the stress (intensity) at its surface falls to the ionizing value. *Native ionization strengthens the stress near the terminal and diminishes the distance to the ionizing zone. This distance is required to accomplish the process of general ionization by collision, i.e. the formation of corona.* At a stress of 76 kilovolt-in., or 30 kilovolt-cm., ions travel nearly one inch in 0.0002 second. The region about the electrode enclosed by the zone in which the corona starts contains mostly native ions of opposite polarity. Such ions will strengthen the stress and lessen the striking distance to the corona forming zone.

Recent studies of the normal in-door air show that the value of J. J. Thomson and the one in which the author of this paper expressed confidence, a year ago, is correct, namely, 76 kilovolt-in. There is much evidence that 40 kilovolt-cm. as given now by the author is too high for normal in-door air.

The rapid outward spread of the stress from the surface of a small conductor and the greater concentration of native ions combine to make the striking distance to the initial corona zone shorter. Since the initial corona zone always forms in the normal air at 76 kilovolt-in., the net result is that the surface stress of the conductor rises as the initial corona striking distance falls.

In regard to the statement " In view of these discrepancies one naturally turns to Mershons' method for measuring the loss as a possible source of error." A careful study of the methods used at Niagara and recent laboratory tests have convinced the writer that Mershon's methods and results are correct. There are no real discrepancies. The surprises are due mainly to the larger native ionization at the Falls. Mershon's Niagara corona zone stresses go below 76 kilovolt-in., because of irregular distribution of stress about parallel conductors worked with alternating high-tension; this irregularity is produced and enhanced by the larger supply of native ions occurring at Niagara Falls. The vapor-product is an indirect evidence of their quantitative variation.

R. D. Mershon: Referring to the paper by Mr. Hayden and Dr. Steinmetz, I would ask them to make clear how they determined the energy available at the spark gap; how they found out what energy was effective.

C. P. Steinmetz: We did not determine it, do not know it.

R. D. Mershon: Then it seems to me it is pretty hard to arrive at any definite conclusion.

C. P. Steinmetz: The only conclusion is the total energy supplied to the apparatus, hence the energy at the spark gap must be less than that. We give only the energy limit.

R. D. Mershon: The question of energy is related to that of voltage. I do not see how you can have any idea of the voltage finally impressed upon the dielectric.

C. P. Steinmetz: I will answer that in the final discussion.

R. D. Mershon: Referring to Dr. Whitehead's paper, the questions and doubts he raises in regard to the accuracy of my high-voltage measurements at Niagara are all of them questions and doubts which I myself raised at the time the results were obtained, and which I feel were resolved by the careful tests made of the accuracy of measurement. We tested out the method of measurement in every way possible and in consequence of these tests I am well satisfied that the method of measurement is a reliable one, and that the results obtained are substantially correct. I feel confident the accuracy of the measurement is within 5 per cent, and probably much closer than that. Reference to my paper will show the kind of tests made, and the method of making them.

The apparatus used at Niagara was not that used at Telluride. It was of the same kind, but better designed and executed. At Telluride I had a 1,000,000-ohm resistance with which to test out the accuracy of the measuring apparatus. At Niagara no such resistance was available, but in view of the closely checked results obtained at Telluride making use of the resistance, together with the fact that the Niagara apparatus was an improvement on that at Telluride, and in view of the results of such check-readings as could be taken at Niagara, I have no suspicion whatever of the accuracy of the Niagara apparatus and the results obtained with it.

Dr. Whitehead says:

> " Since Mershon's observations appear to have been taken in all seasons, it may be stated that a range of temperature of 35 deg. cent. and a pressure of 25 mm. of mercury, and an error of 5 per cent in the critical point as taken from the curves, would give a range of critical voltage as wide as that attributed by him to moisture ".

I judge from this that Dr. Whitehead thinks the relation I found between critical point and vapor product may be the result of a series of errors. If this is the case, it is curious that these errors should have occurred so consistently over a year and a half, during which time measurements were taken almost every day.

I do not see how it is possible that any errors in our observations or in our method of measurement could account for the variation of critical point with vapor product. The effect was entirely too marked to be so accounted for. Before we discovered the relation between loss and vapor product, we would sometimes get consistent results over a period of several days, and then the results of the next day would be all out of line. It even happened at times that of a set of observations all taken on the same day the results would be erratic and entirely inconsistent. But all these readings, when interpreted by means of the vapor product, came together and were consistent; the results of different days came together; discrepancies occurring on the same day were reconciled. So I cannot conceive of the relation referred to as being in any way due to errors in either measurements or apparatus.

In this connection I would call your attention to the facts brought out in one of the other papers here, relative to the very small amount of moisture necessary in oil in order to enormously change its dielectric qualities. In what condition does that moisture exist in the oil? Is it water, or vapor? It certainly must be very finely divided, at any rate, for it is uniformly distributed through the oil. This may have a considerable bearing upon the loss in air due to moisture; a loss entirely aside from the so-called ionization loss.

The only error that I can conceive of as possible, due to the method of measurement, would arise from phase displacement in the measuring apparatus itself. The tests made of the apparatus, as detailed in my paper, seem to me to pretty clearly show that there was no such error, or at any rate it was not great enough to account for the discrepancies, if you may call them such, between my results and those of Professor Ryan and Dr. Whitehead.

I would call your attention to the fact that the results obtained by Dr. Whitehead, and to a considerable extent, the results obtained by Professor Ryan, are not necessarily comparable with my results. I did not investigate the matter of ionization. I investigated the point at which the loss between outdoor transmission line conductors begins to rise rapidly, which point I called the critical point. I do not think this loss is necessarily all ionization loss. It seems to me it may include losses other than those due to ionization. The results of Professor Ryan and Dr. Whitehead were obtained under laboratory conditions. My results were obtained under engineering conditions. I do not believe we are safe in applying the results of laboratory investigation to the engineering problem, unless we can check up these results under engineering conditions.

There are too many other elements which may enter to modify laboratory results as applied in practice.

What I have said applies to the conclusions. Conclusion 5 says, " Water vapor or moisture has no influence on the electric strength of air. Increasing moisture content probably lessens the loss above the critical voltage ". That depends on what you mean by the critical point. If you mean the point at which ionization begins, the statement is possibly true, but if you mean the point at which the loss between the wires of a transmission line begins to rapidly ascend, I do not agree with that at all. Similarly with regard to Conclusion 6—" There is no loss through air until the critical voltage accompanied by ionization and corona is reached ". I believe there may be a loss below the critical point, as I have just defined it, and that this critical point does not necessarily correspond to the inception of ionization.

Now, as regards Conclusion No. 10: " The corona has high conductivity, and most of the loss takes place beyond it ". I do not remember anything in the paper which would appear to justify this conclusion. If there is, I shall be glad if Dr. Whitehead will bring it out more strongly.

Referring to Mr. Tobey's paper, Fig. 7 would be much more interesting if the melting point of the oil were shown, and it is to be hoped that in closing Mr. Tobey will give us the melting point. This curve presents some facts in regard to which I have often wondered. I have been afraid sometimes that if the oil in transformers was allowed to solidify, due to cold, we might get into trouble, but according to this curve we are safer with the oil solidified than with it in its normal condition.

C. P. Steinmetz: First, to answer some questions regarding our paper—the energy values, are, as stated in the paper, not the energy appearing at the spark-gap, but are the total amount of energy supplied to the system through the transformer, and, as stated in the paper, the actual energy supplied to the spark-gap probably is only a small part thereof, so that these values merely mean the upper limit of energy, which is sufficient to break down the gap, and probably much less energy will be enough.

As regards the question whether the voltage was actually at the spark gap or not, we carefully looked into the matter and came to the conclusion that this voltage is there, at least approximately this voltage, as near as it was possible to judge. Mathematically, I gave the reasoning in the appendix, which shows how we calculated the voltage which appears at the secondary terminals and thereby at the spark-gap. We know if there is one thing where experiment and calculation agrees, it is in transient phenomena, provided you consider all the factors involved in the problem.

There are two factors which have not been included in that mathematical calculation. One is the variation of the inductance; the second is the capacity of the secondary circuit. It can easily be seen that the variation of the inductance with the voltage has no effect on the voltage, but merely modifies the shape of the voltage curve of the secondary. There remains then the consideration of the secondary distributed capacity. From the constants of the transformer, its estimated resistance, inductance and capacity, it appears obvious, that the effect of capacity could result only in an oscillation, not in a steady change, that is, that at the beginning of the impulse there might appear and probably does appear an oscillation superimposed on the steady discharge curve, calculated in the appendix. Such oscillation may be either limited to the high voltage circuit, and then be of very short duration or small energy, or it may extend into the primary circuit.

In the paper we gave evidence that such oscillation did not extend into the primary circuit, by changing the resistance of the primary circuit, increasing the non-inductive resistance of the primary supply circuit nearly a hundred-fold, and getting the same result. It is obvious if there is any oscillation taking effect in the primary, that by increasing the resistance of the oscillating circuit nearly one hundred-fold, from about $\frac{1}{3}$ ohm to 26 ohm, the oscillation must be enormously reduced and damped out, and we found the same transient discharge. I believe, however, there was in the high potential secondary circuit an oscillation superimposed on the exponential curve of the calculated voltage ratio, but of extremely short duration, and as the entire effect is a transient, you see that an oscillation of still much shorter duration at the beginning of the effect, could not well be expected to have an appreciable effect. It is, however, desirable, and we hope some time to be able to carry out corresponding investigations by some other method of producing the transient voltage, and thereby being able to determine exactly the amount of energy existing at the spark-gap.

A most interesting paper we have in the next paper, that by Dr. Whitehead, which I consider as extremely valuable and important at present. I may say, indeed, that we had intended to make the same investigation, even assembling apparatus of the same kind, a conductor in the center of a tube, and measuring the beginning of the breakdown by an electroscope. We expected to carry that investigation a little further, that is, to lower air pressure, so as to study more carefully the effect of higher altitudes, since we know that transmission lines at the present time extend to altitudes where the air pressure is appreciably reduced.

There is only one point in Dr. Whitehead's paper, concerning which I do not agree with him, and that is his opinion that the explanation of the apparently greater breakdown strength of air with small wires cannot well be given by the assumption of the zone of condensed air around that wire. We know, and it can easily be shown physically, that all solids are surrounded by a zone of condensed air, and a rough calculation will show that the densities of this air at the immediate neighborhood of the conductor, by gravitational or molecular attraction, may reach considerable values. This phenomenon of the great increase of disruptive strength of air close to the solid terminals I observed and gave the explanation, that it is due to the condensed layer of air, some years ago, I believe in the paper which I read on disruptive strength before the Institute in 1893. There I found that in testing very small air gaps the disruptive strength very greatly increased, beyond that observed in the case of larger air-gaps between parallel plates.

As we know, Professor Ryan has very carefully looked into this effect, and in his paper of 1904 gave it a numerical value. I believe it would be very interesting, first, to take his numerical value of the layer of condensed air, and reduce Dr. Whitehead's tests by this assumption, thereby seeing whether we do not get a greater constancy, and then, inversely, from the data of this test, calculate how thick a layer of condensed air we have to assume to get constant break-down strength of the air. It is reasonable to assume that the layer of air is not the same, but decreases with decreasing diameter of the wire, due to the effect of divergence.

If there exists such a layer of condensed air, the result would be that the initial break-down occurs, not at the surface of the conductor, but at a small, though finite distance from the conductor surface, and with the increasing voltage the break-down extends outwardly, but also extends inwardly towards the conductor, and at a second higher voltage reaches the conductor.

This gives a second point in the curve where a change of the phenomenon might be expected to occur. It is very interesting to realize that with our increasing knowledge of the phenomena of disruptive strength, we are more and more impressed with the similarity of the electro-static strength, and its laws and phenomena, with the laws and phenomena existing in the case of mechanical forces, as pointed out also by Dr. Karepetoff. Only I do not agree that the electrostatic phenomena are simpler than the mechanical, due to the absence of shear, but there is very good evidence which makes it probable that electrostatic shear also exists, because at the edge of the electrostatic field, where the electrostatic field very abruptly changes, for instance, at the edge of two parallel plates, there is a very much greater disruptive force; although the potential gradient would be the same, and there is some evidence qualitatively, though not sufficient quantitatively, that not only the disruptive potential gradient, but also the abrupt variation of the potential gradient causes a breakdown. This was discovered first in the old Ferranti system in London, England, in bygone ages, when the cables had the unhappy habit of breaking down at the edge of the insulation—where there is an abrupt change in the electrostatic field, that is an electrostatic shear, and it is so well known in the industry that we always carefully avoid abrupt changes of the electrostatic field, for instance, at the end of lead covered cables taper the field, etc. Experience has shown that if we allow too sudden variations of the static field, we break the insulation down, although the insulation is just as thick as where the field is uniform.

Originally when electrostatic phenomena were first investigated, they did not appear to agree with a constant breakdown strength of air, but gradually the phenomena lined themselves up in the direction of law and order, pointing towards a definite strain which air will stand, and beyond that will break down, and what we here are mainly interested in is the range beyond the break down, that is the phenomena beyond the electrostatic elastic limit of insulating material, where the phenomena have ceased to be reversible and become irreversible. It is the same thing in mechanical engineering, and we shall listen still to a paper dealing with an analogous problem in the mechanical force. This is an extremely interesting field, but the difficulty of exploring it is the same as in the case of almost all phenomena— you never find in nature a clear cut case of the action of one phase or one form, you always have it complicated by numerous other conditions, forces or phenomena which are existing as secondary actions, and practically most of the work of the electrical engineer and other engineers consists of a very simple calculation of the theoretical condition, and then he must calculate and estimate the secondary actions which modify, and sometimes entirely obscure the primary action of the phantom apparatus under phantom conditions.

The most important secondary actions in electrostatic phenomena are:

First, the phenomena of the effective terminal. That is, when we have electrostatic fields, the terminals of the field are not the solid terminals, the needle points or spheres, but are made up of that space surrounding the solid terminals within which the air or space is broken down, has passed beyond its elastic limit and is more or less conductive. Between needle points, even at extremely low voltages, the break down strength is excedeed at the points, nevertheless the spark discharge does not occur until much higher voltages are reached, and when it occurs it is not a discharge between needle points, but between these effective terminals, these approximately spherical spaces of conducting or ionized air.

The study of that phenomenon mathematically is rather difficult; is not as simple as it appears. We can easily consider the electrostatic field with its force lines and equi-potential surfaces between needle points or spheres, and then see at a given voltage what is the equi-gradient surface which corresponds to the break-down of air, and all the air space inside of this surface would become conductive. But as soon as the space becomes conductive up to the equi-gradient surface, the equi-gradient surface becomes an equi-potential surface, while it is not an equi-potential surface in the original electrostatic field. That means the distribution of the lines of force changes and the entire field changes and the problem is to find that equi-gradient surface which at the same time is an equi-potential surface, and has the particular numerical value of the break down strength of air, and that is rather a more difficult problem.

The second phenomenon is the layer of condensed air which surrounds the solid material. The result is that the disruptive strength at the surface of the terminal is different from what it is in the space at some distance. At atmospheric pressure it is very much higher. The result of that would be, as I stated, that the initial break-down occurs at a voltage corresponding to, not the break-down gradient at the conductor surface, but at the space some distance away, or, in other words, it occurs when the ratio of the electrostatic gradient to the density of the air has reached the maximum at some point at some distance from the conductor. This also requires further theoretical investigation, which probably can be done, because we know the law of gravitation, and the gas laws, and the layer of condensed air could be calculated.

When you have electrostatic forces acting, the phenomena may be expected to be complicated still further, as Dr. Kennelly pointed out, by the electrostatic attraction, which changes the density of the layer of air and its volume.

Lastly, and one feature which we usually overlook, is the resistance of the conducting space of the effective terminals. It is not correct to say that the space within which the air is broken down and which forms the effective terminal, is a perfect conductor, but it has some resistance, and therefore quite considerably modifies the phenomena. To illustrate it by the discharge between needle points—we have a discharge occurring between these effective conductors, spherical spaces of ionized air, but these spaces are not perfect conductors—they have a certain resistance, and the resistance has the characteristic of gas resistance, that is, it increases enormously with decreasing current density. Now, the current density depends on the size of the conducting terminals, the volume which has to be ionized, and also on the frequency, and you see, then, within this range, until you have reached so large conducting spheres, effective terminals, that the amount of current required for ionization is large enough to give a negligible resistance, the frequency as well as other features, have no effect. That is very markedly shown in the striking distance curve between needle points. Theoretically, we can calculate it, allowing for the effective terminals, the ionized air space, and no matter what allowance we make we can easily show that the striking distance between needle points should be a straight line going through the origin. Now, the actual curve, as we found it by test, is given in the paper in the 1898 TRANSACTIONS, at 125 cycles; it differs from the straight line at lower voltages. More recent tests at 60 cycles seem to show a curve in which the deviation from a straight line extends to somewhat higher voltages, and there seems to be some evidence which makes it probable that at extremely high frequencies, 100,000 cycles, the curve remains straight practically down to zero, that is, is the true theoretical curve. The cause of this deviation from the true theoretical curve seems to be the resistance of the effective terminals which, within that range, are still so small that the current consumed by them is sufficiently low to give a resistance, consuming a voltage comparable to the voltage between the needle points. At higher voltage the space ionized is so large and the current absorbed is so great that the effect has disappeared. That is another secondary phenomenon which requires consideration.

Again, we really do not observe the break down voltage, or the elastic limit of air directly, but always indirectly by different methods, and there is no evidence that the point we observe by different methods is the same point. We get it by the disruptive discharge. We get it by observing the beginning of ionization, as described in Dr. Whitehead's paper. We get it by the corona. We get it by measuring the energy loss in the conductor as in Mr. Mershon's paper or Mr. Ryan's paper. Then we get it by the increase of capacity of the conductor, at the voltages where the corona spreads out and increases the effective conductor. There is no reason why the different methods should really give you the same point. As soon as the air begins to break down anywhere in space, an irreversible process occurs. The energy consumed by it is not returned. It means at that point the energy loss in the electric system must appear. If we could measure the beginning of the energy loss exactly, which is an extremely difficult problem, we could show the beginning of the energy loss, the beginning of the break down.

As there is a layer of condensed air, that initial break down occurs at some distance from the conductor, and the conductor, therefore, is surrounded by a zone of conducting air which is separated from the conductor by a layer of compressed and insulating air. There is no conduction of current from the conductor into the ionized air region until a higher voltage is reached, when the zone of disrupted air spreads to the conductor and current begins to flow into the zone. It appears possible that the point where the capacity of the conductor increases is not the point where the initial break down occurs, but is the point where the zone of broken down air gas spread up to the conductor and reached it.

It is curious to note that there are also two visible steps in the luminosity which are quite sharply marked, and are also apparently sharply distinguished by their chemical action. First appears the glow, the noiseless or silent discharge. Perhaps this is the break down at some distance from the conductor, not at the conductor—while the air at the conductor still is insulating, but at some distance therefrom has broken down. This does not appear at needle points, where the break down must occur at the beginning, but it appears very markedly at plane surfaces. Then at higher voltage, the blue glow is superseded by violet streamers, which are noisy and are interrupted, intermittent, and appear to represent conduction of current, when that ionized layer of air has reached the conductor. When conduction occurs into the space, that conduction, following the gas laws, has the effect that as soon as current begins to pass locally the resistance at the space falls, a discharge occurs, the voltage disappears and the current disappears, so by the laws of gas conduction the current must be intermittent and must always be a localized expenditure of energy as a spark or streamer. At this point, apparently, the chemical action changes. Where we have the blue glow, the energy seems to be sufficient to dissociate the oxygen molecules, but not the nitrogen molecules, and ozone formation takes place. As soon as you see these violet streamers, not only the oxygen molecules, but also the nitrogen molecules split, and you get nitric-oxide, but less ozone, because at the high temperature of that streamer discharge the ozone is broken up, so that there seems to be a sharp dividing line. Below that the blue discharge produces ozone, above it the streaming discharge or brush is intermittent, and of different color, noisy, and seems able to fix nitrogen.

The whole subject is an extremely interesting one, and what I have said here I do not want to have taken as conclusive evidence, as the entire field is altogether too new to accept final conclusions. This is only my present personal opinion of what, from the evidence, appears to be probable. We must all be governed by further evidence, which may and probably will change our opinions more or less.

John B. Whitehead: Before answering the questions which have been asked in connection with my paper, I want to say a few words in general comment on the three papers which have been presented at the morning session.

These three papers all deal with the effects of high voltage on insulation. Each of the papers presents a set of experimental results on this perhaps most important of all electrical questions. All of them fail, however, to explain the observations in terms of simpler phenomena or physical laws at present understood. Nor do the few suggestions of explanations which are offered coincide either in point of view or language of expression. There is here then a sharp indication of present uncertainty surrounding these highly interesting phenomena. The uncertainty, however, is by no means as great as may appear from this confusion. The phenomenon of spark discharge in all its manifestations has been a subject of study by experimental physicists for many years. As a result of this study the ionic theory has not only paved the way for most fruitful investigation, but has been finally established as a medium through which many electrical manifestations now receive their explanations in terms of the laws of simple mechanics. For no set of phenomena is this more true than for the spark discharge in gases. While there are still many phenomena which have not yet been brought into perfect accord, those which have been studied most widely show conclusively that for a proper understanding of the conditions governing the break-down of insulation whether gaseous, liquid or solid, the way must be through the knowledge of the properties of ions which has been already gained. These comments are suggested by the mode of interpretation used by Messrs. Hayden and Steinmetz in discussing their results. We are to be congratulated upon the presentation of so careful and accurate a set of experiments in a field so little understood. The conclusions drawn from the experiments by the authors, however, invite some comment.

Disruptive discharge is said to require a definite minimum amount of energy. The laws of spark discharge in air which may be said to be firmly established, explain the phenomena in terms of motion of gaseous ions, *i.e.*, charged particles, acted on by electric force. These ions have mass, and therefore acceleration and momentum when in an electric field. The laws of motion and impact of the simple mechanical system thus presented lead in many cases to complete explanation. Spark discharge is the result of secondary ionization or the collision of a charged particle moving under electric force with a neutral molecule, thus breaking up the latter into new ions and so furnishing the conductors for the discharge. Since the free ions have mass they require time to attain speed. If the electric force is transient and of sufficiently short duration the ion may remain practically unaffected. The study then of the phenomena of transient voltages should be extended to that of the shape and duration of the voltage impulse, *i.e.*, the integrated product of intensity and time in relation to the known properties of gaseous ions. Even granting that the initial discharge voltage of the experiments is properly deduced from the ratio of turns, this value cannot exist for more than an infinitesimal time and the appendix concludes that the shortest and longest time durations of a pulse are in the ratio 1 to 100. It is concluded that the discharge does not instantly follow the application of voltage, although the observations leading to this conclusion are not described. It is also stated that during the interval energy is being supplied to the dielectric, and relations are deduced between energy and sparking distance for air and oil, as given on page 770. Although the observed points in the two cases fall on curves of different shape they are assumed to have the same equations, and although the energy is measured at the transformer primary, it is assumed to be a basis of comparison for the secondary spark-gaps. It would be interesting to know what part of the energy delivered to the magnetic circuit is regained upon opening the primary circuit. It would also be interesting if the authors would present a conception of the mechanism by which a dielectric accumulates energy leading up to disruptive discharge.

Taking up the points that were brought out in connection with my own paper, the first question was that of Mr. Mershon as to the point on the voltage wave at which the corona ceases in relation to the point at which it starts, and he raised the question as to just how you could expect the corona to stop at a lower voltage than that at which it started. The indication is that there is only a small lag, if any, in the point of disappearance of the corona. The corona, however, is a source of heat in the gas, and the raising of temperature has the effect of lowering the corona voltage.

Regarding Mr. Thomas' questions—first, the conditions at the ends of the tube: The wire is carried through a cylindrical metal bushing set in a glass receptacle of the shape very much as indicated in the drawing on page 1063. There is no observation of spark discharge, no corona nor anything else indicating ionization at this point, occurring before that on the length of wire within the tube. If you carried the wire through a rubber or other insulating bushing, ionization would first set in at that point, and would spread to some extent along the wire inside of the tube. The variation of electric field at the end of the tube is quite marked, of course, outside the tube, but does not extend to the region inside for any considerable distance. As soon as corona forms, it is very evident that no error is introduced on this account. The whole apparatus was, of course, enclosed with the idea of conducting any ionization that was generated out through the gap leading to the electrode. I think there was no error on this score.

With reference to the question as to whether in a small wire rapid change of gradient at the surface would explain any of these phenomena: The potential gradient does change very rapidly; however the distances within which the potential gradient varies widely are very much greater than mean free paths of the molecules and ions.

P. H. Thomas: You did not catch my point—the question is whether the volume of air which was subjected to something like the critical strain was not greater in the case of the large wire, not that the mean free path was involved, but the surrounding presence of supporting ionized air might prevent the overwhelming of the very narrow zone there, very narrow particles, with reference to the free paths.

J. B. Whitehead: I am not sure that I get the idea. Ionization in this case is a sharply cumulative effect. As soon as you get a region where there is this secondary ionization, when this second ionization starts, it is a continuous thing, and if you attempt to explain it by any relation between the mean free paths of the ion or the molecule, and the variation in diameter of the wire, there is the widest kind of discrepancy. I have given the figure 10^5 in the paper showing that the two quantities are of different orders of magnitude.

Referring to the question as to the state of the air as it leaves the wire, whether it has positive or negative ions—I think Mr. Lincoln asked a similar question—a gas ionized in this way has both positive and negative charges—the point of initial break-down will be observed by charging the electroscope either positively or negatively. The only differences which come in are in the shape of the discharge curve of the electroscope. These differences are to be expected in view of the known fact of the difference in the rates at which the positive and negative ions move in the gas and the different rates at which they diffuse. The point of break-down can be observed with either kind of ion. I have not worked with any other gas than air.

The question as to the positive and negative corona is taken up in the paper, rather briefly, and I have pointed out that there is no apparent difference in the positive and negative corona unless it be possibly the somewhat greater brightness and sharper definition of one. I am not prepared to say that there was any noticeable difference.

As to the relation of initial ionization to the following arc, the corona starts evenly, as you are, of course, aware. As you go on increasing the voltage you will finally get to either a spark or an arc. Now then, just what this range of voltage is will depend on the relative diameters of the inner wire and the tube. The potential gradient between a tube and the central wire depends upon the diameter of the wire in such way that under some circumstances an increase in diameter will mean a lowering of the electric intensity and under other conditions it will mean an increase in the electric intensity. With the increase in corona diameter, resulting from increased voltage, when the corona reaches a point so that any further increase means an increase of intensity the spark or arc follows.

Dr. Kennelly and Dr. Steinmetz have each suggested that an increase due to pressure in the neighborhood of a small wire may offer a means of explaining the increase of electric intensity of corona and break-down. I am not quite sure that I grasp Dr. Steinmetz's idea, in that I cannot see why you should expect any difference between the case of small and large wires. Professor Kennelly's idea is, of course, a possible one, and there is no difficulty about imagining such a thing to occur. I would say, however, that I have made efforts to observe any increase in pressure in the neighborhood of these wires by optical means—the increased density of this air in its relation to the neighboring portions, permits the use of a very simple optical method of observation. Such experiments were negative in my case, although I cannot say I think that is any conclusive proof that some such increase of pressure may not explain the observed facts. Since we are dealing with extremely small distances, and I am not sure that even with the optical method I have used the layer would be sufficiently thick to manifest itself in this way. The test is known to physicists as the " Schlieren " method.

Professor Creighton made some comments as to the auto-ionization of the air and the necessity of removing ions. I do not know the word auto-ionization. Ions may be generated by secondary ionization, as in coronæ, and recombine very promptly; the air is then to all appearances in quite the same state as it was before secondary ionization or coronæ set in. This is shown very well by the sharpness with which the corona stops and by the absence of any after effects of ionization. There are always a certain number of free ions in the air, and these ions account for the small conductivity which air has. If you generate ions by some external means, and put them in the air, it simply means you can get a greater leakage current, but the presence of these ions does not in any way hasten or lower the point at which secondary ionization steps in, it simply increases the leakage current. There are numerous ways of removing free ions from the air; the use of glass wool, or crude raw cotton and various materials of like nature, through which the air can be drawn to a perfectly pure state, so far as ionization is concerned, but it will always have a certain extremely small number of free ions. The natural conductivity of the air is entirely explainable on this basis. For reasons which will be found in the remarks I have just made, I do not think Professor Ryan's suggestion, as well as I was able to gather it from hearing his letter read in the meeting, that there may be a difference between indoor and outdoor ionization, offers an explanation of the discrepancies that he is calling attention to. The range of natural ionization throughout the regions which have been investigated all over the earth, is about in the ratio of 1 to 4, and as I have said, the presence of more or less free ions in the air, simply increases conductivity, but I do not believe under any circumstances it would hasten the point at which secondary ionization, spark discharge, or corona would start.

Mr. Mershon has asked the effect of the wave form on the observations. The discussion of the wave form is given in the paper, showing the relation of maximum to effective values, and also in the reference to the curve Fig. 5. It is possible to observe the corona very close to the peak of the wave, and it is so sensitive that it was possible by careful voltage adjustment to pick up the three little peaks by the stroboscopic method with intervening dark spaces corresponding to the dimples.

As to Conclusion 10, that the corona has high conductivity and most of the loss takes place beyond it, that is based on the results given in the paper, where it is shown that the intensity at the edge of the corona is the same, practically the same, differing from it by a small amount, as that of a solid wire of the same diameter, and if that is the case it is a fairly reasonable assumption that the corona has high conductivity, and marks the limit at which ionization takes place.

In calling attention to Mr. Mershon's method of measurement I have been led by the process of elimination of all other explanations of the discrepancies between our results. Mr. Mershon has pointed out that his critical point is not necessarily the same as my own, but I am unable to see any other explanation than that of corona and break-down for the sharp, upward bend of his curves. I am unable to think of any means, also, by which there is a possible loss through the air below this point.

It has been suggested by several that laboratory methods present conditions different from those obtained outside and that this may be an explanation of some of these differences. I should be interested to hear some one suggest some means or method by which a loss could take place through air at voltages below those at which it actually breaks down.

M. A. de Chatelain (by letter): The writer and his associate, Professor V. F. Mitkevitch, were led to the question of corona formation and the accompanying losses in connection with the question of possibility of high-tension power transmission in the vicinity of St. Petersburg, Russia.

Laboratory experiments were performed on cylindrical conductors of different diameters, placed at different distances from each other. In view of discrepancies in the values of the critical voltage, as given by Messrs. Scott, Mershon, Ryan, Kapp, and Berg, among themselves and with our results, Professor Mitkevitch was led to investigate the matter theoretically. Based upon J. J. Thomson's researches on conductivity of gases he has found the following formula for the critical voltage:

$$E_{eff} = 35 \frac{H}{273+t} \cdot r \log_{10} \frac{d}{r} \text{ (in kilovolts)}$$

where

H is the barometric pressure in mm. of mercury;
t is the temperature of air in degrees centigrade;
r is the radius of the conductor, in cm.;
d is the distance between the centers, in cm.

Changes in humidity did not produce any appreciable variations in results. The values calculated according to the foregoing formula were checked experimentally in the electrical laboratory of St. Petersburg Polytechnic Institute, and were compared to the results given by Professors Ryan and Kapp for the same conditions. The comparison is given in Tables I and II. It will be seen that the difference between the voltages at which the corona became visible, and those calculated according to Professor Mitkevitch's formula, are not large.

It may be appropriate to mention here that Professor Kapp's adaptation of Mershon's formula (Journal of the Inst. El. Engs., February, 1910) leads to an odd result, namely, that the critical voltage, beyond a certain limit, becomes lower with increasing diameter of conductors (see Table III).

Mr. Mershon's statement that the losses increase with the frequency led us to investigate the effect of frequency. Our results seem to indicate that the loss is practically independent of the frequency, and rather decreases at higher frequencies. Namely, we measured the losses between two parallel planes, 27 x 27 cm. each, one of which was covered with needles of the same length. The distance between the points and the opposite plane was 2 cm. The frequency was varied from 15 to 90 cycles per second. After having taken into account the necessary corrections for the capacity, etc., we found the following values of losses:

Cycles	Watts
15	56
50	54.5
90	54

TABLE I

2 *r* (mm.)	*d* mm.	Critical kilovolts Observed	Critical kilovolts Calculated*
5 (cable)	1000	65	60
11 (cable)	"	120–125	115
11 (tube)	"	125–130	115
14.3 (tube)	"	145–150	141

*Formula Professor Mitkevitch

TABLE II
CRITICAL KILOVOLTS

d mm.	2 *r* = 10 mm.			2 *r* = 15 mm.			2 *r* = 20 mm.		
	Ryan	Kapp	Mitke-vitch	Ryan	Kapp	Mitke-vitch	Ryan	Kapp	Mitke-vitch
500	143	82	98	180	89.5	135	212	92.5	165
1000	165	94	110	209	104	155	250	109.5	195
2000	187	106	125	236	119.5	177	287	125.5	225
3000	200	114	135	256	128	190	310	135	240

TABLE III

d mm.	2 *r* mm. 5	10	15	20	25	30	50	100	150	200
2000	79.3	106	119.5	125.5	128.5	131	130	119.5	—	—
10000	98	136	154	164	171	172	177	169	163	156

A paper presented at the 27th Annual Convention of the American Institute of Electrical Engineers, Jefferson, N. H., June 29, 1910.

VECTOR POWER IN ALTERNATING-CURRENT CIRCUITS

BY A. E. KENNELLY

It has long been known that in any simple alternating-current circuit, the current and voltage may be conveniently regarded as rotatable vector quantities.[1] It is also known that the power in such circuits is not to be regarded as the vector product of the rotating vector voltage and rotating vector current.[2] It does not seem to have been pointed out, however, that, under certain restrictions, it is proper to regard the power in an alternating-current circuit as a non-rotating vector quantity. Moreover, it does not appear to be generally known, although the fact has not escaped notice, that the imaginary component of vector power, or so-called "wattless power" is, in a restricted sense, just as much power, and just as "wattful" as the real component.[3]

The objects of this paper are:

1. To indicate the limitations under which power in an alternating-current circuit may be treated as a stationary vector;
2. To extend the technology of vector alternating-current quantities;
3. To combat the use of the terms "wattless power" and

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[1] J. A. Fleming, " Notes on Alternate Currents "," The Electrician ", Nov. 18, 1887, Vol. 20, page 28.

[2] Symbolic Representation of General Alternating Waves and of Double Frequency Vector Products, by Dr. C. P. Steinmetz, TRANSACTIONS A.I.E.E., Vol. 16, pp. 269–296. June, 1899.

The use of Complex Quantities in Alternating Currents, by Geo. W. Patterson, Physical Review, Vol. 26, No. 3, Mar. 1908, pp. 266–271.

[3] The Improvement of Power Factor in Alternating-Current Systems, by Miles Walker, Journal of the Inst. of El. Engrs., Vol. 42, pp. 599–625, Jan., 1909.

" wattless current ", offering more logical terms as substitutes, and

4. To offer a plea for the standardization of the direction of phase rotation in the vectors used in alternating-current theory.

Preliminary Definitions. The vectors, or directed magnitudes, employed in alternating-current technology, with rare exceptions that do not come within the scope of this discussion, are all confined to a single plane of reference. That is to say, they relate to two dimensions of space, as distinguished from the vectors of three-dimensional geometry. This limitation may be expressed by saying that the vectors of alternating-current technology are *plane vectors*. A plane vector may be defined as a quantity having both a direction and a magnitude, but confined to one plane of reference. In what follows, we may for brevity conveniently assume that the term " vector " is an abbreviation for the more strictly logical term " plane vector ".

Subdivision of Vectors. There are three classes of vector used in dealing with alternating-current circuits, namely:

1. Vectors that are capable of rotation in their reference plane about a fixed point, and whose projections on a reference axis, or whose intercepts with polar curves, measure the instantaneous values of the quantities represented by the vectors. That is, the rotating vectors may be either *projected* or *intercepted*. These vectors may be called *rotative vectors*.

2. Vectors that are not capable of rotation in their reference plane for any purpose of projective or interceptive representation. These may be called *non-rotative vectors*.

3. Rotative-vectors that for special purposes are arrested, or treated as though non-rotative. These may be called *stationary vectors*. Stationary vectors are rotative, but non-rotating.

The above classification and nomenclature may be revealed more clearly by the following table:

TABLE I

Nomenclature and algebraic classification of alternating-current vectors.

Rotative ($l \underline{/\omega t}$)	....	Rotating ($l \underline{/\omega t}$)
	Stationary ($l \underline{/\omega T}$) (T = constant)	Non-rotating ($l \underline{/\theta}$)
Non-rotative ($l \underline{/\theta}$)	....	

Example of a Rotative Vector. As an example of class (1), let us consider the vector $O\,E$, Fig. 1, rotating in the plane $O\,X\,Y$, about the origin O, with a uniform angular velocity of ω radians per second. Then the length $O\,E$ may represent to an assigned scale of volts per cm., the maximum cyclic value of a certain sinusoidal e.m.f., say the e.m.f. generated harmonically in the secondary winding of a particular transformer. The direction of rotation may be positive, as indicated by the orbital arrows.

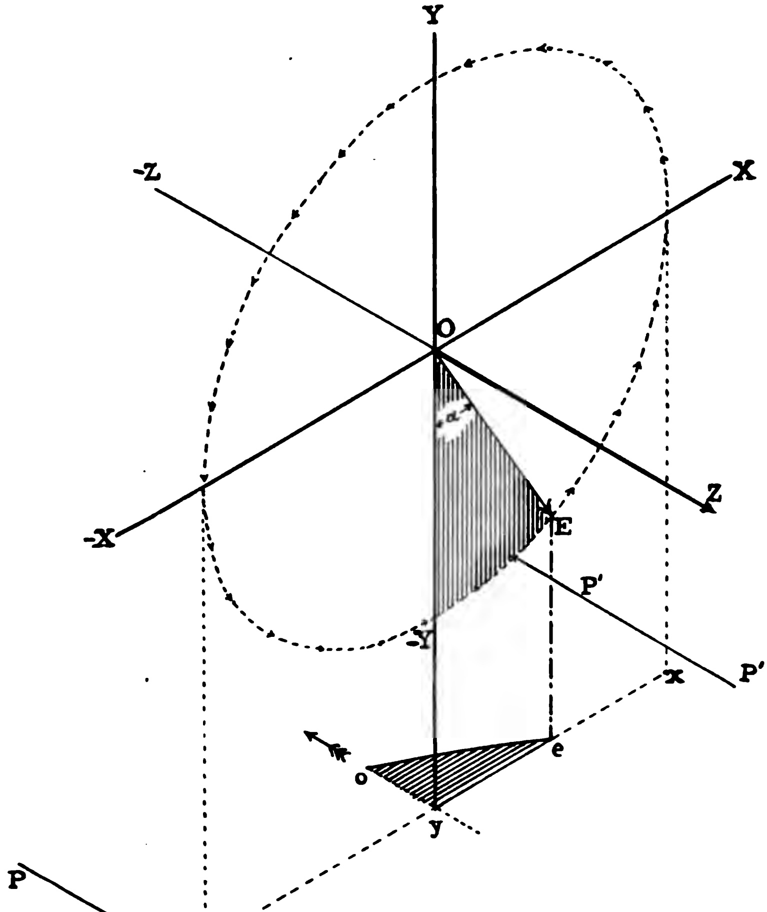

FIG. 1.—Rotative vector and sinusoidal projection. Isometric projection. $X\,O\,Y$ plane of rotation, $P\,P\,P'\,P'$ plane of projection.

If the frequency of the voltage in the transformer is n cycles per second; then we know that the angular velocity of rotation must be $\omega = 2\pi n$ radians per second. Moreover, the vector $O\,E$ must, of course, coincide with $O\,X$ when the generated voltage attains its maximum positive value.

The circular orbital motion of the end E of the rotation vector will then correspond to the vector equation:

$$O\,E = E_0\,\epsilon^{j\omega t} \qquad \text{volt-scale cm.} \ \angle \qquad (1)$$

where t is the time, in seconds, from the start at a particular axis such as $O\,X$, ϵ is 2.71828..., the base of Naperian logarithms, $j = \sqrt{-1}$, and E_0 is the maximum cyclic value of the e.m.f. to a voltage scale of length. Equation (**1**) is sometimes written:

$$O\,E = E_0\,cis\,(\omega t) \qquad \text{volt-scale cm.} \ \angle \qquad (2)$$

We shall represent either of the above expressions by the briefer and more convenient notation:

$$O\,E = E_0\,\underline{/\omega t} \qquad \text{volt-scale cm.} \ \angle \qquad (3)$$

where the quantity ωt within the angle sign $\angle$ means that the angular distance of the radius vector $O\,E$ from the initial reference axis is ωt radians, or degrees, according to the unit of angle adopted.

As is well known, the orthogonal projection of the radius vector $O\,E$ upon the plane of reference $P\,P$, $P'\,P'$, which is parallel to the plane $O\,X\,Y$, performs a simple harmonic motion. If the reference axis of starting, at time $t = 0$, is $O\ -Y$, then at any instant, t seconds thereafter, the distance $y\,e$, or projection of $O\,E$, will be:

$$\overline{y\,e} = E_0 \sin \omega t = E_0 \sin \alpha \qquad \text{volt-scale cm.} \qquad (4)$$

which will correspond to the e.m.f. generated at that instant in the transformer.

Again, if the reference axis of starting, at time $t = 0$, is $O\,X$, then at any time t:

$$\overline{y\,e} = E_0 \cos \omega t = E_0 \cos \alpha \qquad \text{volt-scale cm.} \qquad (5)$$

If the plane of projection $P\,P\,P'\,P'$ be moved parallel to itself in the direction shown by the arrow at o; or, if with the plane of projection at rest, the coördinate system of axes moves in the direction *O Z*, with uniform linear velocity, then, as is well known, the projecting point will trace out a sinusoid *o e* having amplitude ordinates *o x*, and time abscissas *o y*.

RELATION OF PHASE TO THE DIRECTION OF ROTATION

Convention No. 1. If we employ two co-frequent rotative vectors, such as *O E* and *O I*, Fig. 2, representing say an impressed e.m.f., to a certain volt-scale, in a simple alternating-current circuit, and the current strength thereby produced in the same circuit, to a certain ampere-scale; then, if there is inductive reactance in the circuit, we know that the current will lag behind the impressed e.m.f. This means that the orthogonal projection of *O I* on the axis *O X* of reference, must reach its maximum after *O E* has passed its maximum projection on that

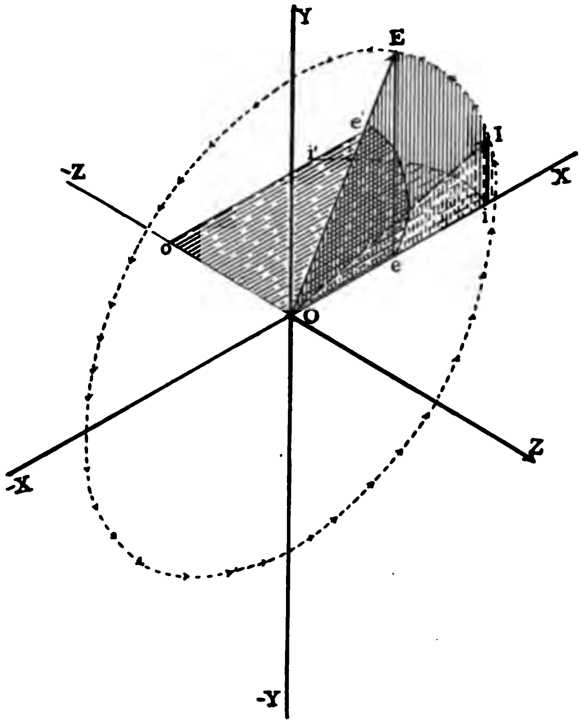

FIG. 2.—Pair of rotative vectors of the same frequency and their cosinusoidal projections. Representation direct. Current lagging. Isometric projection. *X O Y* plane of rotation. *X O Z* plane of projection.

axis. Consequently, with the plane $X\,O\,Z$, fixed in space, and with the vectors $O\,E$, $O\,I$, rotating in the positive direction, as shown by the orbital arrows, $O\,I$ must make a negative angle with $O\,E$; or, $O\,E$ must make a positive angle with $O\,I$; so that the angle $E\,O\,I$ is trigonometrically ***negative***, as shown in Fig. 2. If the vector $O\,E$ starts from the position $O\,X$, at time $t = 0$, the orthogonal projection of $O\,I\ \underline{/\omega t - \theta}$ proceeds to execute on the axis $O\,X$ the cosinusoid:

$$\overline{O\,i} = I_0 \cos(\omega t - \theta) \qquad \text{ampere-scale cm.} \quad (6)$$

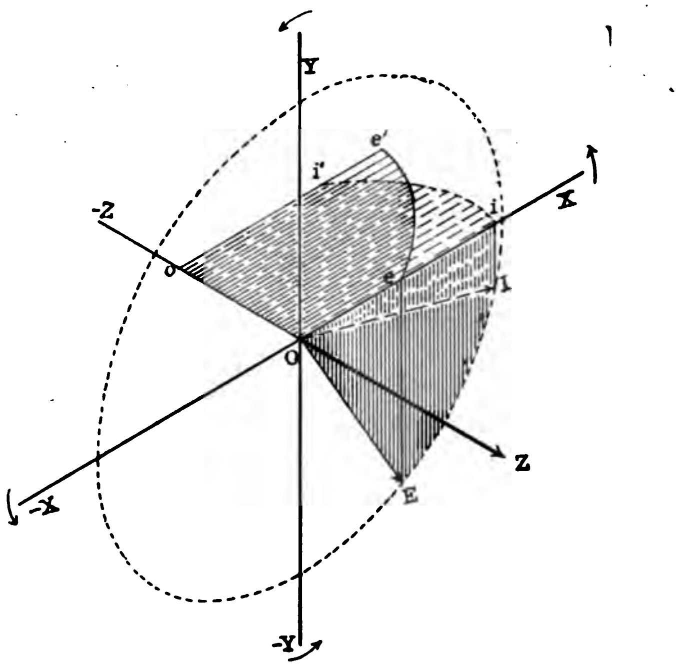

Fig. 3.—Pair of rotative vectors of the same frequency and their cosinusoidal projections. Representation inverse. Current lagging. Isometric projection. $X\,O\,Y$ plane of rotation. $X\,O\,Z$ plane of rotation.

If the origin O and system of axes advance uniformly with respect to the stationary plane of projection $X\,O\,Z$ in the direction $O\,Z$; or, what is equivalent, if the plane of projection moves in the direction $O\,Z$ past a fixed origin O, the cosinusoids $e'\,e$ and $i'\,i$ will be traced as curves with amplitude ordinates, and times as abscissas. This convention was adopted in alternating-current technology by Fleming in 1887.[1]

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[1] Fleming, loc. cit.

Convention No. 2. If, however, we reverse the direction of rotation of the vectors $O\,E$, $O\,I$ in their orbit; *i.e.*, if we adopt negative rotation, we shall require that the leading vector make a negative angle with the lagging vector, a condition opposite to that above defined.[2] Or, keeping the direction of rotation positive, we may assume that the vectors are fixed in their plane; but that the plane of projection rotates positively at the uniform angular velocity ω. Thus in Fig. 3, the two vectors $O\,E$ and $O\,I$ may respectively represent, as before, the impressed e.m.f. and the current in an inductively reactive circuit. If these two vectors remain fixed; but the axis $-X\,O\,X$, and with it the plane of projection $Z\,O\,X$, rotates in the positive direction, of the curved arrows, about the $O\,Z$ axis, the e.m.f. vector $O\,E$ must make a negative angle with the lagging current vector $O\,I$; or the pair will take relatively opposite positions to those they had in Fig. 2, and the angle $E\,O\,I$ will be *positive*.

Convention No. 3. Some writers, instead of employing rotative vectors to be projected orthogonally upon an axis of reference, prefer to represent simple harmonic motion by the device of an *intercepting circle*.[3] Thus, in Fig. 4, the heavy circle $O\,G\,E\,F$, in the plane $X\,O\,Y$, may be regarded as stationary in space, and the axis $O\,R$, sometimes called a "time-axis," rotates positively in this plane about the origin O, as shown by the curved arrows, with uniform angular velocity ω radians per second, or n revolutions per second, commencing at the position $O\ -Y$, when $t = 0$. As the axis $O\,R$ advances, it becomes intercepted by the circle $O\,G\,E$, and forms to that circle a chord of increasing length, until it reaches the position occupied in the Figure by $-X\,O\,X$, when the chord will have become a diameter, and the length of the moving axis intercepted by the fixed circle will be a maximum in the positive direction. As the rotation of $O\,R$ about O continues, the length intercepted by the circle will diminish, until it will be zero in the position $O\,Y$. Continuing the rotation, we may adopt either of two equivalent conventions, between which writers are divided. We may either use a second circle, shown in dotted lines at $O\,g\,e\,f$, equal and opposite to the first, and consider this to be a negative circle, such that all intercepts upon

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[2] Gisbert Kapp, "Alternate-Current Machinery", Fig. 7, Proc. Civil Engineers, London, 1889, reprinted in Van Nostrand Science Series, New York, 1889, p. 27.

[3] Kapp, loc. cit., Fig. 8.

C. P. Steinmetz, "Alternating-Current Phenomena", 1897.

O R shall be considered negative, intercepts on *O r* being ignored; or, we may dispense with the second circle, and allow intercepts on *O r* to count as negative intercepts, during the second half of the revolution. In either case, the length of the intercept on the moving axis will follow a simple harmonic law, according to the expression $O\,E \sin \omega t$ units of length, *O E* being the diameter of the intercepting circle.

If the rotating axis starts, at time $t = 0$, from the position $-X\,O\,X$ in Fig. 4, the length intercepted by the fixed circle will likewise follow a simple harmonic law according to the expression $O\,E \cos \omega t$.

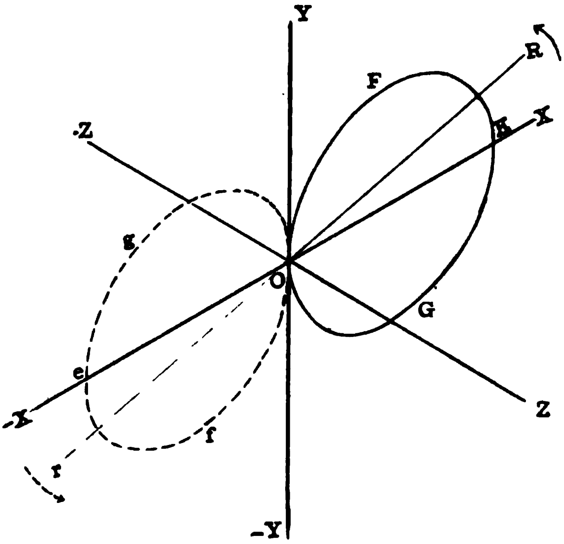

FIG. 4.—Uniformly rotating vector and fixed intercepting circle, with simple harmonic intercept. Isometric projection. *X O Y* plane of rotation.

In order to represent the relation between a simple harmonic current in an inductively reactive circuit under a simple harmonic e.m.f. by convention 3, two intercepting circles are required, as in Fig. 5. Here the negative counterparts are omitted, and negative intercepts are assumed with each circle. As shown in the figure, it is necessary, with the positive direction of rotation of the moving axis *O R*, to have the diameter of the circle *O I* make a positive angle with the diameter of the circle *O E*, in order that the intercept on the current circle shall reach its maximum later than the intercept on the voltage circle. A lagging current, therefore, requires a *positive* angle *E O I*.

In the practical use of convention 3, the circles are commonly omitted, for convenience, and are merely represented by their diameters $O\,E$ and $O\,I$, which become respectively the stationary-vector e.m.f. and current of the diagram.

As regards the use or disuse of the negative circle, as in Fig. 4, it is simpler to dispense with it, and to use negative intercepts on $O\,Y$, except when the positive and negative waves are not symmetrical. In that case, the retention of the negative loop simplifies the diagram, since it avoids superposition of loops, and ambiguity of paths.

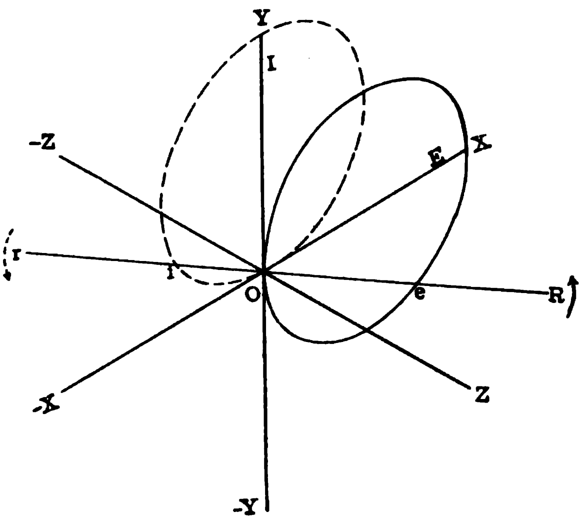

FIG. 5.—Pair of intercepting circles representing a simple harmonic e.m.f. and a simple harmonic current lagging 90 deg. behind the same. Isometric projection. $X\,O\,Y$ plane of rotation. Representation inverse.

Convention No. 4. If we assume that the axes of Fig. 5 are fixed in space, but that the intercepting circles $O\,E$ and $O\,I$ rotate together in the positive direction about the center O, measuring off from moment to moment intercepts on some axis, say $O\,X$, equal to the respective instantaneous voltage and current; then in order to represent an e.m.f. and a lagging current, it will be necessary for the diameter of $O\,E$ to make a positive angle $I\,O\,E$ with the diameter of $O\,I$, or the angle $E\,O\,I$ will be *negative*, the opposite condition to that in Fig. 5. According then to convention 4, Fig. 5 would represent a current *O I* leading the e.m.f. *O E* by 90 degrees.[1]

Convention No. 4 does not seem to be in use, but is introduced here in order to complete the classification symmetrically, see Table II.

TABLE II

Conventions Employed in Rotative - Vector Diagrams

Convention		Direction of rotation	Plane of projection	Vectors	Intercepting circles	Vector	Angle *E O I* for an inductive circuit	User	Date of use	Expression of inductive impedance	Representation
Type	No.										
Orthogonal projection or clock diagram	1	+	Fixed	Rotating			−	Fleming Blakesley	1887 1889	$r+jx$	Direct
		-	Rotating	Fixed			−	...		$r+jx$	
	2	+	Rotating	Fixed			+	...		$r-jx$	Inverse
		−	Fixed	Rotating			+	Kapp	1889	$r-jx$	
Polar coördinates or Intercepting circles	3	+			Fixed	Rotating	+	Kapp Steinmetz	1889 1893	$r-jx$	Inverse
		-			Rotating	Fixed	+	...		$r-jx$	
	4	+			Rotating	Fixed	−	...		$r+jx$	Direct
		-			Fixed	Rotating	−	...		$r+jx$	

REPRESENTATION OF COMPLEX HARMONIC QUANTITIES

It has been claimed that a complex harmonic quantity is only capable of being represented as a closed curve to polar coördinates by the method of the intercepting curve, and that the projecting curve, or "clock-diagram", cannot be used in

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[1] The above four conventions by no means exhaust the possibilities of rotative-vector representation. For example, as a subtype of interceptive or polar representation, we might assume the two circles *O E*, *O I* of Fig. 5 to have their diameters on one and the same line, instead of being angularly displaced. Two angularly rotating displaced vectors could then be employed for e.m.f. and current intercepts respectively, instead of the single rotating vector *O R*. With such an arrangement, a lagging vector current *O I* would make a negative angle with the e.m.f. vector *O E*, or would reverse the relations of Fig. 5. That is, it would produce direct representation. Since, however, this method does not seem to have been used, it is omitted from the Classified Table of Conventions.

such cases.[1] It is true that the simple projecting-circle or clock-diagram, with uniform angular velocity of the radius vector, cannot represent a non-sinusoidal or complex harmonic wave; just as it is true that the simple intercepting circle, with uniform angular velocity of the radius vector, cannot represent a complex harmonic wave. But in the same manner that a change in the form of intercepting curve will permit of any complex wave being presented in polar coördinates, so a corresponding change in the form of the projecting curve will permit of the same result. Thus in Fig. 6, the sinusoid *A B C D*, drawn to rectangular coördinates, may be represented either by the projecting circle

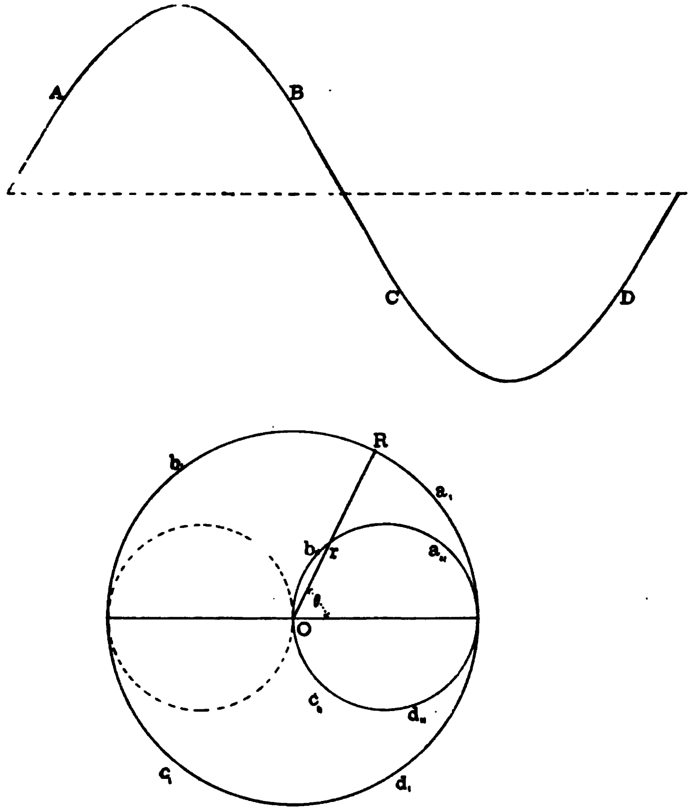

FIG. 6.—Sinusoidal wave and its projecting circle and its intercepting circle.

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[1] Alternating-Current Phenomena, by C. P. Steinmetz, 4th Edition, 1908, p. 44.

$a_{\prime}\ b_{\prime}\ c_{\prime}\ d_{\prime}$, or by the intercepting circle $a_{\prime\prime}\ b_{\prime\prime}\ c_{\prime\prime}\ d_{\prime\prime}$, with or without its dotted neighbor. Similarly, in Fig. 7, the triangular wave $A\ B\ C\ D$, drawn to rectangular co-ordinates, may be represented either by the projecting curve $a_{\prime}\ b_{\prime}\ c_{\prime}\ d_{\prime}$, or by the intercepting curve $a_{\prime\prime}\ b_{\prime\prime}\ r\ O$, with or without its dotted neighbor. The relation between corresponding radii on the polar curves is always:

$$\overline{O r} = \overline{O R} \cos \theta \qquad \text{cm.} \quad (7)$$

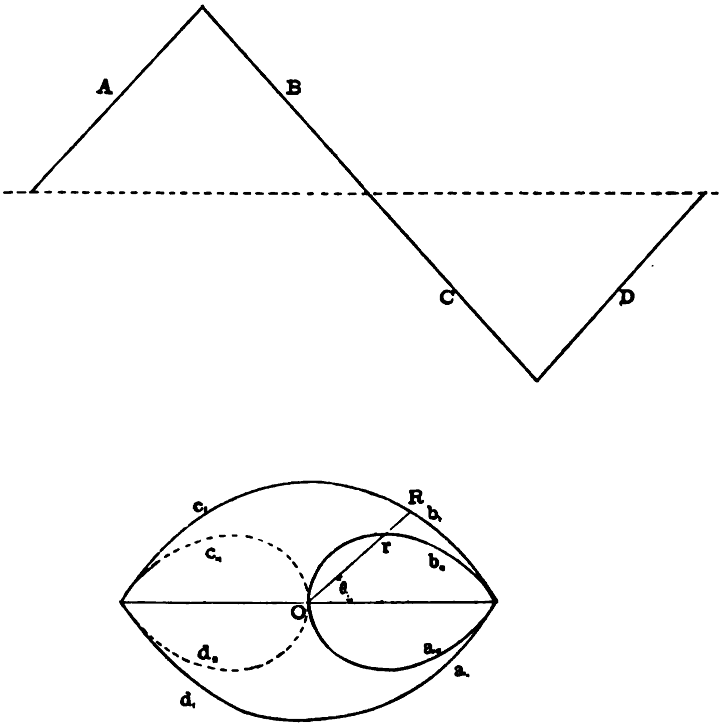

Fig. 7.—Triangular wave, its projecting curve, and its intercepting curve.

where $\overline{O r}$ is the radius vector (Figs. 6 and 7) of the intersecting curve, at the angle θ with the initial line of reference, and $\overline{O R}$ is the corresponding radius vector of the projecting curve. Consequently, having given either the polar projecting curve, or the polar intercepting curve of any complex harmonic alternating-current wave, the other can be immediately deduced.

It will be evident from the above considerations that with a pair of rotative vectors (Fig. 8) in the plane $X\ O\ Y$, one $\dot{O}\ E$

representing an impressed e.m.f., and the other $O\,I$ the resulting current, in a simple alternating-current circuit, the question as to whether $O\,I$ is to be interpreted as a leading or a lagging current does not depend upon the use of projecting as against intercepting curves. It may be either a leading or a lagging current with either the " clock " diagram (Fig. 1) or the " spectacles " diagram (Fig. 4). It depends entirely upon the convention employed. If, with a projecting curve, the two vectors of Fig. 8 rotate (in the positive direction) as in convention No. 1, then $O\,I$ represents a lagging current. If on the contrary, the vectors are to be considered as stationary, and the axis of reference rotates positively with respect to them, as in convention No. 2, then $O\,I$ represents a leading current. Again, if with a fixed intersecting axis $O\,X$, a pair of circles located with their rotating diameters on $O\,E$ and $O\,I$, the vectors of Fig. 8 rotate in the positive direction, as in convention No. 4, $O\,I$ represents a lagging current. Finally, if the vectors $O\,E$ and $O\,I$ are fixed, and represent the diameters of fixed intersecting circles, with respect to which an axis of reference rotates positively, as in convention No. 3, $O\,I$ represents a leading current.

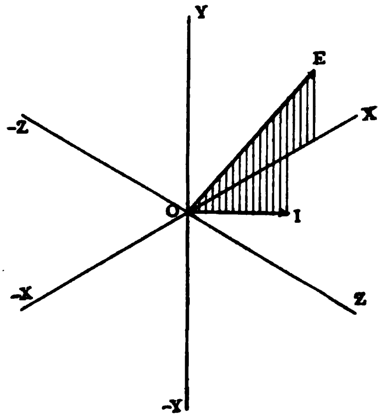

FIG. 8.—Vector e.m.f. and current in simple alternating-current circuit. The current is either a leading or a lagging current according to which convention used in vector representation. Isometric projection. $X\ O\ Y$ plane of rotation.

Aside from mental habit and psychological inertia, any one of these conventions appears to be as good as another. If the positive direction of rotation is understood in all cases, each convention appears to be logical and systematic. It cannot be maintained that one or more are right and the rest are wrong. The question is essentially one of arbitrary convention, not of demonstration. Nevertheless, it is very important that the matter should be settled definitely by general agreement.[1] Much ambiguity results from the present dissension; because it is often difficult to ascertain, when opening a text-book in order to consult it, which method of representation the author follows. Imagine the confusion which would ensue in the worlds of pure and applied mathematics, if it were left to the choice of each writer to select which direction of the axis $-X\,O\,X$ Fig. 8, say, should be positive; so that some books should be written on the assumption of $O\,X$, Fig. 8, being plus, and others on the basis of $O\,X$ being minus. Or again, suppose it were left open to individual selection, which direction of rotation in a plane, clockwise, or counter-clockwise, should be taken as positive. These arbitrary selections have long been fixed by universal agreement among mathematicians. Yet this is the kind of dissension which exists to-day in the world of vector alternating-current technology.[1]

Moreover, it is not enough that the decision should be made and accepted nationally. The only satisfactory decision must be made and accepted internationally.

DIRECT AND INVERSE REPRESENTATION

In what follows, this paper will conform to what seems the majority of opinion on this matter, and $O\,I$ in Figs. 8 and 10, will be regarded as a lagging current with respect to the e.m.f. $O\,E$. This means adhering to conventions 1 and 4, and by preference to convention 1. This method of representation which, in the direction of positive rotation, makes a *leading* current *lead*, and a *lagging* current *lag*, with respect to its e.m.f., will be called, for the purposes of distinction, *direct representation*, and the opposite method, involving either convention 2 or convention 3, will be called *inverse representation*.

Tables III and IV contain lists, which are by no means exhaustive, of publications using direct and inverse representations

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[1] The urgent need for the standardization of alternating-current vector rotation has been pointed out by various writers, both in this country and in Europe. See W. S. Franklin: A discussion of some points in Alternating-Current Theory. TRANSACTIONS A.I.E.E., May 1903, Vol. 21, pp. 589–601, and Carl Richter, Alternating-current Diagrams, Elek. u. Maschinenbau, July 12, 1908, pp. 608, 609.

respectively. No attempt has been made to discover more publications using one method than the other, and in the search that led to the formulation of these lists, no publications which contained vector diagrams were discarded, except such as made it difficult to decide which method was followed. The fact that 42 publications appear in the list of direct representation and 24 in the list of inverse representation, indicates a distinct preponderance in favor of direct representation. The dissension is not confined to any single country, or group of countries, and it dates as far back as 1889 at least.

TABLE III

PUBLICATIONS EMPLOYING DIRECT REPRESENTATION OF ALTERNATING-CURRENT VECTORS

Name of publication	Author	Publisher	Date
1. Conductors for Electrical Distribution.	F. A. C. Perrine	D. Van Nostrand, N. Y.	1907
2. Electrical Engineer's Pocket Book	H. A. Foster	"	1908
3. Alternating-Current Machines.	Sheldon, Mason and Hausmann	"	1909
4. Standard Handbook for Electrical Engineers		McGraw Pub. Co., N. Y.	1908
5. Munroe & Jamieson's Pocket Book		Ch. Griffin & Co., London	1908
6. Direct and Alternating Current Testing	F. Bedell	D. Van Nostrand, N. Y.	1909
7. Elements of Electrical Engineering	Franklin & Esty	MacMillan Co.	1909
8. Electric Waves	W. S. Franklin	"	1909
9. Standard Polyphase Systems	M. A. Oudin	D. Van.Nostrand	1909
10. The A. C. Transformer	F. G. Baum	McGraw Pub. Co.	1903
11. Electric Power Transmission	L. Bell	"	1907
12. Problems in Electrical Engineering	W. V. Lyon	"	1908
13. Electrical Engineering Leaflets	Houston & Kennelly	The Elec. Engineer	1897
14. A Laboratory Manual of Physics and App El:	E. L. Nichols	MacMillan Co.	1894
15. Alternating Currents	Bedell & Crehore	W. J. Johnston Co.	1893
16. Alternating Currents	D. C. & J. P. Jackson	MacMillan Co.	1896
17. Electrical Transmission of Energy	A. V. Abbott	D. Van Nostrand	1904
18. Alternating-Current Motors	A. S. McAllister	McGraw Pub. Co.	1907
19. The Elements of Alternating Currents	Franklin & Williamson	MacMillan Co.	1901
20. Alternating-Current Machinery	W. Esty	Am. Sch. Corresp.	1909
21. Electrical Measurements	Carhart & Patterson	Allyn & Bacon	1895
22. A Text Book of Electrical Machinery	Ryan, Norris and Hoxie	John Wiley	1903
23. The Principles of A. C. Working	A. Hay	Biggs & Co.	1897
24. Telephone Lines and their Properties	W. J. Hopkins	Longmans Green	1894
25. Experimental Electrical Engineering	V. Karapetoff	John Wiley	1908
26. Electrical Problems	Hooper & Wells	Ginn & Co.	1902
27. The Dynamo	Hawkins & Wallis	MacMillan Co.	1909
28. Electricity and Magnetism	F. E. Nipher	J. L. Boland Co.	1895

Name of publication	Author	Publisher	Date
29. Alternating Currents	C. G. Lamb	Ed. Arnold, London	1906
30. Lecons d'Electrotechnique Générale	P. Janet	Gauthier-Villars	1908
31. Pratique Industrielle des Courants Alt:	G. Chevrier	Carré & Naud	1900
32. Recherche Elémentaire des Relations:	O. de Bast	Léon de Thier	1899
33. Distribution de l'Energie par Courants Polyphases	J. Rodet	Gauthier-Villars	1903
34. La Technique de la Houille Blanche	E. Pacoret	Dunod et Pinat	1908
35. Moteurs Synchrones	A. Blondel	Gauthier-Villars	—
36. Die Wissenschaftlichen Grundlagen der Elek:	G. Benischke	J. Springer	1907
37. Fernleitung von Wechselströmen	G. Roessler	J. Springer	1905
38. Handbuch der Elektrischen Beleuchtung	Herzog & Feldmann	"	1907
39. Messungen an Elektrischen Maschinen	R. Krause	"	1907
40. Ein-und Mehrphasen W: Erzeuger	F. Niethammer	Hirzel	1900
41. Der Drehstrom	J. Krämer	H. Costenoble	1896
42. La Tecnica delle Correnti Alternate	G. Sartori	Ulrico Hoepli	1903

TABLE IV

PUBLICATIONS EMPLOYING INVERSE REPRESENTATION OF ALTERNATING-CURRENT VECTORS

Name of Publication	Author	Publisher	Date
1. Dynamo-Electric Machinery	S. P. Thompson	Spon & Chamberlain	1905
2. Elements of Electrical Engineering	C. P. Steinmetz	El. W. & Engr.	1902
3. Electrical Energy	E. J. Berg	McGraw Pub. Co.	1908
4. Whittaker's El. Engr's. Pocket Book		Whittaker & Co.	1906
5. Electrical Engineering	Thomälin	Longmans Green	1907
6. Electrical Engineering	Rosenberg, Gee & Kinzbrunner	John Wiley	1908
7. The Induction Motor	B. A. Behrend	El. W. & Engr.	1901
8. Transformers	Gisbert Kapp	Whittaker & Co.	1908
9. Vectors and Vector Diagrams	Cramp & Smith	Longmans Green	1909
10. Alternating-Current Engineering	E. B. Raymond	D. Van Nostrand	1907
11. Polyphase Currents	A. Still	Whittaker & Co.	1906
12. Practical Calculation of Transmission Lines	L. W. Rosenthal	McGraw Pub. Co.	1909
13. Electrical & Magnetic Calculations	A. A. Atkinson	D. Van Nostrand	1903
14. Laboratory & Factory Tests in El: Engg:	Sever & Townsend	"	1907
15. Electricity and Magnetism	Foster & Atkinson	Longmans Green	1896
16. Electric Motors	H. M. Hobart	Whittaker & Co.	1904
17. Single-phase Commutator Motors.	F. Punga	"	1906
18. Essais des Machines	Duquesne et Rouviére	Béranger	—
19. Stromverteilungssysteme	P. Häfner	Jänecke	1906
20. Untersuchung elektrischer Systeme.	H. Hausrath	J. Springer	1907
21. Der Drehstrommotor	J. Heubach	J. Springer	1903
22. Die Wechselstromtechnik	E. Arnold	"	1902
23. Ruhende Umformer	V. Bondi	Jänecke	1908
24. Impianti Elettrici a Correnti Alternate	A. Marro	V. Hoepli	1907

EXAMPLE OF A NON-ROTATIVE VECTOR

A simple example of a non-rotative vector is an ordinary impedance of the type $z \underline{/\theta}$ ohms, as indicated in Fig. 9. An ordinary impedance does not pass through zero cyclically, like an alternating e.m.f. or current, and no practical use is at present derivable from the notion of rotating a vector impedance about its origin. In direct representation, the impedance of Fig. 9 is essentially an inductive impedance, as distinguished from a condensive impedance. That is, it represents the impedance of some particular reactance coil. With inverse representation, however, it would necessarily represent a condensive impedance, or the impedance of some particular condenser, operated at a certain frequency, in series with a certain resistance.

Impedances, admittances, reluctances and permeances, when treated as vectors, are essentially non-rotative vectors.

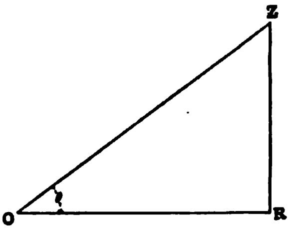

FIG. 9.—Non-rotative vector inductive impedance. Direct representation.

Quantitatively, the application of a non-rotative vector to a rotative vector as a multiplying factor alters both the magnitude and the phase of the resultant rotative vector, without altering the frequency or angular velocity of rotation. Thus the relation:

$$I \underline{/\omega t} \times Z \underline{/\theta} = I\, Z \underline{/\omega t + \theta} \quad \text{volts } \underline{/\ \ } \qquad (8)$$

indicates that the product of a vector current I amperes, rotating with the angular velocity ω radians per second, and a vector impedance of Z ohms, with the fixed angle θ radians, gives rise to a vector voltage $I\, Z$, rotating with the same angular velocity as I, but advanced θ radians in phase beyond I. The orthogonal projection of the voltage product will follow a simple harmonic motion, θ radians advanced in phase with respect to the corresponding motion of I.

DEGRADATION OF A ROTATIVE VECTOR INTO A STATIONARY VECTOR

It frequently happens that a quantity which is capable of being regarded as a rotative-vector quantity, needs only to be designated as a vector in respect of phase relation to another vector or vectors; as, for example, when a simple harmonic alternating current, of say 10 amperes r.m.s., is desired to be designated as a vector lagging, perhaps 37 degrees in phase, behind a simple harmonic impressed e.m.f. of 100 volts r.m.s. It would be possible to give a direct representation of this condition as in Fig 2 with a rotative vector $O\,E$ of 141.4 volt-scale length, followed at 37 deg. by a rotative vector $O\,I$ of 14.14 ampere-scale length. But if there is no necessity for drawing attention to the orthogonally projective properties of these vectors, they may be represented as a simple non-rotative pair, $O\,E$, $O\,I$, Fig. 10, in which case it is convenient to use their virtual or root-mean-square values, instead of their maximum values. We may consider that, quantitatively, this diagram represents the following conditions:

$$O\,E = O\,I\,\underline{/0^\circ} \times Z\,\underline{/37^\circ} \qquad \text{volt-scale cm. } \underline{/\quad} \qquad (9)$$

and

$$O\,I = O\,E\,\underline{/0^\circ} \div Z\,\underline{/37^\circ} \qquad \text{ampere-scale cm. } \underline{/\quad} \qquad (10)$$

That is, there is some non-rotative vector impedance of $10\,\underline{/37^\circ}$ ohms which connects, by Ohm's law, a virtual e.m.f. of 100 volts with a virtual current of 10 amperes lagging 37 deg. behind it.

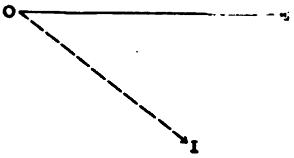

FIG. 10.—E.m.f. and lagging current. Stationary vectors.

In general, therefore, a non-rotative vector operator, such as an impedance, multiplied into a rotative vector, produces a rotative vector of changed amplitude and phase, but when multiplied either into a pure non-rotative vector, or into a stationary vector, produces a non-rotating vector of changed amplitude and phase, according to the property of multiplication of complex numbers:

$$a\,\underline{/\alpha} \times b\,\underline{/\beta} = a\,b\,\underline{/\alpha+\beta} \qquad \text{numeric } \underline{/\quad} \qquad (11)$$

POWER IN SIMPLE ALTERNATING-CURRENT CIRCUITS

It is well known that if a simple harmonic e.m.f. $E_0 \cos \omega t$ volts, where E_0 is the maximum cyclic value, propels a simple harmonic current $I_0 \cos (\omega\, t \pm \theta)$ amperes; so that the e.m.f. and current differ in phase by the positive or negative angle θ, the electric power developed in the circuit by the source of e.m.f. on the current is at any instant:

$$p_t = \frac{E_0\,I_0}{2}\,\{\cos\theta + \cos\,(2\omega t \pm \theta)\,\} \qquad \text{watts} \qquad (12)$$

$$= E\,I\,\{\cos\theta + \cos\,(2\omega t \pm \theta)\,\} \qquad \text{"} \qquad (13)$$

where E and I are respectively the virtual or root-mean-square e.m.f. and current; or if P be the product $E\,I$, of root-mean-square volts and amperes:

$$p_t = P\left\{\cos\theta + \cos\left(2\omega t \pm \theta\right)\right\} \qquad \text{watts} \quad \mathbf{(14)}$$

Consequently, any projective or interceptive rotating vector which represents the power in a simple alternating-current circuit must possess an angular velocity double that of the e.m.f. or current. Moreover the origin or axis of the rotating vector power must be displaced from the origin of the e.m.f. and current components.

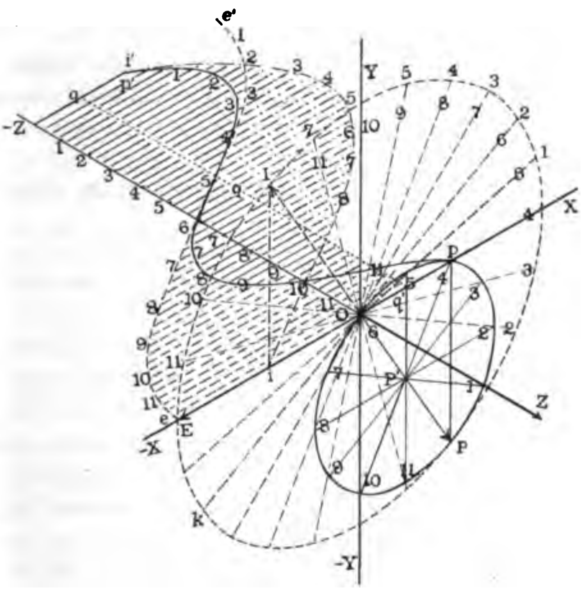

FIG. 11.—Rotative vector e.m.f. and current in inductively impedant circuit with double-frequency rotative vector power. Power factor 0.5. Isometric projection. Direct representation. $X\,O\,Y$ plane of rotation, $X\,O\,Z$ plane of projection.

It has been pointed out by Mr. J. Irving Brewer[1] that a construction which satisfies the rotative-vector power relations is to lay off $O\,E$, the maximum cyclic e.m.f., along the $O\,X$ axis, (Fig. 11) and $O\,I$ at the proper phase angle; in the case presented,

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[1] "Electrical World" Jan. 21, 1909, Vol. 53, No. 4, pp. 217–218. Inverse Notation.

$X\,O\,P$. Then on $O\,P$ at a point P', such that $O\,P' = E\,I$, to watt-scale, is the center of the rotating power vector which starts with doubled angular velocity from the position $P'\,P$, at the moment when E_0 starts from $O\,X$, and I_0 from $O\,P$.

Under these conditions, the three rotating vectors will project on the fixed axis $-X\,O\,X$, and on the moving plane $X\,O\,Z$, the respective instantaneous values of power, e.m.f. and current.

NON-ROTATIVE VECTOR POWER

If a simple harmonic current of I root-mean-square amperes flows through an alternating-current circuit of impedance $R+j\,X = Z\,\underline{/\alpha}$ ohms, ($A\,C$, Fig. 12), the root-mean-square potential-difference E volts on the circuit will be obtained by the operation:

$$E\underline{/\alpha} = I\underline{/0} \times Z\underline{/\alpha} = IZ\underline{/\alpha} \qquad \text{root-mean-square volts } \underline{/} \quad \textbf{(15)}$$

Here I is taken either as an ordinary real number, or as a plane vector number of zero angle, and therefore at standard phase. That is, I is taken as a stationary vector, so that E is also a stationary vector e.m.f., ($D\,F$ Fig. 12), advanced in phase α radians or degrees ahead of the current. The real component $D\,E$, is the effective root-mean-square component of potential difference, so far as concerns the average liberation of power from the source into the circuit, and the imaginary component $E\,F = j\,I\,X$, is the reactive root-mean-square component potential-difference, or the component which develops reactive power on the current. This reactive power is directed from source to circuit, and back again, in one power cycle, or in one half-cycle of current.

Again, if we multiply the non-rotative vector p.d. $D\,F$ by the stationary, vector current, according to the formula:

$$P\underline{/\alpha} = I\underline{/0} \times E\underline{/\alpha} = I\,E\underline{/\alpha} = E\,I\underline{/\alpha} \qquad \text{watts}\underline{/} \quad \textbf{(16)}$$

we obtain a stationary vector power G K, advanced α degrees or radians ahead of the current. This power is the apparent power, commonly called volt-amperes. It is perhaps practically advantageous to call the unit of apparent power the volt-ampere in order to distinguish apparent power from effective power in engineering; but a volt-ampere is essentially a watt, and the apparent power is correctly stated as apparent or resultant watts, the vector sum of effective and reactive watts[1]. The effective component $G\,H$ is the average power delivered to the circuit by the generator, and is usually called the " real power ". The reactive power $H\ \,K$ is, however, when considered from within the circuit, just as real as the effective power $G\,H$; so that the term " real power " is unsuitable. The reactive power $H\,K$ is the maximum cyclic power expended in transmitting energy into and out of the magnetic flux linked with the circuit, being alternately plus and minus, or from and to the generator, in successive quarter cycles of current. This energy is kept in the circuit; whereas the effective power $H\,G$ transmits energy out of the circuit. The maximum reactive cyclic power $H\,K$ is all internal. The effective power $G\,H$ is the average of that delivered externally, is the cyclic average of the instantaneous total internal power, and is also the maximum cyclic value of the externally delivered power.

Finally, if we divide the stationary vector power by $2\,\omega$ according to the equation:

$$W\underline{/\alpha} = P\underline{/\alpha}\ /\ (2\omega) \qquad \text{joules per energy cycle } \underline{/\ \ } \qquad (17)$$

we obtain the stationary energy vector $L\,N$. This is the maximum cyclic apparent, or resultant oscillatory, energy delivered by the generator to the circuit in each energy cycle, over and above the average effective energy delivered at the rate $G\,H$. The perpendicular component $M\,N$ is the maximum cyclic change of reactive energy in the magnetic flux of the circuit. The horizontal component $L\,M$ is the maximum cyclic oscillation of effective energy.

A practical example will illustrate the above conditions. We may assume a large single-phase 60-cycle alternator delivering at its switchboard eight megawatts (8,000 kw.) of effective power, and three megawatts of reactive power, or 8.544 apparent megawatts, under a power factor of 0.936. If the delivered current is 4,000 amperes, its terminal voltage will be 2,136 volts.

The stationary-vector power diagram for this generator is shown at $G\,H\,K$ in Fig. 12. The analysis of the circuit conditions is given in Fig. 13, to rectangular coördinates and to

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[1] A useful diagram of this type—essentially a stationary-vector power diagram—appears at page 540 of Mr. Percy H. Thomas' paper on " Calculation of the High-Tension Line ". PROCEEDINGS of A.I.E.E., June, 1909.

sinusoidal current phase. The current I has a maximum cyclic strength of $4000\sqrt{2}$, or 5,656 amperes. The potential difference E is ahead of the current by $\alpha = 20.6$ deg. It is analyzed into the effective component ($D\,E$ Fig. 12) of 2,000 volts root-mean-square, or $E_f = 2{,}828$ volts maximum (Fig. 13)

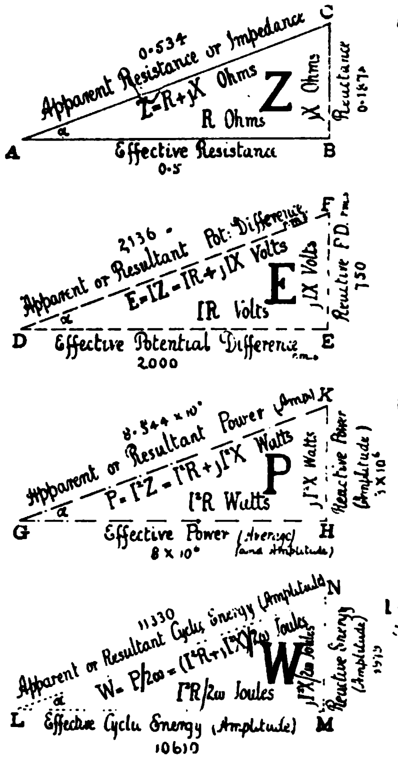

FIG. 12.—Stationary vector diagrams of impedance, potential-difference, power and cyclic energy in an alternating-current circuit to phase of current as standard.

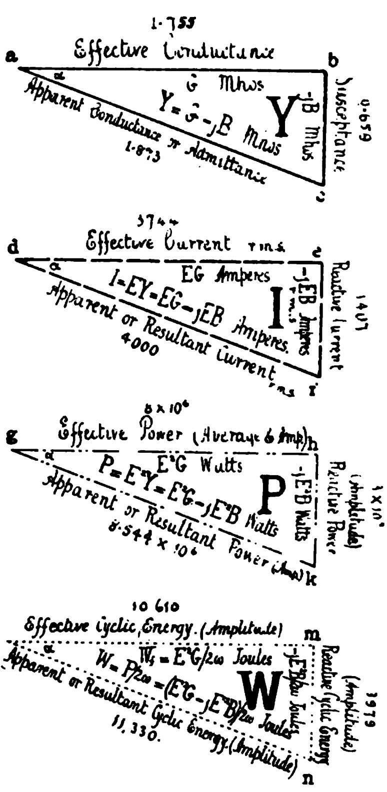

FIG. 14.—Stationary vector diagrams of admittance, current, power and cyclic energy in an alternating-current circuit to phase of potential-difference as standard.

and the reactive component $E\,F$ of 750 volts root-mean-square ($E_k = 1061$ volts maximum). The product $I\,E_f$ produces the effective power P_f of eight megawatts amplitude, ($G\,H$ Fig. 12) above and below the average P_m of eight megawatts. The product $I\,E_k$ produces the reactive power P_k of three megawatts amplitude (*H K* Fig. 12). The sum of these two quadrature power components is the total apparent power $I\,E = P$ of 8.544 megawatts above and below the mean P_m.

The reactive power P_k is associated with a cyclic energy change of $W_k = 0.3979$ myriajoule = 3,979 joules = 405.6 kilogram-meters or 2940 ft-lb. This energy (*M N* Fig. 15) is stored

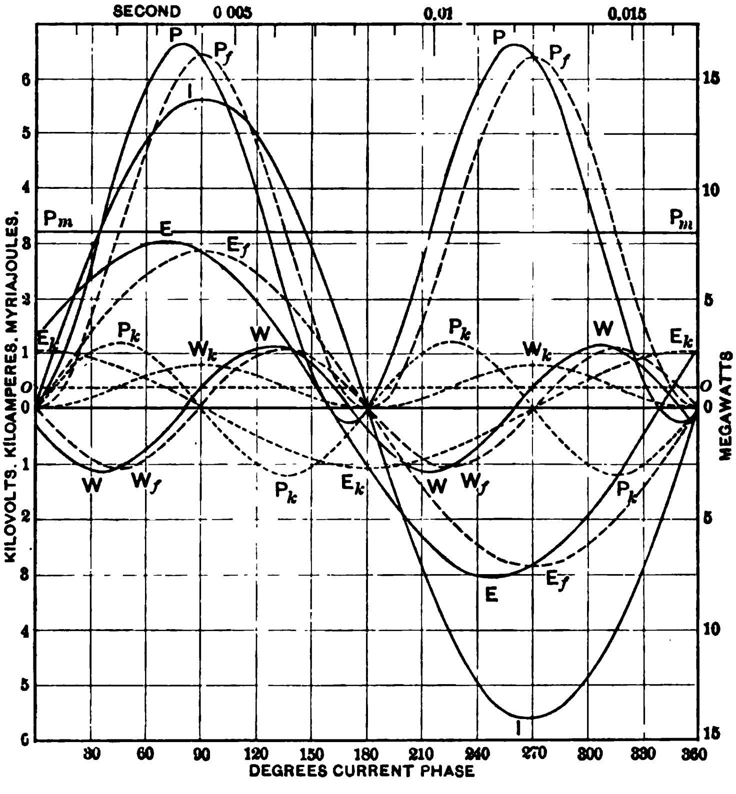

FIG. 13.—Analysis of potential-difference, power and energy to current as standard of phase.

in, or removed from, the magnetic flux of the circuit in one quarter of an energy-cycle, or one eighth of a current-cycle (0.00208 second) over and above a steady stock of energy *o o* (Fig. 13) of equal amount. The total magnetic energy in a current half-cycle is therefore:

$$2\,W_k = I^2\,X/\omega \qquad \text{joules per cycle of current} \qquad (18)$$

or 7958 joules (0.7958 myriajoule), at 90 deg. and at 270 deg. of current-phase.

The effective power P_f is associated with a cyclic energy change of $W_f = 1.061$ myriajoule in each cycle (*L M* Fig. 12) above and below the average of eight megajoules per second, or 13.333 myriajoules per current cycle, delivered by the generator outside of the circuit.

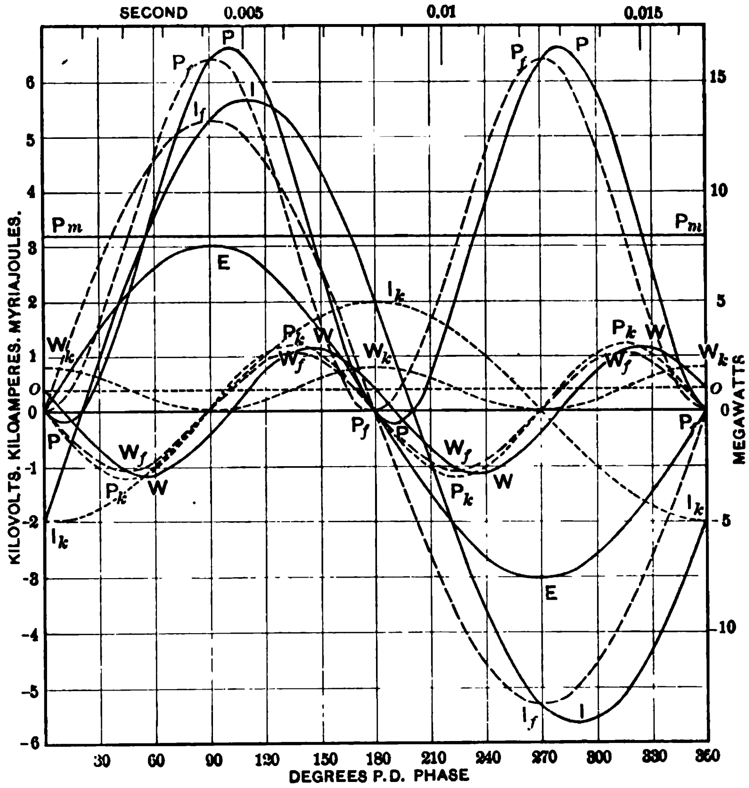

FIG. 15.—Analysis of current, power and energy to potential-difference as standard of phase.

The total cyclic energy change is $W = 1.133$ myriajoule (*L N* Fig. 12) above and below the average of 6.667 myriajoules per energy cycle.

Fig. 12 contains, therefore, a non-rotative impedance triangle *A B C* of ohms, a stationary potential-difference triangle *D E F* of root-mean-square volts, a stationary power triangle *G H K* of maximum cyclic or amplitude watts, and a stationary energy triangle $L\,M\,N$ of maximum cyclic or amplitude joules. These four non-rotating vector triangles pertain to every alternating-current circuit, considered with reference to the stationary vector current $I\underline{/0}$ root-mean-square amperes. If the circuit contains condensance, instead of inductive reactance, the four triangles will all be inverted, with negative reactive quantities, or of the geometrical type indicated in Fig. 14. If the current and p. d. in the circuit are sinusoidal, then all of the 18 vector quantities involved will be strictly interpretable by simple harmonic theory. If the current, or the potential-difference, or both, are only approximately sinusoidal, the vector triangles may still be computed, and they permit of being considered as " equivalent sinusoidal " triangles.[1] In this case, however, the various vector quantities cease to be strictly interpretable physically. Finally, if the current or potential-difference, or both, depart widely from the sinusoidal type, the vector triangles, although still existing logically and geometrically, may fail completely to be interpreted physically. That is, the vector impedance, voltage, power and energy may be inconsistent with the physical conditions. In such cases, it is necessary to analyze the current and potential-difference into harmonic components, develop a series of vector triangles, one for each component, and aggregate the separate effects.[2]

If in a single-frequency (simple harmonic) circuit, the impedance triangle be given and the root-mean-square current, the other three vector triangles of E, P and W, follow immediately, and without any ambiguity. That is, the stationary-vector series Z, E, P and W is unique. But if either the power or energy triangle be given initially, the Z triangle which follows therefrom is ambiguous, because there may be condensance associated with the reactance, either in series or parallel, and a doubly infinite system of circuits could therefore be devised that would satisfy the W, P, and E vectors. The only definite conclusion in such a case is that the reactance preponderates over the condensance to the amount indicated by the X of the Z triangle.

If one or more impressed counter-electromotive forces exists in

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[1] Steinmetz, " The Law of Hysteresis ", TRANSACTIONS A.I.E.E., May, 1894, Vol. 11, pp. 570, 616.

[2] Steinmetz, " Symbolic Representation of General Alternating Waves and of Double-Frequency Vector Products ", TRANSACTIONS A.I.E.E., June, 1899. Vol. 16, pp. 269–304.

the circuit, as, for example, that of a synchronous alternating-current motor, the Z diagram that follows from a given P diagram and current I, is logically consistent, and may be practically useful, but is purely fictitious.

If instead of taking the phase of the current as standard, we take the phase of the potential-difference as standard, we exchange $E\underline{/0}$ for $I\underline{/0}$ as the fundamental stationary vector, and we obtain the four stationary vectors Y, I, P, and W of Fig. 14, connected by the relations:

$$I \,\overline{\diagdown}\,\alpha = E\underline{/0}\,.\; Y \,\overline{\diagdown}\,\alpha \qquad \text{root-mean-square amperes } \underline{/\quad} \tag{19}$$

$$P \,\overline{\diagdown}\,\alpha = E\underline{/0}\,.\; I \,\overline{\diagdown}\,\alpha \qquad \text{max. cyclic watts } \underline{/\quad} \tag{20}$$

$$W \,\overline{\diagdown}\,\alpha = (P \,\overline{\diagdown}\,\alpha)/(2\,\omega) \qquad \text{max. cyclic joules } \underline{/\quad} \tag{21}$$

It will be observed that the P and W triangles in Fig. 14 are inverted by comparison with those in Fig. 12, and yet the same single-phase alternator is supposed to be operating on the same circuit in each case. The anomaly is explained by the fact that as shown by Figs. 13 and 15, the resultant power curve P lies intermediate in phase between the current curve I and the potential-difference curve E, so that while the power is leading with respect to the current, it is lagging with respect to the potential-difference. Consequently, the stationary power vector of an alternating-current circuit has, with direct representation, either a negative or a positive angle, according as the phase of one or other of the two quantities E and I is taken as standard, as well as whether the circuit is reactive or condensive.

By comparing Figs. 13 and 15, it will be seen that the curves E, I, P and W, or resultant potential-difference, current, power and energy, all correspond, or may be superposed each on each; but the components E_f, E_k, I_f, I_k, P_f, P_k and W_f, W_k lie on reversed sides of their respective resultants in the two figures, as called for by the two sets of stationary-vector diagrams in Figs. 12 and 14.

It follows therefore that the P and W stationary-vector diagrams exist in two mutually inverted forms for every single-frequency alternating-current circuit; whereas the E, I, Z and Y stationary-vector diagrams are single, their position (erect or inverted), depending upon whether the circuit is inductively or condensively reactant, as well as upon whether direct or inverse representation is employed.

ROTATIVE PROPERTIES OF THE STATIONARY VECTORS $E, I, P,$ AND W

In Fig. 12 the vector $E = I Z$ is taken as stationary; but it is of course capable also of being considered as a rotative vector, rotating about the vertex D, with the angular velocity ω. In that case, the three voltages E, E_f and E_k should each be increased in the ratio of $\sqrt{2}$, or should be changed in scale, in order that their orthogonal projections on a stationary reference axis, or interceptions on a stationary circle, should correspond to the several instantaneous voltages of impressed potential-difference, effective potential-difference and reactive potential-difference.

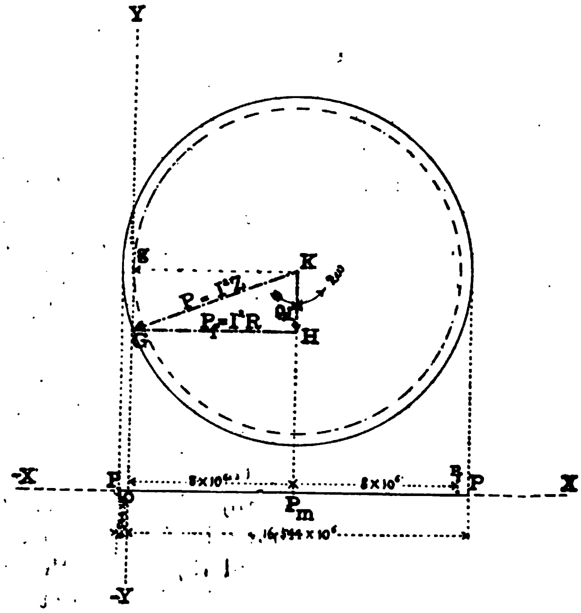

FIG. 16.—Rotative vector power diagram for current standard phase.

In Fig. 12 the power vector $P = I^2 Z$ is also taken as stationary; but it is capable of being considered as a rotative vector without any change of scale, by rotating the triangle $G H K$, about the vertex K, with the positive angular velocity 2ω. This is represented in Fig. 16, where K is the center of rotation in the plane $X\,O\,Y$ of the paper, $K\,g = H\,G$, and the extreme left-hand projection of g is taken at o, as the origin of power coördinates, in the plane $X\,O\,Z$ of projection. The projection of K, at P_m, then marks off the steady average power of the system in watts, while the projection points $P\,P$, marking the limits of the rotating vector $I^2\,Z$, indicate the range of cyclic oscillation of the power. Thus, as shown in Fig. 13, the power pulsates between -0.544 and $+16.544$ megawatts once in each power-cycle, or half current-cycle. Similarly, the rotating vector $K\,H$ projects, with respect to the center P_m, the instantaneous magnitude of the reactive power P_k about the zero line $O\,O$, Fig. 13. In accordance with Fig. 13, the rotation of Fig. 16 is assumed to start at a moment when the vector current I, rotating with angular velocity, ω, if applied with its center on K, would occupy the direction $K\,H$.

Similarly, if we rotate the power triangle in Fig. 14 about its vertex k, with the angular velocity $2\,\omega$, we shall obtain the same diagram as Fig. 16, except that the phase order of advance will be reversed; *i.e.*, P_f, followed by P and P_k, instead of P_k followed by P, and P_f. The orthogonal projections of these three vectors will then correspond to the curves P_f, P and P_k as given in Fig. 15 to potential-difference phase.

In Fig. 12, the energy vector $W = I^2\,Z/(2\omega)$ is also taken as stationary; but it is capable of being considered as a rotative vector without any change of scale, by rotating the triangle $L\,M\,N$ about the vertex N with the positive angular velocity $2\,\omega$, and taking instantaneous projections—not on the $X\,X$ axis—but on the $Y\,Y$ axis, as shown in Fig. 17. Here the successive rotating vectors, W_k, W, and W_f project the sinusoidal curves W_k, W, and W_f of Fig. 13, each with respect to its own zero line. At the moment represented in Fig. 17, the current I is supposed to start with angular velocity ω from the position $N\,M$, with center N, and to project orthogonally on the $X\,X$ axis.

Similarly, if we rotate the stationary energy triangle $l\,m\,n$ of Fig. 14, about the vertex n, with positive angular velocity $2\,\omega$, and project upon the $Y\,Y$ axis, we shall obtain a diagram like that of Fig. 17, except that the order of vector succession will be reversed, in accordance with the projected curves of Fig. 15.

But the rotating energy vector of Fig. 17 only projects the fluctuation of energy in the circuit. There is, in addition to this fluctuation of energy, a steady stream of energy delivered from the circuit, corresponding to the steady average power

$O\,P_m$ of Figs. 13, 15 and 16. If we represent the steady energy stream by the straight line $O\,P_m$ in Fig. 18, which shows 8 myriajoules in 0.01 second, or at the rate of 8 megajoules per second, then the resultant oscillation of energy, by Figs. 12, 13, 14, 15, and 16, is the sinusoidal curve *W W*, completing two cycles in 1/60th of a second. Superposing the fluctuation on the steady stream, we obtain the broken wavy line *a*, *b*, *c*, *d*, of energy delivered from the generator against time, or current phase, as abscissas. It will be seen that, between 150 and 200 degrees of phase, the energy flow halts, and slightly reverses. At this time, and at corresponding times in successive energy cycles, the energy ceases to flow from the generator to the circuit; but ebbs back from the circuit to the generator.

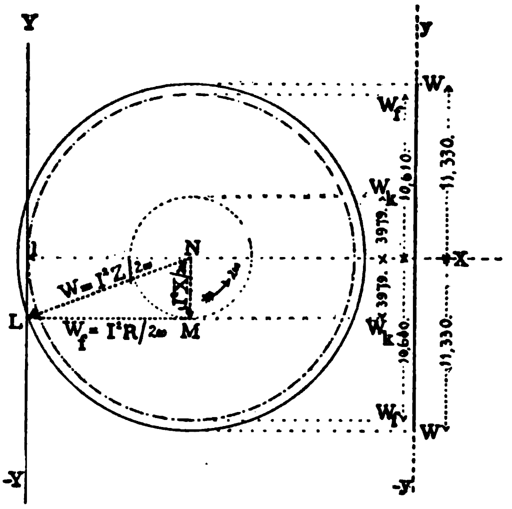

FIG. 17.—Rotative-vector energy diagram for current standard phase.

The above state of energy affairs may be represented projectively by imparting to the center of the uniformly rotating energy vector *N L* or *n l* (Fig. 17), a uniform velocity of translation of P_m joules per second in the direction of the *Y* axis. But this is equivalent to mounting the energy vector on a wheel whose axis is at *N* (Fig. 19), the rotation being on the *X Y* plane. The tread radius of the wheel is made equal to W_f, to joules scale, the flange radius of the wheel is made equal to *W*, to joules scale. A point on the flange is then allowed to project orthogonally on the *Y Y* axis, as the wheel rolls on the *Y Y* rail at the angular velocity 2 ω radians per second. The path of the moving flange point L, on the $X\ Y$ plane, will be an oblate trochoid as shown, and the projection of the point, at 24 successive equal time intervals during the motion, is indicated on the line $y\ y$. It will be seen that the trochoid forms a small recedent loop at the end of its curve, and while the tracing point describes this loop, the energy projection-point undergoes a small recession. If the tracing plane $Y\ O\ Z$ should move uniformly in the direction $O\ -Z$ during the motion, the trace could be made to correspond to the curve a, b, c, d, of Fig. 18.

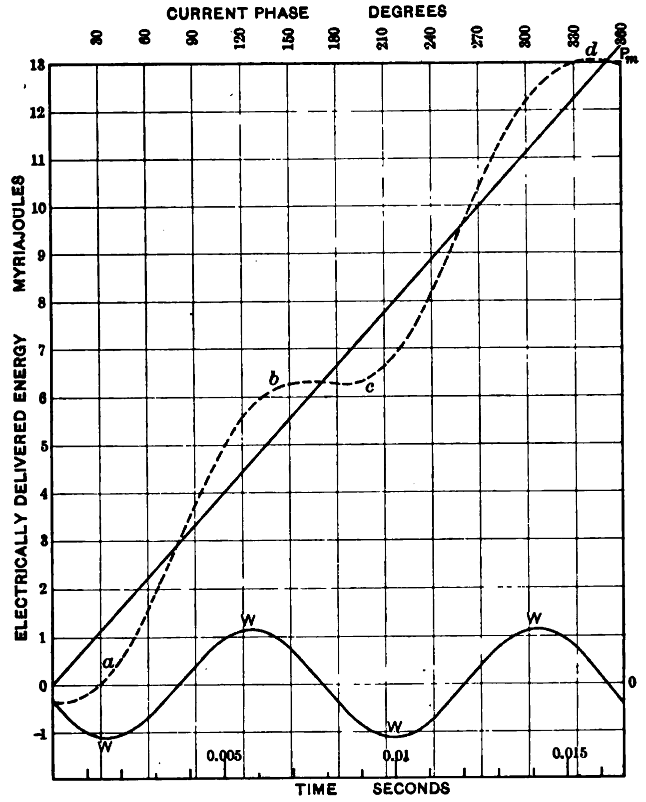

FIG. 18.—Energy-time diagram of alternating-current generator.

If the circuit, instead of being inductively reactive with a power-factor of 0.936, should be non-inductive (with power-factor 1.0), the flange on the rolling wheel disappears. The tracing point then lies on the tread of the wheel. As shown in Fig. 20, the tracing point describes a cycloid in the $X\,O\,Y$ plane, and the recessional loops in the tracing path disappear. The energy delivered by the generator to the circuit then halts at each cycle of energy vector rotation, or turn of the wheel; but it does not reverse.

If, on the contrary, the impedance factor Z/R of the circuit increases, either inductively or condensively, the flange radius bears the same proportion to the tread radius. The oblate trochoid described, as in Fig. 21, by the tracing point on the flange, develops larger recessional loops to the left of the line $Y\,Y$, with more marked reversals of motion and energy in the projected point.

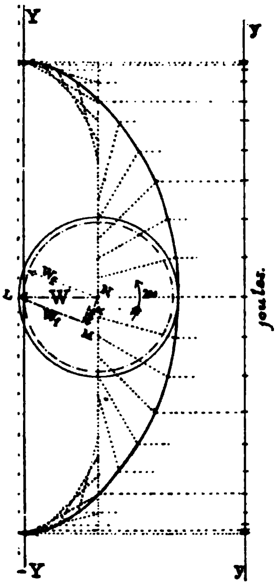

Fig. 19.—Projection energy of rotative- and rolling-vector energy triangle.

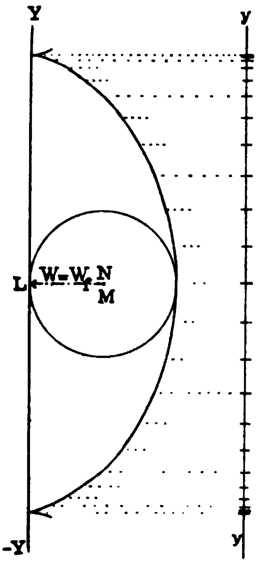

Fig. 20.—Rotating- and rolling-vector energy for non-inductive circuit.

Analytically, if W be the flange radius, and W_f the tread radius of the rolling wheel, the distance of the projected point along $y\,y$ from the initial position at which W lies parallel to the $-X\,X$ axis is:

$$w_t = W_f\, 2\omega t + W \sin 2\omega t \qquad \text{joule-scale cm.} \qquad (22)$$

or substituting for W_f and W their values $P_f/2\omega$ and $P/2\omega$ respectively,

$$w_t = P_f t + \frac{P}{2\omega} \sin 2\omega t \qquad \text{joules} \qquad (23)$$

$$\therefore \quad p_t = \frac{d w_t}{dt} = P_f + P \cos 2\omega t \qquad \text{watts} \qquad (24)$$

as already deduced from Figs. 13 and 15.

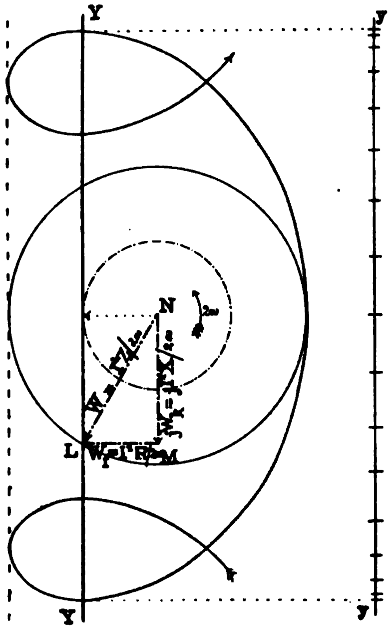

Fig. 21.—Rotative- and rolling-vector energy triangle for circuit of power factor 0.5.

Finally, if the circuit be purely reactive, or resistanceless, the tread radius becomes zero, and the wheel spins without rolling. The path of the tracing point on the flange is then a pure circle. Its projection on the $Y\,Y$ axis is a simple harmonic motion, and on the $Y\,O\,Z$ plane, a pure sinusoid.

Consequently, with suitable convention as to direction and sign of translatory motion, the energy given to an alternating current circuit may be represented by the vertically falling shadow, on the horizontal supporting rail, of a point on the flange of a uniformly rolling wheel. The rate of motion of this shadow will be the power given to the circuit. The average power will be represented by the uniform speed of the axle. The instantaneous power by the instantaneous velocity of the shadow. If a second wheel be geared with the axle so as to rotate in the same direction with half the angular velocity, suitably selected radii on the latter wheel will represent the p. d. and current in the circuit, the instantaneous projections of these radii being measured on a vertical coördinate axis, and not on the horizontal rail.

CONFORMITY OF THE ALGEBRA OF THE ALTERNATING-CIRCUIT AND CONTINUOUS-CURRENT CIRCUITS

Finally, it should be pointed out that just as, in regard to impedances, admittances, currents, and e.m.fs., the algebra of the single-frequency alternating-current circuit is the same as the algebra of the continuous-current circuit, the former dealing with complex quantities while the latter deals with real quantities;[1] so the algebrá of both circuits is the same, or at least may be regarded as the same, in dealing with power. For the power product of an e.m.f. $E\underline{/0}$ and a current $I\underline{/\theta}$, or of an $E\underline{/\theta}$ and a current $I\underline{/0}$, is $E\,I\underline{/\theta} = I\,E\underline{/\theta}$ watts and not $E\,I\cos\theta$ watts. The average externally delivered power, as well as the average instantaneous power, is however $E\;I\cos\theta$ watts and the maximum cyclic internally-reactive power is $E\,I\sin\theta$ watts.

SUMMARY OF CONCLUSIONS

The algebra and geometry of vector alternating-current technology, as developed in text books, are, at present, in a state of great and unnecessary confusion as to direction of rotation.

The confusion has existed for more than twenty years, and is not confined to any one country or language.

Calling that representation " direct " which denotes a *leading* current as *leading*, in the order of positive rotation, some two thirds of the alternating-current text-books use direct representation, and the remaining one third inverse representation.

The existing dissension relates to conventions and not to facts.

The directions of rotation and representation should be standardized by mutual international agreement.

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[1] This law was first announced by the writer, restricted however to impedances and admittances, in the paper on " Impedance ", TRANSACTIONS A.I.E.E., April 1893, Vol. 10, pp. 175–232. The law was speedily extended by Dr. C. P. Steinmetz to cover currents and e.m.fs.

The terms "real power" and "wattless power" are inaccurate and misleading.

It is readily possible to compute and discuss the power in an alternating-current circuit as a stationary-vector quantity, without reference to the double frequency of rotative-vector power.

The power developed by any single-frequency alternating e.m.f. E root-mean-square volts on a co-frequent current $I\underline{/\pm\theta}$ root-mean-square amperes, is algebraically $E\,I\underline{/\pm\theta}$ watts. The externally liberated power is $E\,I\cos\theta$ watts, and is usually the principal consideration in power-transmission systems.

In any alternating-current circuit, or portion of the same, there are four non-rotating vectors Z, E, P, W to standard current phase, and also four Y, I, P, W, to standard potential-difference phase, all connected by ordinary vector arithmetic, and not involving double-frequency products.

The energy in a single-frequency alternating-current circuit follows the projection, upon the rail, of a flange-point on a wheel rolling along the rail with uniform angular velocity. The path of the flange-point is an oblate trochoid for reactive circuits—but is a cycloid for a non-reactive circuit.

The algebra of alternating currents may be regarded as the same as the algebra of continuous currents, for power as well as for other quantities; so that any formula relating to direct-current circuits is also a formula relating to single-frequency alternating-current circuits, when complex numbers are substituted for real numbers.

NOTATION EMPLOYED

a, b, Vector lengths (cm.).

α, β, θ, Vector angles, or phase angles (radians or degrees).

B Susceptance of a circuit, as a whole, or beyond a pair of points in the same (mhos).

c Capacity of a condenser (farads).

E_0, E E_f E_k, Maximum cyclic, virtual or root-mean-square, effective, and reactive e.m.f. in a circuit, or potential-difference at a pair of points in the same (volts).

e_t Instantaneous voltage or P. D. in a circuit at time t (volts).

$\varepsilon = 2.71828\ldots.$ (numeric).

G Conductance of a circuit as a whole, of beyond a pair of points in the same (mhos).

I_0, I, I_f I_k Maximum cyclic, virtual or root-mean-square, effective, and reactive current strength in a circuit (amperes).

i_t Instantaneous current strength in a circuit (amperes).

$j = \sqrt{-1}$ (quadrantal operator).

L Inductance in a circuit (henrys).

l Polar radius-vector of a complex number.

n Frequency of alternation (cycles per second).

ω Angular velocity of a rotating vector, or of an alternating quantity, (radians per second, or degrees per second).

P, P_f, P_k, Resultant, effective, and reactive maximum cyclic power in a circuit (watts).

P_m Average power in a circuit (watts).

p_t Instantaneous power in a circuit at time t (watts).

$\pi = 3.14159\ldots.$ (numeric).

R, r, Resistance in a circuit, or conductor (ohms).

T, A constant time interval (seconds).

t Elapsed time interval (seconds).

W, W_f, W_k, Resultant, effective and reactive maximum cyclic energy (joules).

w_t Instantaneous energy in a circuit (joules).

X, x, Reactance in a circuit (ohms).

Y, Admittance, or resultant conductance, in a circuit (mhos).

Z, z, Impedance, or resultant resistance in a circuit (ohms).

$X\,X$, $Y\,Y$, $Z\,Z$, Rectangular coördinate axes.

DISCUSSION ON "VECTOR POWER IN ALTERNATING-CURRENT CIRCUITS". JEFFERSON, N. H., JUNE 29, 1910.

C. P. Steinmetz: The standardization of vector notation in alternating current theory is of importance. Considering the difficulty which college students often have to get a conception of one method of vector notation, the existence of two methods, of which the one appears the reverse of the other, evidently is very regrettable. A standardization of vector notation would therefore be very desirable, if feasible. The difficulty is, that we are here in the field of applied mathematics, and in mathematics, the right of priority, and resulting therefrom an international method of notation, is generally recognized. Thus, whatever standard we select, must conform with the existing standards of mathematics, as it obviously would not be reasonable to expect all other sciences to change their notation to conform with our standards; and inversely, no action of ours could exclude from use in electrical investigations, methods which are standard in other sciences.

To explain the situation, we may for a moment discard all the various conventions of vector analysis, which have been proposed in electrical engineering, and go back to the starting point, the conventional methods of elementary mathematics, which the student brings with him when he enters the field of electrical engineering.

In analytic geometry we become familiar with the representation of geometrical figures, curves, etc., by rectangular co-ordinates. Then we learn a second method of representation, by the system of polar co-ordinates, in which the angle represents the independent variable, the radius the dependent variable. We find that the polar co-ordinate system is especially convenient and suitable for periodic functions.

Entering the field of electrical engineering, we meet in the alternating current a function of time, and naturally represent it graphically in rectangular co-ordinates, with the time as abscissae and the current, or voltage etc., as ordinate, by a wave line, the usual sine wave, as shown in Fig. 1, which is familiar to all, even the non technical men; or, if we happen to deal with a current which is not a sine wave, by a wave line of some other shape, for instance like Fig. 2. Such are the records given by the oscillograph.

Now we realize that the alternating current is a *periodic* function of time, and that periodic functions are more conveniently represented by polar co-ordinates. We thus plot the current wave in polar co-ordinates: the angle, ϕ in Fig. 3, is the abscissa of the rectangular co-ordinate representation Figs. 1 and 2, that is, the time t; the radius i is the ordinate, the current, voltage, etc. This gives us as the polar curve, that is, the representation in polar co-ordinates, of the sine wave Fig. 1, the *circle* Fig. 4; the distorted wave of Fig. 2, that is, a wave differing from a sine shape, gives in polar co-ordinates a curve differing from a circle. Fig. 5.

Thus far we have followed the existing international convention of mathematics, and thus far therefore no occasion nor possibility exists for electrical standardization, but we follow the already existing and immovable standards of mathematics.

In many electrical problems, we can replace the distorted wave, Figs. 2 and 5 respectively, by its equivalent sine wave. The polar circle, which represents the equivalent sine wave, is easily derived from the polar curve Fig. 5. It is a circle having the same area as the polar curve of the distorted wave, Fig. 5, and its diameter is the bisector of the area of curve Fig. 5. Thus the representation in polar co-ordinates lends itself very conveniently to the determination of the equivalent sine wave and the effective value of the wave. Irrespective of any further use in vector analysis, the polar co-ordinate system of representation thus is largely employed for deriving the effective value of a distorted wave, and, with the increasing use of the oscillograph will be increasingly used. Thus, in working up oscillograph records, the curve given by the oscillograph (for instance Fig. 2) is replotted in polar co-ordinates (Fig. 5), its area measured by planimeter, and this area, divided by $\frac{\pi}{2}$, is the effective value of the distorted wave, or the value of its equivalent sine wave.

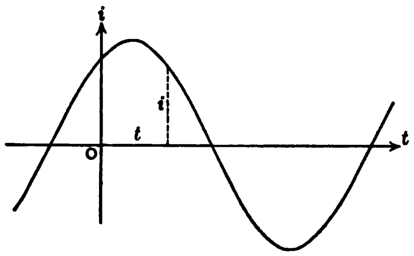

FIG. 1

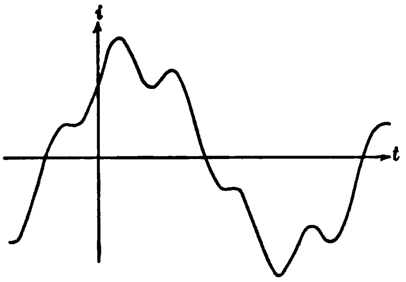

FIG. 2

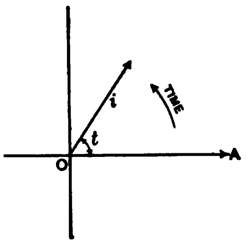

FIG. 3

The circle, Fig. 4, thus is the representation of the sine wave, or of the equivalent sine wave of the distorted wave, in polar co-ordinates.

In those electrical problems, in which we do not have to deal with the instantaneous values, but with the current as a whole, we may omit drawing the circle, but merely give its diameter, $\overline{OI}$ in Fig. 6. Thus, as a natural sequence of the standard methods of analytic geometry, we get in the diameter $\overline{OI}$ of the polar circle the vector representation of the alternating current, voltage, etc. The length $\overline{OI}$ then represents the intensity, its angle $A\ O\ I$ the time, at which the maximum value of the current occurs, that is, its phase. If then, in Fig. 6, $\overline{OI}$ is a current vector, $\overline{OE}$ a voltage vector, Fig. 6 completed by drawing the polar circle with $\overline{OI}$ and $\overline{OE}$ as diameters, gives in Fig. 7 the current wave i, and the voltage wave e in polar co-ordinates. As shown in Figs. 6 and 7, $\angle A\ O\ I$ is greater than $\angle A\ O\ E$; that is, the current i reaches its maximum, and thereby also any other point of the wave, at a later time, $\angle A\ O\ I$. Then the voltage e reaches its maximum (and thereby also any other corresponding point of the wave) at $\angle A\ O\ E$. That is, current i lags behind voltage e in Figs. 6 and 7.

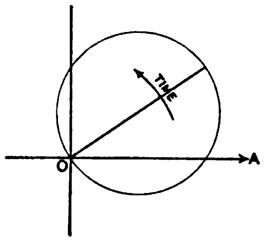

FIG. 4

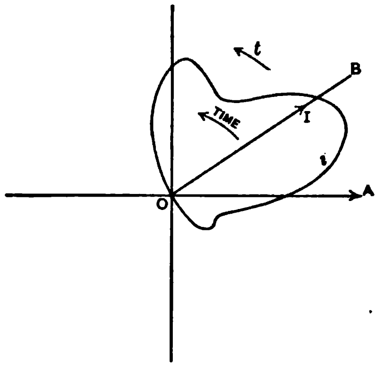

FIG. 5

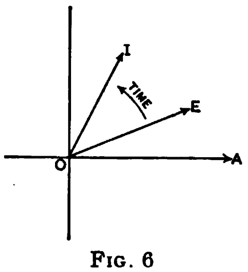

FIG. 6

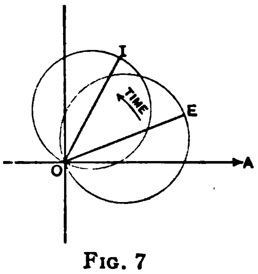

FIG. 7

When, some twenty years ago, I desired to represent alternating waves graphically, I thus used this method as the customary and thereby obvious method of dealing with periodic functions in analytic geometry, rather than attempting to devise a new and different method.

Such a different method has however been devised, in the crank diagram, and is used to a considerable extent. It is the method preferred by a number of engineers, but which always appeared to me as rather forced in its derivation, and thus more difficult for the student to get a really good conception of it, as it has no relation to the representation of alternating waves in rectangular co-ordinates (Figs. 1 and 2), which after all is the most obvious and intelligible, and therefore most generally understood method, though less suitable for theoretical investigation.

In the representation by the crank diagram, we discard altogether the usual representation in rectangular co-ordinates, as for instance given by the oscillograph, and proceed to devise a new method: Let, in Fig. 8, a line $\overline{OI}$ be drawn, which by its length represents the maximum value of a sine wave of current, and assume, that this line $\overline{OI}$ revolves uniformly, like the crank of a reciprocating steam engine, making one revolution per *cycle*. Then the projections of $\overline{OI}$ on the horizontal represent the instantaneous values of the current. At the moment of time, when the revolving vector $\overline{OI}$ passes the horizontal $\overline{OA}$, the wave reaches its maximum; at the moment, when it passes the vertical, the wave reaches its zero value. If, in Fig. 9, $\overline{OI}$ and $\overline{OE}$ represent respectively a current and a voltage in the crank diagram, in the relative position shown in Fig. 9, $\overline{OI}$ lags behind $\overline{OE}$, since during its rotation it passes the horizontal $\overline{OA}$ later, than $\overline{OE}$ passes it. As seen, the crank diagram, Fig. 9, is the reverse, or the image of the polar diagram Fig. 6, and to the casual inspector, familiar with one of the diagrammatic representations, the other diagram thus looks as if it used a rotation in opposite direction, that is, clockwise. This obviously is not the case, but both types of diagrams use counter-clockwise as positive direction.

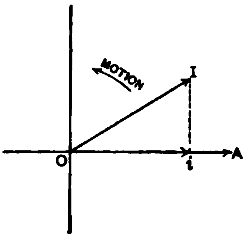

FIG. 8

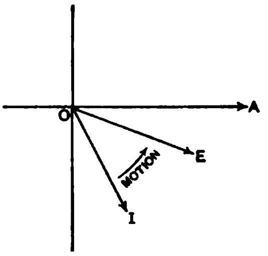

FIG. 9

One of the main objections to the crank diagram is, that it is suitable only for sine waves, and with the increasing importance of wave shape distortion, and the increasing necessity of studying distorted waves, resulting from the rapid extension of the use of the oscillograph, this appeared to me as a very serious objection. To assume, when dealing with distorted waves, that the vector of the crank diagram revolves with a varying speed, or that during its revolution it shrinks and expands in accordance with the deviation of the wave from sine shape, leads to such complication as to be impracticable. This limitation to sine waves appears to me as one of the main reasons, why a standardization of the crank diagram could not fulfil the purpose of securing uniformity of notation, by eliminating the polar diagram, since the latter would still have to be used when dealing with distorted waves, as for instance when working up oscillograph records, etc.

As regards to the terms " direct representation ", and " inverse representation ", used for distinguishing the two methods of representation, these terms obviously are relative only, and either representation would appear as inverse representation to the engineer familiar with the other representation. To me the polar diagram, which uses the time as co-ordinate, in representing the periodic function of time, always appeared as the more direction representation, and the crank diagram, which introduces mechanical rotation as intermediary, appeared as rather an indirect representation of a function of time, and I am somewhat of the opinion that the crank diagram owes its existence to the notion of mechanical analogy with the motion of the reciprocating steam engine, but it does not appear to me desirable to tie our standard electrical notation to conceptions of steam engine design, but rather to use the established conventions of mathematics, that is, the standard system of polar co-ordinates.

The second topic discussed in Dr. Kennelly's paper is a very interesting and ingenious method of representing power in the vector diagram. I am afraid however, that this method has the same disadvantage as the two methods of representing double frequency quantities, which I once devised, namely, it is rather complicated. This seems to be an inherent difficulty resulting from the attempt to represent a double frequency quantity in a single frequency vector diagram.

Gano Dunn: It would be a great advantage if there were uniformity in vector representation, and as we have the International Electrotechnical Commission, a tribunal that has been organized for the very purpose of acting upon questions of this kind, I move that the International Electrotechnical Commission be asked for a ruling upon the standardization of the direction of vector representation.

This will set to work a large body of authorities whose decisions would be respected by technical authors and those finding would contribute toward removing what is now a serious difficulty.

Those of us who have had the advantage of employing engineers brought up at the feet of Dr. Steinmetz know, when those engineers make a certain diagram, what it means, but there are many other engineers educated under other auspices, who mean just the reverse by diagrams that look like Dr. Steinmetz's and the confusion is growing worse every day.

The difficulty cannot be corrected all at once, but it would disappear in time if all future representations should follow as a standard, one or the other of the present forms.

Wm. W. Crawford: As a pupil of Professor Franklin, to whom Dr. Kennelly has given three places in his tabulation of text-books, I do not feel like allowing this opportunity to pass without saying a word in defense of the counter-clockwise rotating vector diagram. In the elementary text-book of trigonometry which I studied, a positive angle is considered as an angle measured from a certain horizontal reference axis to another line which is rotated in a clockwise direction from the reference axis. . The sine of the angle is defined as the projection of a unit length of this line on a vertical axis, and the cosine as the projection on the horizontal axis.

When we come to the study of the alternating current, we are taught that it is represented by a sine curve. To my mind no simpler conception can be obtained than by referring at once to the definition of the sine function and representing our sine wave by the projection on a vertical axis of a rotating vector. Since the trigonometric vector rotates counter-clockwise the alternating current vector should do the same.

John B. Taylor: The use of two confusing methods of representing the same conditions in a vector diagram still continues —a condition which is far from satisfactory. Personally, I studied the direct method, but later, on going to Schenectady, I worked with men who had been under the influence of Dr. Steinmetz, and who naturally were more familiar with his " inverse " method.

It seems fair to say that the two methods discourage many from reading the work of others; cause occasional errors in connections and mistaken predictions and conclusions, besides consuming much time and mental effort which have some sort of a monetary equivalent. For these reasons I want to second the motion made by Mr. Dunn that the matter be brought to the attention of the Board of Directors, for whatever additional formality is necessary, to bring the matter to the attention of the International Electrotechnical Commission, with a view to simplifying this double state of affairs.

Dr. Kennelly does not like the term " wattless power ". Mr. Thomas is with us to-day, and he made quite extensive use of the term last year—some people thought it was a very good term and some did not like it. Possibly some of the members may have looked over the TRANSACTIONS of the Institution of Electrical Engineers and noted the objections to the term in England. From their published proceedings it appears that objections were raised to the expression " wattless power " in the discussion of a paper, and in defense of the term Dr. Steinmetz was quoted. However, the man who objected to it, said that he did not see that any one other than " a genius unfettered by the ordinary limitations of language " had title to use it.

L. T. Robinson: I also rise in support of the motion. I believe it is the right thing to have this matter referred to some body that will try to decide it in a satisfactory way. Although I have some quite definite views, which are in accordance with Dr. Steinmetz's views in the matter, I think there is no need to put them forth at this time. After hearing the views of two such prominent exponents of the two different ways; at the same time we should have it one way or the other, and have it settled, and I wish to support Mr. Dunn's motion.

C. P. Steinmetz: I also would like to support the motion to refer the matter to the International Commission, because thereby we will have an opportunity to discuss the matter fully. It needs full discussion, before all misconceptions are cleared up. I rotate counter-clockwise, but the quantity which revolves in my diagram is the independent variable, the time, and the vector represents the complete curve of instantaneous values in polar co-ordinates of time. Thus the vector of the time diagram does not represent an instantaneous position, a momentary condition of the periodic wave, but represents the wave as a whole, and the position of the vector is the time of the maximum value of the wave, or of the equivalent sine wave. Thus, on one point we all agree, that counter-clockwise is the positive direction, but the question in dispute is whether in representing alternating waves, we shall consider the alternating wave as represented by the mechanical rotation of a revolving vector, or represented by the stationary vector, of polar co-ordinates of time.

L. T. Robinson: I would suggest that when this matter is submitted to the International Electrotechnical Commission, that Dr. Steinmetz and Dr. Kennelly be asked to submit in behalf of this Institute a brief memorandum covering the facts as they understand them, to aid the Commission in coming to a rapid decision.

Gano Dunn: It was my intention that the question should reach the International Electrotechnical Commission through the American Committee, which would transmit the request of the Convention. Action by the American Committee in bringing the matter to the attention of the Commission would have greater weight if there were the request of this Convention behind it.

It was not intended in referring the question to the Commission that this reference should carry with it any intimation as to which of the two directions of vector representation the American Institute of Electrical Engineers, preferred. My motion was merely to get our difficulty before the Commission for such suggestions or ruling as they might care to make, and I intended that the channel through which it should be presented to the Commission should be the Commission's American Committee. Our Committee might feel unauthorized to present the question unless there was some desire on the part of the Convention, to have it presented.

It appeared at first that a large majority of those present favored direct rotation but this majority might not have been willing to submit the question to the arbitration of the International Electrotechnical Commission, having in mind that submission involved some responsibility for acting according to what the Commission might find.

As a member of the American Committee I wish to place it in the position of feeling authorized to ask for a ruling from the Commission.

The Chairman: You have heard the motion, which is seconded. All in favor signify by saying Aye; contrary, No. (The motion was carried.)

F. Creedy In connection with Dr. Kennelly's very interesting paper on " Vector Power " a short account of a rather different manner of representing it, which occurred to the writer some time ago, may be of some interest. This makes use of the system of point-analysis due to Mobius and Grassmann, which although very well known to mathematicians, has not hitherto received any engineering applications as far as I am aware.

According to this system the power flowing through a given circuit is represented, not by a vector, but by a point, in a manner slightly akin to the Steinmetz " topographic " representation. The rule for the addition of points is, however, entirely different from that in Dr. Steinmetz's system. The point, moreover, in this system is not a mere mark of position but has a number associated with it which is called its " weight." If the " weight " is zero the point is absent. A point may have a negative " weight." This " weight " is used to represent the effective power while the position of the point with respect to the origin represents the reactive power. We establish the following definitions by convention.

Let S_1 S_2 be any two points of unit weight and M_1 M_2 be the weights which we attribute to them. Then:

Def. 1
$$M_1 S_1 + M_2 S_2 = (M_1 + M_2)\,\overline{S} \qquad (1)$$

where $\overline{S}$ is a point having the position of the mass-center of the points S_1 and S_2 when we attribute to them the weights M_1 and M_2. (See Fig. 1). This may be extended to any number of points.

This is the law of point addition. The sum of two points is always in the line joining them and has a weight equal to the sum of their weights.

Def. 2. *The difference of two points of equal weight is the vector joining the points.*

A vector of course has no definite position but may be moved anywhere in the plane.

Def. 3. The effect of adding a vector to a point, say $S+\rho$ is to transport the point from one end of the vector to the other in the direction of the arrowhead on the vector. This follows at once from Def. 2. It is put here merely for convenience. For if

$$S' - S = \rho$$

obviously $$S' = S+\rho$$ See Fig. 2

This may be applied to the representation of alternating current power as follows:

Dr. Kennelly's equation (14) is

$$p_t = P\,\{\cos\theta + \cos(2\,\omega\,t \pm \theta)\} \tag{2}$$

This may be written

$$p_t = P\cos\theta\,\left\{1 + \frac{\cos(2\,\omega\,t \pm \theta)}{\cos\theta}\right\} \tag{3}$$

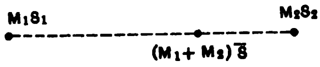

FIG. 1

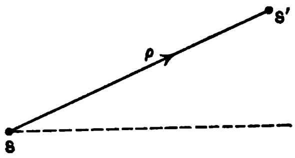

FIG. 2

Case I. All quantities of power which contain no varying component are represented by one point, the origin, associated with a weight corresponding to the amount of power considered.

Case II. Every purely reactive power containing no steady or effective component is represented by a vector exactly as in the ordinary clock-diagram. It shows the position at time *o* of a rotating vector whose projection on an arbitrary axis is $P \cos (2\,\omega\,t \pm \theta)$. The length of a vector representing $\cos (2\,\omega\,t \pm \theta)$ is, of course, unity.

Case III. A quantity of power containing both an effective and a reactive part is represented by adding the vector of case II to the point of case I (the origin). Before we can carry this out properly we must express the power as the product of the effective power, which is the weight of the point, into a unit point. This is done in equation (3) where the expression

$$S = 1 + \frac{\cos(2\omega\,t \pm \theta)}{\cos\theta}$$

represents a unit point at a distance $\frac{1}{\cos\theta}$ from the origin measured along a line making an angle $\pm\theta$ with the axis of reference. See Fig. 3.

Hence we interpret the entire expression (3) as a point at a distance $\frac{1}{\cos\theta}$ from the origin measured in the proper direction, and having a weight $P\cos\theta$. It may be noticed that, as $\cos\theta$ diminishes, the point decreases in weight and at the same time gets further and further from the origin. When $\cos\theta$ vanishes it becomes a point of zero weight at an infinite distance. Now *definition I* gives us the same result when applied to the difference of two points of equal weights, and *definition II* was introduced to remove this ambiguity. *Definition II* enables us to state that:

"A vector is symbolically identical with a point of zero weight at an infinite distance." So that the vanishing of $\cos\theta$ does not introduce any inconsistency but simply reduces case III to case II. In fact, as θ varies the point S moves along the straight line $\overline{S S_0}$ perpendicular to the axis of reference. See Fig. 4.

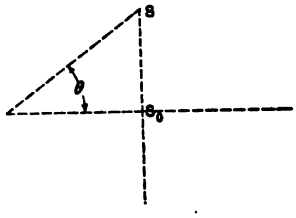

FIG. 3

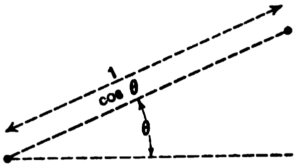

FIG. 4

Suppose we have a number of powers

$$p_1 = \rho_1 \cos\theta_1 \left\{ 1 + \frac{\cos(2\,\omega\,t+\theta_1)}{\cos\theta_1} \right\}$$

$$p_2 = \rho_2 \cos\theta_2 \left\{ 1 + \frac{\cos(2\,\omega\,t+\theta_2)}{\cos\theta_2} \right\}$$

$$p_3 = \rho_3 \cos\theta_3 \left\{ 1 + \frac{\cos 2\,\omega\,t+\theta_3}{\cos\theta_3} \right\}$$

etc.

these may be written, by the principles enunciated above

$$m_1\,(1+\alpha_1),\ m_2\,(1+\alpha_2)\ m_3\,(1+\alpha_3),\ \text{etc.}$$

where α_1 α_2 α_3 are the vectors representing $\frac{\cos(2\omega t+\theta)}{\cos\theta}$ etc.

The origin at unit weight, is here typified by the scalar or numeric, 1, and may be called the " scalar point "
Adding these together, we get

$$m_1(1+\alpha_1)+m_2(1+\alpha_2)+m_3(1+\alpha_3)$$

$$=(m_1+m_2+m_3)+m_1\alpha_1+m_2\alpha_2+m_3\alpha_3$$

$$=(m_1+m_2+m_3)\left(1+\frac{m_1\alpha_1+m_2\alpha_2+m_3\alpha_3}{m_1+m_2+m_3}\right) \qquad (4)$$

$$=M(1+\alpha)$$

The expression

$$\alpha=\frac{m_1\alpha_1+m_2\alpha_2+m_3\alpha_3}{m_1+m_2+m_3}$$

is the well known expression given in the first chapter of every textbook of vector analysis for the vector to the mass center of three points, of masses m_1, m_2, m_3, situated at the extremities of the vectors α_1, α_2, α_3. Or, alternatively, let us add the expressions p_1, p_2, p_3, together direct. We get

$$p_1+p_2+p_3=$$

$$\rho_1\cos\theta_1+\rho_2\cos\theta_2+\rho_3\cos\theta_3$$

$$+\rho_1\cos\theta_1\frac{\cos(2\omega t+\theta_1)}{\cos\theta_1}+\rho_2\cos\theta_2\frac{\cos(2\omega t+\theta_2)}{\cos\theta_2}$$

$$+\rho_3\cos\theta_3\frac{\cos2\omega t+\theta_3}{\cos\theta_3}$$

$$=\rho_1\cos\theta_1+\rho_2\cos\theta_2+\rho_3\cos\theta_3\left\{1+\frac{\rho_1\cos\theta_1\frac{\cos(2\omega t+\theta_1)}{\cos\theta_1}+\rho_2\cos\theta_2\frac{\cos2\omega t+\theta_2}{\cos\theta_2}+\rho_3\cos\theta_3\frac{\cos2\omega t+\theta_3}{\cos\theta_3}}{\rho_1\cos\theta_1+\rho_2\cos\theta_2+\rho_3\cos\theta_3}\right\}$$

which is of exactly the same form as the above expression (4) in vectors so that the appropriateness of the point-analysis is quite clear.

These remarks are already too long, so that I must refrain from giving any applications, of which few have yet been made.

However, for the benefit of anyone who cares to pursue the subject further, I give a few references.

Although the point-analysis is actually due to Möbius and Grassmann, the immediate inspiration of this application, and the notation, is due to Professor C. J. Joly's memoir "The Interpretation of a Quaternion as a Point Symbol" Trans. Royal Irish Academy, Vol. 32, Sec. A, Part 1, further amplified by him in his "Manual of Quaternions" and "Quaternions and Projective Geometry" Phil. Trans. Royal Soc.

The best books on Grassmann's Algebra in the English language are

"The Directional Calculus" E. W. Hyde, (Ginn & Co.), Boston; and "Universal Algebra" A. N. Whitehead, Camb. Univ. Press.

A very rudimentary acquaintance with these subjects is enough to enable one to do much useful work. I do not want to give the impression that the method cannot be used until all these ponderous volumes have been thoroughly mastered.

A. E. Kennelly: I think we all agree, as a result of this very interesting discussion, that vector representation can be arrived at in two ways—by Dr. Steinmetz's method and also by the trigonometrical method, and the fact that we can legitimately divide them in these two ways is what causes the trouble. If we can get some expression from the International Electrotechnical Commission, and if we can get an international decision upon that point, I for one, and I am sure that all of us would be very willing to adopt that one method, whichever it may be, and if this action of the Institute will bring that happy result about, I think it will be a great boon to electrical engineers all over the world.

The first official meeting of the Commission is scheduled for next year in Berlin, but an unofficial meeting is scheduled for this year in Brussels, and if this matter can be brought to the attention of the body at the unofficial meeting this year, it is possible that the work of the body on this subject could be completed in a year's time.

In reference to the able remarks of Dr. Steinmetz, we must all admit that whatever convention is internationally adopted on vector diagram directions, it must not conflict with fundamental mathematics. If it were demonstrable that inverse representation in vector diagrams conformed to the established laws of analytical geometry, whereas direct representation contravened those laws, then it would follow that inverse representation should be followed internationally as a matter of necessity. To my mind, however, no such necessity exists. If we plot a polar-coördinate representation of a voltage and a current, as we have a perfect right to do mathematically, and in the manner described by Dr. Steinmetz, we are not forced to make any vector diagram by drawing diameters to the circles, or equivalent circles, on the curve-sheet. The representation of the vector voltage and current, by straight lines taken on the diameters of their respective circles, seems to be a pure convention, not fundamentally involved in the analytical geometry. This convention of taking the diameters for vectors in a vector diagram, leads indeed to inverse representation, as pointed out in the paper; but another convention might equally well be adopted, which would involve direct representation. For instance, the two polar circles of voltage and current might be brought into line with each other, diametrically, and two separate suitably dephased radii vectors might rotate together, so as to intersect these circles, and represent by their intercepts at any instant, the respective magnitudes of the cyclic quantities. The two radii vectors would then, by convention, represent the voltage and current of the vector diagram, with direct representation. Or convention 4 of the paper might be used, with direct representation, from polar coördinates.

Again, exception may be taken to Dr. Steinmetz's view that the crank diagram " has no relation to the representation of alternating waves in rectangular coördinates ". In a number of text-books, the rectangular-coördinate diagram of a wave is derived from, and made dependent upon, the crank diagram. It seems evident, on deliberation, that a vector diagram is essentially a conventional diagram. That is, it is based upon fundamental mathematics through the medium of some particular convention or conventions. We may safely standardize our conventions without discriminating against the fundamental mathematical operation or laws. Surely it cannot be maintained that because we represent our vectors on paper as having a certain order of angular sequence, that therefore we cannot plot our cyclic magnitudes in any particular coördinate system.

Apart from the preference that springs from mental habits, it is submitted in the paper that either of the conventions here called " direct representation " and " inverse representation " is as good as the other. Each can claim to be descended from pure mathematics, the direct representation from trigonometry, and the inverse from polar coördinates. The only reason claimed in the paper for calling the former *direct* representation, is that when laid off in this manner, the vectors follow in the order of time. The leading vector quantity is ahead of the lagging quantity in the direction of positive rotation.

It is surely of the utmost importance to adopt a standard universal convention of vector sequence and representation. The advantage to each engineer of having one and only one representation in use in alternating-current literature, far outweighs the trouble of having to change one's own familiar method. I would much rather change my own habit in this matter than continue to encounter the perennial medley of different methods of representation in different papers, and I believe that most of our confreres all over the world are of the same opinion.

The important thing is a unanimous agreement. It is of relatively lesser importance which way the decision is taken.

A paper presented at the 27th Annual Convention of the American Institute of Electrical Engineers, Jefferson, N. H., June 29, 1910.

DETERMINATION OF TRANSFORMER REGULATION UNDER LOAD CONDITIONS AND SOME RESULTING INVESTIGATIONS

BY ADOLPH SHANE

INTRODUCTORY

For some time past the writer has been suspicious of the accuracy of the results obtained in calculating transformer regulation by the now popular method of adding the impedance volts vectorially to the pressure impressed on the load, the data for the impedance triangle being obtained by the common short-circuited secondary method and by the measurement of the resistance of the transformer winding. Indeed, the only check on this method heretofore has been the comparison with the direct method of reading the primary and secondary pressures, reduced to like terms, and ascertaining the difference, or, what amounts to the same thing, reading the secondary pressure under full (current) load and under no load, keeping the primary pressure constant the while. These direct methods are inexact unless great precautions are taken due to the impracticability of reading normal pressures with sufficient degree of accuracy for this purpose.

For example: Suppose the normal e.m.f.s of a transformer can be read to an accuracy of 0.25 per cent and the regulation is actually 2.5 per cent. The value of regulation may be found to be anywhere between 2.25 per cent and 2.75 per cent, causing a possible maximum error of 0.5 per cent in 2.5 or 20 per cent in the value of the regulation.

If some means could be devised whereby the regulation volts might be read off directly by a low-reading voltmeter, results of the same order of accuracy as the reading of normal pressures could be obtained. It is the purpose of this paper to point out such a direct method, as well as an accurate calculated method, to check the results obtained with particular transformers, to point out errors existing in the ordinary calculated method referred to above, and, as far as possible, to give the causes for such errors.

TRANSFORMER REGULATION

1. *The Direct Method.* If two transformers, A and B (Fig. 1) exactly alike, be connected to the same source of power their secondaries connected in opposition series, the e.m.f. between the open ends a b will be zero until load is applied to one (A) of the secondaries, when this e.m.f. is equal to the *true* impedance pressure of the loaded transformer.

If now a third transformer C is connected to the line and its secondary connected in series with the other secondaries, but in opposition to B, and a galvanometer G connected to the free terminals of this secondary series system we have the electrical connections necessary for the proper performance of the test.

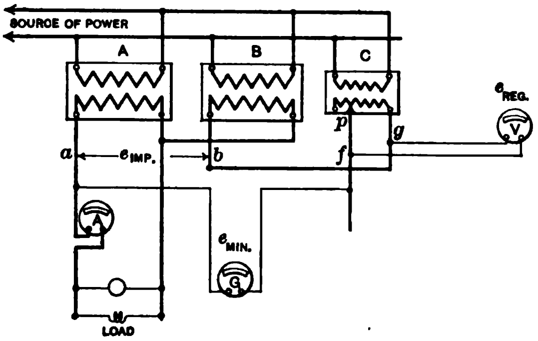

FIG. 1

Normal load is applied to transformer A. The secondary winding of C is gradually cut out of the circuit, turn by turn, by shifting the contact point P along the winding, until the galvanometer G reads a minimum. The e.m.f. of the secondary C between the points f, g is the regulation volts required for transformer A and may be read off directly by a low-reading voltmeter V.

Theory. Fig. 2 represents the common transformer vector diagram using 1 to 1 ratio of transformation for simplicity, with the secondary current I'' lagging θ deg. behind the secondary terminal pressure e''. If to this pressure is added vectorially the secondary resistance and reactance drops ($R'' I''$ and $X'' I''$ respectively, Fig. 2) the secondary induced e.m.f. E'' is the result. This is also the e.m.f. of self-induction of the primary. That part of the impressed e.m.f. which overcomes this latter is designated in the figure by e', equal and opposite in vector position to E''. To this is added vectorially the primary resistance and reactance drops, producing finally the impressed e.m.f., E'.

The foregoing represents the load conditions of transformer A in Fig. 1. Transformer B being unloaded has a secondary e.m.f. equal and opposite to the primary. Thus in Fig. 2, E' also represents the primary e.m.f. of B. Equal and opposite to this is the secondary e.m.f., E, which leads the terminal pressure e'' of transformer A by a small angle α. The vector difference $c\,a$ of these two e.m.fs. (e'' and E), which are respectively the secondary pressures under load and no load, represents the total impedance drop $Z\,i$ or e_{imp} of the transformer (A) under load. The vectors $a\,b$ and $b\,c$ are respectively the resistance and reactance drops $R\,I$ and $X\,I$ of the transformer, each being made up as follows:

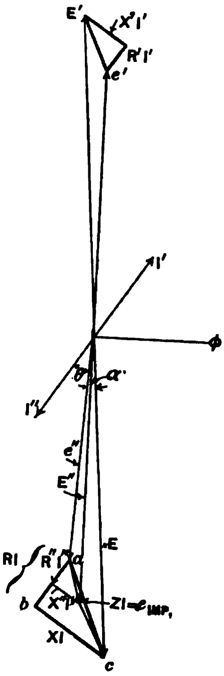

FIG. 2

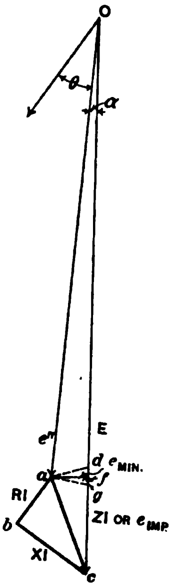

FIG. 3

$$R\,I = R'\,I' + R''\,I''$$

$$X\,I = X'\,I' + X''\,I''$$

The *working* transformer diagram is represented by the two vectors e'' and E, capped by the impedance triangle $a\,b\,c$. This is shown separately in Fig. 3 for clearness. The lengths of the vectors e'' and E are, however, made longer, without any corresponding increase of the impedance triangle, in order to more nearly represent actual relative conditions.

Consider now the third transformer *C*. Since it is unloaded and since its secondary is connected in opposing series with *B* the secondary pressure is exactly 180 deg. opposite to *E*, the terminal pressure of *B*, but variable in value, depending on how many secondary turns are in the circuit.

This is shown in Fig. 3, *c g*, *c f*, or *c d* representing the variable secondary pressure of transformer *C*, opposing *O C* or *E*. The only e.m.f. active between the secondary terminals of *A* and *B* is the impedance pressure e_{imp}, since these two secondaries are in opposing series. The points *a b* between which this pressure exists is indicated in Fig. 1, and the vector position is *a c* in Fig. 3. The pressure at the terminals of the entire secondary system is *a g*, *a f*, or *a d*, since the e.m.f. of *C* partially opposes e_{imp}. The instrument *G* of Fig. 1 indicates the value of this final resultant pressure, which may be any value depending on the number of active turns in the secondary of *C*. But there is a *definite* minimum value caused by the correct number of active turns in *C*. Any increase or decrease of this particular number will *always* cause an increased reading of *G*. This is clearly shown in Fig. 3. With *c d* as the pressure of *C*, there is a corresponding value *a d* for the secondary pressure of the entire system. Similarly for *c g* there is a corresponding pressure *a g* and for *c f* there is *a f*. Manifestly *c f* is the particular pressure of *C* which causes *a f* ($= e_{min}$) to be the minimum, *a d* and *a g* being each greater in value. From the geometry of the figure e_{min} must be perpendicular to *E* for this condition. Since in any modern constant pressure transformer the angle *a* is very small, *O f* differs from *O a* or E'' in but a very minute degree. Hence the difference between *E* and e'' is very closely *c f*. But this difference is the regulation volts sought after. Therefore the regulation volts e_{reg} may be read off directly by a low-reading voltmeter of suitable scale connected to the active secondary terminals of *C*, after the adjustment for e_{min} has been made.

II. *The Calculated Method.* If the common short-circuited test should give data for the correct impedance triangle, the value of regulation obtained by this means would be above criticism. But such is not the case as will be shown later. The true transformer impedance volts can be found only under actual load conditions. This is e_{imp} referred to above. Hence to find the true impedance triangle the transformer *C* is dispensed with, the connections of *A* and *B* remaining precisely the same. A wattmeter suitable for the full-load current of transformer *A* and for low voltage, is inserted into the load circuit (W_2 in Fig. 4) the pressure terminals being connected to the free secondary ends *a b*, precisely where the low-reading voltmeter V_2 is connected to indicate e_{imp}. The reading of this wattmeter is the true $R\,I^2$ loss of *A* under load conditions. With the above two readings and the load current the correct impedance triangle may be found. That is, dividing the value of the wattmeter reading by the value of the load current gives the $R\,I$ drop, which together with the impedance drop solves the triangle. From thence on the calculations are as usual in such cases.

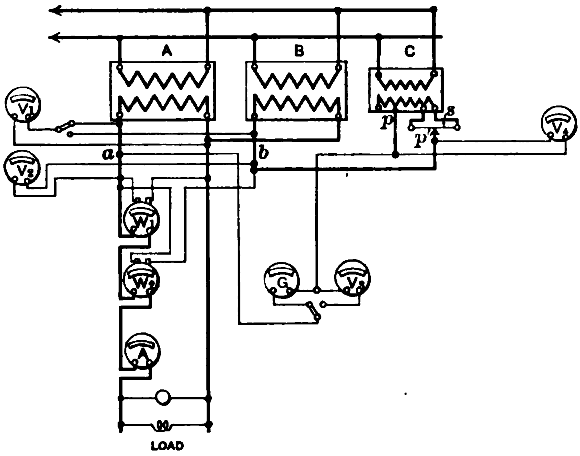

FIG. 4

It may be argued that it might not always prove easy to procure two absolutely identical transformers for the above methods, that the voltage ratios might be just sufficiently different to spoil the test. In answer to this it might be said that the writer had at his disposal three pairs of transformers, each pair of different manufacture, and these checked out very well. The check was made by connecting a delicate alternating current galvanometer to the free ends of the secondaries of each pair connected in opposed series. Scarcely a deflection in any case was observed, though the trifling load of a wattmeter pressure coil connected to the secondaries of one transformer caused sufficient unbalancing to give a decided deflection. This would indicate that absolute voltage equality should be the rule rather than the exception with similar transformers from the same manufacturer. A fairly elaborate test was made to substantiate the above theory, the results of which are incorporated in curves of Figs. 5 and 6. These curves all refer to the regulation volts with respect to power factor, of a particular pair of transformers with noticeably small leakage. Fig. 5 is the curve obtained by the direct method (I) using three transformers. Attention is called to the generous scale of volts in spite of which the observed points appear very consistently on the curve. Curve *A*, Fig. 6, is a duplicate of Fig. 5, without any points being present belonging to this particular curve. The points (.) so near this curve as to seem to form part of it were really obtained by calculation, using method II of this paper. One checks the other. The points (*x*) represent the values obtained by carefully taking the

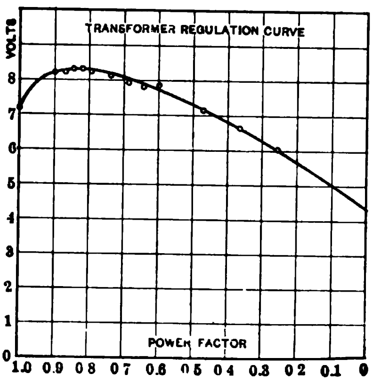

FIG. 5

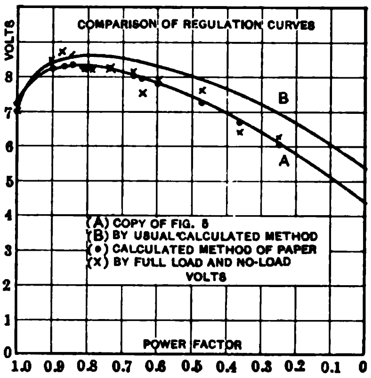

FIG. 6

difference between the no-load and load values of e.m.f. ($E - e''$). Of course the inherent inaccuracy of this method is evident by the staggered position of the points, but they agree closely enough with curve A to confirm the above methods. Curve *B* is the regulation curve obtained by the usual short-circuit test and resistance measurement, and the departure from the three lower sets of results is marked. So decided is the discrepancy that the writer believes, by the use of an ordinary voltmeter, taking full load and no-load readings, the truth is more nearly told. True, the regulation curve is not relatively so consistent and smooth in this latter case, but any point by reasonable care may represent less percentage error than a corresponding point on the calculated curve by the short-circuit test.

The Test. More than one set of transformers were tested for regulation, but only a sample of one set of readings are here given. The data for both methods were taken at the same time, the connections for the test being as indicated in Fig. 4. Transformers *A* and *B* were exactly alike, rated at 2 kw. each, with 220 volts secondary. It was found that with 12.5 amperes load (12.56 corrected) no excessive heating ensued, so the current was maintanied at this value. Transformer *C* also happened to be rated at 2 kw. though the value of capacity here is immaterial. The regular secondary winding was not used. Instead, a few turns of wire were wrapped over the fixed windings, care being taken to have a somewhat greater total e.m.f. here than the impedance of transformer *A*, since at one point of the regulation curve, the impedance pressure equals the regulation.

Each turn was brought out to a switching arrangement whereby it could be instantly cut in or out of circuit, excepting the last turn, the terminals of which were connected to a slide-wire resistance allowing perhaps one ampere to flow. The purpose of this latter arrangement was to permit of exact adjustment for e_{min}. The procedure followed was to start with the full number of turns active, gradually cutting them out one by one until the galvanometer *G* indicated as near a minimum value as possible, the final adjustment being made by moving the point *P′* along the slide-wire *S*.

The accuracy of the method depends on *C* not being perceptibly loaded, and it might be supposed that the current through the slide-wire *S* does load the transformer to some extent. That the amount is imperceptible may be shown by a numerical example which closely fits this case. Assuming one volt per turn, 220 volts normal e.m.f., and 10 amperes normal load, we find that this load represents 2200 ampere-turns. The one ampere flowing through the slide-wire connected to the terminals of one turn represents but one ampere-turn. The transformer is thus loaded to less than 0.05 of one per cent, an entirely negligible value.

Voltmeter V_1 was so connected that by means of a switch it could quickly indicate the load and no-load pressures across the terminals of *A* and *B* respectively. V_2 indicated the impedance drop under load conditions, V_3 the minimum volts after adjustment had been made by the use of *G* and V_4 the regulation volts. Actually V_2, V_3, and V_4 were represented by one instrument, a low reading voltmeter, which by suitable switches could be readily thrown to the several points. But one instrument was used to insure correct relative readings for purposes of accurate checks. Wattmeter W_1 was connected to read the load. W_2 having its pressure coil connected to the impedance voltage terminals (*a b* in Fig. 4) indicated the copper $I^2 R$ under load conditions. It had ample current capacity and the pressure coil was adjusted for low voltage. The instrument was found to be accurate for low power-factors. The ammeter *A* indicated the current load which was maintained at 12.56 amperes. The galvanometer *G* was merely a piece of annealed iron suspended in a coil and damped with oil. This proved amply sensitive All the instruments were thoroughly dead beat which vastly facilitated the taking of readings and thus guarded against a change of conditions during the taking of a set of observations.

The load consisted of a lamp bank in parallel with a variable ironless inductance. By this means a power-factor as low as 25 per cent was obtained. Constant temperature conditions were reached before any readings were taken.

TABLE I.

	a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	*k*	*l*	*m*	*n*	*o*
No.	Amp. load	Watts I^2R	Watts load	Volts load	Volts no load	Volts min.	Volts imp.	Volts reg.	Room temperature C⁰	Resistance primary by bridge	Resistance secondary by bridge	Power factor $\frac{c}{a \times d}$	Volts reg. $e-d$	Volts reg. calculated	$\sqrt{f^2+h^2}$
1	12.56	89.5	2650	207.7	214.7	4.27	8.29	7.11	24.4	0.252	0.278	1.00	7.0	7.124	8.29
2	"	"	2310	204.0	212.4	0.9	8.24	8.2	24.0			0.901	8.4	8.26	8.25
3	"	"	2240	204.7	213.4	0.8	8.235	8.23		0.252	0.278	0.87	8.7	8.293	8.23
4	"	"	2146	200.0	208.6	0.8	8.30	8.25	24.0			0.855	8.6	8.295	8.29
5	"	"	2095	203.4	211.6	1.02	8.31	8.3				0.82	8.2	8.275	8.36
6	"	"	2023	202.2	210.4	1.34	8.30	8.2		0.251	0.279	0.796	8.2	8.245	8.3
7	"	"	1864	200.8	209.0	1.85	8.33	8.13	25.0			0.738	8.2	8.117	8.33
8	"	"	1728	201.3	209.4	2.45	8.30	7.95				0.684	8.1	7.97	8.32
9	"	"	1618	199.6	207.1	2.8	8.30	7.87	24.0	0.252	0.278	0.645	7.5	7.85	8.35
10	"	"	1497	198.6	206.4	3.21	8.30	7.8				0.60	7.8	7.68	8.45
11	"	"	1168	198.0	205.6	4.232	8.28	7.14	24.0			0.47	7.6	7.14	8.3
12	"	"	925	201.0	207.4	4.97	8.29	6.65				0.366	6.4	6.63	8.3
13	"	"	637	202.0	208.2	5.56	8.26	6.01	24.0	0.252	0.277	0.251	6.2	5.97	8.2

The original data are given in Table I. The sets of readings from 1 to 13 inclusive were taken at nearly normal impressed voltage with power-factors ranging from unity to 25 per cent. This table furnished the data for the curves of Figs. 5 and 6. In Table II the load power-factor was maintained unity, but the e.m.f. was varied from normal to practically zero value. Care was taken to keep the current exactly constant throughout the test.

Inspecting Table I down through the thirteen sets of readings it is seen that with a steady current and voltage about normal (columns *a* and *d*), the copper loss (column *b*), read by W_2 remained constant, though the power factor (column 1) varied from unity to 25 per cent, that is, the real power dropped from 2,650 watts to 637 watts (column *C*). It is also seen that the impedance volts (column *g*) remained sensibly constant during like conditions. The difference between corresponding readings of columns *d* and *e* gives the regulation pressures (column *m*) and as indicated by (*x*) in Fig. 6. Column *h* gives the regulation pressures by the direct method I and columns *a*, *b*, *g* and *l* furnish data for calculating regulation by method II explained above, these calculations being set down in column *n* and plotted as (.) in Fig. 6.

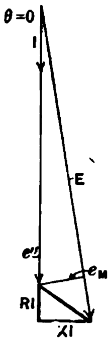

FIG. 7

FIG. 8

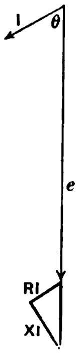

FIG. 9

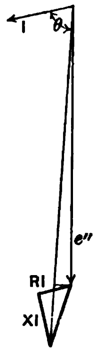

FIG. 10

FIG. 11

It might be of some interest to add other checks on the theory of method I. Inspecting Fig. 7, which is the transformer diagram for non-inductive load, it is evident that e_{min} practically equals $X\ I$ in value. Turning to Table I of data, first line column *f*, e_{min} is found to be 4.27 volts. $X\ I$, when obtained from the correct impedance triangle of method II, was found to be 4.25; a very close agreement. Again, Figs. 7 to 11 are transformer diagrams ranging from unity to zero power-factor. At unity power-factor e'' lags behind E by a small angle α. With diminishing power-factor this angle, Fig. 8, is reduced with a corresponding reduction in the value of e_{min} until some value of power-factor as in Fig. 9 is reached, when both this angle and e_{min} have been reduced to zero and the regulation is represented by the impedance volts. With a further reduction of power-factor, Fig. 10, the angle together with e_{min} again increases with e'' now leading until another maximum displacement is reached at zero power-factor, Fig. 11, when e_{min} is but little different from the $R\,I$ drop. This variation of e_{min} is nicely indicated by the data in column f of Table I. Where its value is about zero the regulation volts should be practically the impedance volts. That such is the case the values of regulation volts of column h testify. Finally at unity power-factor the regulation is practically the $R\,I$ drop, and at zero power-factor it is as closely the $X\,I$ drop. From the data

$$R\,I^2 = 89.5 \text{ watts}$$

Hence $89.5 \div 12.56 = 7.12$, the $R\,I$ drop; where

$$\text{load current} = 12.56$$

The table gives the regulation volts for unity power-factor the value of 7.11, another agreement. Extending the curve of Fig. 5 to zero power factor we find the regulation for this point is about 4.35, which is also but little greater than the $X\,I$ drop.

Check for Accurate Adjustment of e_{min}. The consistency of the curve by method I depends, of course, upon the accurate adjustment of the pointer along the slide-wire S of transformer C. This may be checked directly by repeating an adjustment, as indeed it is desirable to do. A further check may be obtained by the use of the equation

$$e_{imp} = \sqrt{(e_{min})^2 + (e_{reg})^2}$$

That this equation is true may be readily seen by inspection of Fig. 3. If the value of the above radical corresponds closely to the value of the impedance pressure, the adjustment may be said to have been correct. Column o of the Table represents the values of this radical and the corresponding impedance pressures in column g. The agreements here are seen to be rather good, excepting in the tenth line, where the solution of the radical, gives 8.45 while the corresponding impedance pressure is but 8.3. The adjustment here then was hardly exact, with a corresponding inaccuracy in the value of the regulation. Examining the tenth point on the curve of Fig. 5. the inaccuracy is evident. Yet even this error does not amount to much. In other words, an extremely sensitive detector of e_{min} is scarcely necessary. In the test a well damped low-reading alternating-current voltmeter was found to be good enough.

Some Further Investigations

In order to determine the source of the inaccuracy in the usual calculated method for obtaining regulation, the line e.m.f. supplying the transformers under test was gradually reduced all connections remaining precisely as before. The readings taken are given in Table II. It is here seen that the $I^2 R$ (and consequently the $I R$ drop) steadily reduces in value from 89.5 to 86.0 watts. On the contrary the impedance pressure as steadily rises in value from 8.28 to 8.5 volts. That is, as the conditions of the common short-circuit test are approached the copper loss and copper drop become less than under normal conditions of voltage (*i.e.*, normal flux density) while on the other hand the impedance of the transformer is higher in spite of the fact that the $R I$ drop is less. The difference in the two impedance triangles as found by the short-circuit test and the resistance determination, and by method II is clearly seen in

TABLE II

	a	*b*	*c*	*d*	*e*	*f*	*g*	
No.	Amp. load	Watts $R I^2$	Volts load	Volts imp.	Copper drops $b+a$	React-ance drop $\sqrt{d^2-e^2}$	In-duced e.m.f.	Remarks
1	12.56	89.5	220	8.28	7.12	4.227	223.4	
2	"	88.5	196	8.3	7.05	4.38	199.4	
3	"	88.0	173.6	8.305	7.01	4.465	177	Load at unity power-factor
4	"	88.0	147.4	8.32	7.01	4.5	150.8	
5	"	87.5	123.4	8.36	6.96	4.63	126.8	
6	"	86.7	94.2	8.39	6.91	4.75	97.6	
7	"	87.0	71.6	8.44	6.93	4.81	75.0	
8	"	86.7	34.9	8.50	6.91	4.95	69.2	
9	"	86.0	2.0	8.505	6.85	5.05	6.0	

Fig. 12, which applies to transformer *A* of this paper. It is observed that a difference of 20 per cent exists in the value of the reactance drop by the two methods.

The above results are shown in the form of curves in Fig. 13 the abscissas being induced e.m.f.s in all cases. The $R\,I$ and $X\,I$ curves were derived from data forming the $R\,I^2$ and e_{imp} curves. If the slightly parabolic nature of the increase of the copper watts with e.m.f. (*i.e.*, flux density) is due to more than mere chance, this increase may be reasonably supposed to be a true eddy current loss in the copper windings, increasing as the e.m.f. applied to the transformer increases. This additional $R\,I^2$ drop is, no doubt, what is vaguely referred to as "load losses" which disappear as the flux density is reduced to the conditions of the short-circuit test. On the other hand the increase of the $X\,I$ drop with a reduction of the flux density may be due to a somewhat greater permeability of the magnetic circuit. That is, assuming the same leakage magnetomotive forces at low flux densities as at high, the resulting leakage flux will be somewhat greater if the magnetic conductivity is better in one case than another. And at lower flux densities a greater permeability is expected. This, of course, assumes that a part, at least, of the leakage path is through the iron.

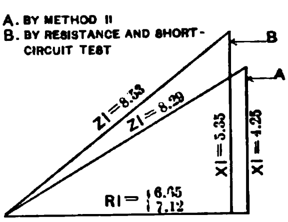

Fig. 12

Conclusions

It is evident from the foregoing that it is possible to use an accurate direct method for obtaining transformer regulation, the value being read off by a low-reading voltmeter following a simple adjustment. Only commercial instruments and apparatus are needed for the test. It is also evident that accurate data for the calculated method is readily obtainable. Both of these methods are presented with but one object in view, that of commercial utility.

Method I is intended to take the place of the ordinary direct method of reading no-load and full-load pressures. Method II is intended to substitute for the calculated methods now in use. The writer hardly thinks it sufficient to consider the older methods as amply accurate, especially when referring to calculated ones, for though a nice smooth curve may be obtained (because it is a calculated method), the truth is probably more nearly told by the simple expedient of reading no-load and full-load pressures.

Either of the above methods should be available for the average central station and on the test floor of a transformer manufacturing company where like transformers are usually at hand.

APPENDIX

In considering the theory of method II it was assumed that the detail of calculating regulation is generally understood. But to insure this point, a brief outline is here given. Either one of two formulas may be used which lead to like results. These are as follows:

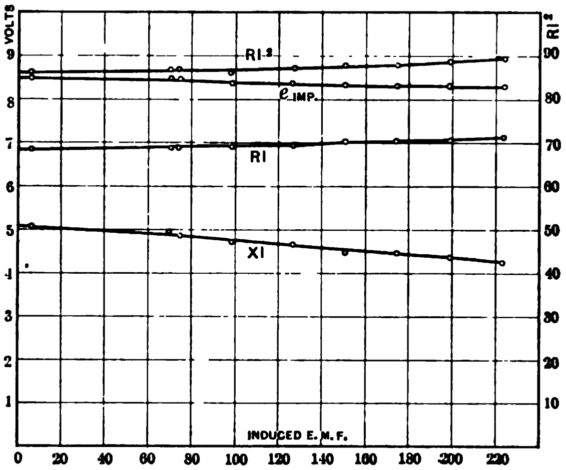

FIG. 13

$$E = \sqrt{(e''+R\,I\cos\theta+X\,I\sin\theta)^2+(X\,I\cos\theta-R\,I\sin\theta)^2} \quad (1)$$

$$E = \sqrt{(e''\cos\theta+R\,I)^2+(e''\sin\theta+X\,I)^2}. \quad (2)$$

Whereas, in the preceding text,

e'' = the secondary terminal voltage = 100 per cent.

E = the impressed voltage (reduced to terms of secondary) necessary to produce E'' under load.

$R\,I$ = equivalent resistance drop.

$X\,I$ = equivalent reactance drop.

θ = angle corresponding to power factor $\cos\theta$ of circuit.

The difference $E - e''$ is the regulation volts sought. e'' may be assumed to be the voltage stamped on the name plate of the transformer; also θ is assumed. $R\,I$ and $X\,I$ are obtained from the solution of the data entering the impedance triangle.

Each of the above equations is based on correct theory. The first supposes the several e.m.fs. of the transformer to be resolved into components parallel to and perpendicular to e''; the second supposes them to be resolved into components parallel to and perpendicular to the current vector. In either case E is the closing diagonal.

A sample set of calculations will make clear the use of the above equations. Use will be made of the following data which refers to transformer A of this paper:

$e_{imp.} = 8.29$

$R\,I^2 = 89.5$

$I = 12.56$

$e'' = 220$ (name plate)

Power factor $= 0.6 = \cos\theta$.

From which is derived the following:

$R\,I = 89.5 \div 12.56 = 7.12$

$X\,I = \sqrt{(8.29)^2 - (7.12)^2} = 4.25$

$$E = \sqrt{(220 + 0.6\times 7.12 + 0.8\times 4.25)^2 + (0.6\times 4.25 - 0.8\times 7.12)^2}$$
$$= 227.68 \qquad (1)$$

$$E = \sqrt{(0.6\times 220 + 7.12)^2 + (0.8\times 220 + 4.25)^2} = 227.68 \qquad (2)$$

Manifestly the accuracy of results depends on the accuracy of the $R\,I$ and $X\,I$ values, that is upon obtaining the values for the correct impedance triangle. The usual method of doing this is to short circuit one of the transformer windings (ordinarily the low tension) and impress a sufficient voltage on the other to allow rated full load current to flow. This gives the impedance drop and with a wattmeter inserted also the $R\,I^2$ which divided by the value of the current gives $R\,I$. Or instead of this latter, resistance measurements of both primary and secondary may be made, reduced to like terms, and added. This sum multiplied by the value of the full load current gives the $R\,I$ drop, and

$$X\,I = \sqrt{(\text{Imp. volts})^2 - (\text{R I})^2}$$

It must be remembered that the data by this method is obtained under conditions of low flux density and hence the discrepancy when compared with method II presented in this paper.

DISCUSSION ON "DETERMINATION OF TRANSFORMER REGULATION UNDER LOAD CONDITIONS AND SOME RESULTING INVESTIGATIONS". JEFFERSON, N. H., JUNE 29, 1910.

Charles Fortescue: The method of measuring the regulation of a transformer, given in this paper, appears to the writer to be open to serious objection for the following reasons.

1. Assuming that adjustment for e_{min} has been satisfactorily effected, the reading across $f\,g$ will not be the regulation of the transformer. It is true that in the example cited by the author of the paper the difference between the value read and the true regulation of the transformer, provided all other conditions of the test are satisfactory, would be negligible. But for a transformer having high reactance volts, in comparison with the ohmic drop, this method of measurement would introduce an appreciable error.

2. If the value of e_{min} is large compared with the regulation of the transformer, a very small error in the observation of e_{min} will produce a large error in the adjustment of electromotive force $f\,g$. In the examples cited in this paper it happens that the value of e_{min} is comparatively small, and therefore the error in adjustment of $f\,g$ is negligible.

3. The accuracy of the method is also dependent upon the resistance of the galvanometer used for adjusting $f\,g$ by means of e_{min}.

With reference to the proposed method of obtaining data for calculating the regulation, it is evident that the accuracy of the results obtained depends upon the resistance of the voltmeter used, of the shunt of the wattmeter and the size of the transformers on which the measurements are made. If the two transformers, A and B, are exactly alike, and we denote the true impedance by Z, and assuming that the reading of the voltmeter is V, I being the load current and R the resistance of the voltmeter, we have for the correct value of Z,

$$Z = \frac{V}{I = \frac{2\,V}{R}}$$

all the quantities being combined in their proper phase relations. It is apparent from the above that the value read on the voltmeter is too small for the true impedance volts and the phase difference as obtained by the voltmeter and wattmeter together is too small. If the shunt of the wattmeter has a different resistance from voltmeter, another source of error is added. For small transformers and with the usual commercial low reading voltmeters, the error due to the above conditions may be quite marked.

The curves shown in Figs. 5 and 6 show remarkable agreement between the regulation measured and calculated by the two methods proposed. But it is possible that the errors due to the instruments in both cases are approximately the same.

In Table 2 it is seen that the impedance volts steadily rises in value for a given current as the impressed voltage is reduced. The author argues from these results that the reduction of the flux density may cause increase in the leakage flux due to the higher permeability of the magnetic circuit. In the opinion of the writer, this is very improbable since in the first place the permeability of the iron at the low induction of the short circuit test is in commercial transformers about the same as that at the working induction. In the second place, with primary and secondary windings interlaced, as they are in such transformers, the length of the leakage path in the iron is very small compared with that in the air, and the density of the leakage flux is lower in the iron than in the air, the effect of the reluctance of the iron on the reactance e.m.f. of the transformer is, therefore, inappreciable. It is possible that the difference in impedance with varying induction in the test referred to, may be attributable to a change in the wave form of the primary impressed e.m.f. due to the method of changing its value.

In order to be able to form some estimate of the errors in the method, due to the causes outlined above, it is necessary to have data on the instruments used, and some knowledge of the wave form of the impressed e.m.f. under the various conditions of the test. It would be extremely interesting to obtain a comparison between the short circuit method and that proposed, with all errors in measurements, etc., eliminated.

To conclude, the writer is of the opinion that the results given in this paper are not sufficient as a basis from which to judge the merits of the two methods, of obtaining data for calculating regulation, that is to say, the old method and that proposed by the author. The latter method has had some commercial applications, but for the reasons given in the preceding discussion by the writer has not been widely used.

Results of some tests made on a standard lighting transformer 2200/220 volts 60 cycles

USING METHOD II

Primary volts	Sec. amp.	Volts imp.	Watts
2000	20.2	5.38	76.8
1000	"	5.3	76.8
520	"	5.32	76.8
73	"	5.3	76.8

Corrected average volts impedance = 5.36.
Corrected watts 77.

Using short circuit method
Impedance volts 5.42
Watts 79.70
Amperes 20.2
Corrected watts = ...79.4
Volts impedance = ... 5.42
The difference between the two methods is
Watts ....3.2 per cent
Volts ....0.8 per cent
This commercially would be considered a good check.

E. A. Wagner: In regard to this paper of Mr. Shane's my views agree with Mr. Fortescue's. I think a small error in measuring the voltage e' by the galvanometer is apt to bring in a large error in the determination of the regulation. The galvanometer undoubtedly will have a certain amount of lag, which will cause an error in the angle, and this error will account for the discrepancy shown on page 1100 in the two impedance triangles. Furthermore, I do not think that the use of three transformers will be a good commercial proposition, as this method of measuring the regulation is intended to be. There is no question but what a simple and accurate means of measuring the regulation directly is very much desired by those having a great deal of transformer work, but I think the method of calculating the regulation through determining the resistance and phase angle of the transformers will give sufficiently accurate measurements and determination of the regulation for commercial purposes.

L. T. Robinson: In reference to Professor Shane's paper it is undoubtedly true that in some transformers at least the regulation may not be accurately found by the usual method of determining the impedance triangle from the volts required to force full load current through one of the windings with the other short circuited.

The required impedance volts may be determined by means of reading the volts and amperes and computing the $I R$ component from the measured resistance of the transformer or the watts can be measured and the energy so read considered to be the $I^2 R$ loss. Sometimes these two methods agree closely and with the measured regulation but sometimes they do not. Also it is necessary to know the regulation and ratio of some transformers especially instrument transformers with very great precision. In fact it may be accepted as a general statement that it is not safe to determine ratio and regulation of transformers by any method of calculation until the method has by accurate measurements been proved correct and reliable for the actual type of transformer to be dealt with.

Although the value of determining the impedance triangle under load conditions, as shown in the paper in Fig. 4, as against determining it by similar means at low density with a short circuited winding seems quite apparent, still the chief reason for believing in it is the excellent agreement between regulation calculated using the values of the impedance triangle determined in this way, and the tested results rather than any theoretical considerations that might be urged in advocating the method used. There are so many secondary actions within transformers that may or may not affect the ratio and regulation that a ready means of determining their effects directly is always of interest and value.

The test that is described is one that requires two or really three transformers. Two of these are exactly alike and the third is a small auxiliary transformer *C*. The voltage of the loaded transformer *A* is connected to one terminal of the small transformer *C* which is connected to have its voltage in the same direction as *A* and opposed to *B*. This small transformer slides, etc., then forms a ready means of getting voltage in phase with *B* varying by small steps.

The point *f* Fig. 3 on *C* corresponding to e_{min} is found and the regulation volts are read from the auxiliary transformer *C*.

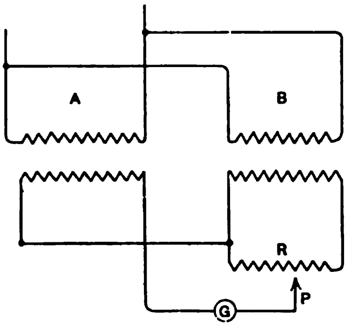

Fig. a

It is not always easy to get two transformers exactly alike. Perhaps some of the most desirable cases where it would be necessary to have an accurate measure of the regulation would be large transformers, where it may be that only one at a time is made. It is, therefore, proper to consider some means whereby the methods of the paper, which are in a sense quite similar, although differently carried out, to methods which have been developed for potential (instrument) transformers may be used to get the same results as those obtained in the paper, without the necessity of employing the two identical transformers.

For the second or unloaded transformer *B* there may be employed any transformer of known characteristics with a resistance across its secondary, and the secondary volts delivered by it changed by a slide resistance *R* Fig. *a*, or the test could be made at low voltage (2200 and under) using resistance on the primary side and omitting the auxiliary transformer altogether, Fig. *b*.

For ratio and regulation testing it is not necessary to have the transformer *B* unloaded (as shown in Fig. 1, Shane) because the phase displacement between primary and secondary current due to carrying moderate load would be small and almost always in a direction to bring the voltage on the secondary of *A* and *B* more nearly in phase so that E_{min} may be read as a smaller value. The regulation will be found from the change in position of the contact ρ between the points where the E_{min} balance for no load and full load on the small transformer *C* is found, the volts per step on *C* being known from a voltmeter in the secondary of *B* or *A*. If the connection of Fig. *a* or *b* is used the absolute ratio also may be read by knowing the resistance *R* and the ratio of transformer *B* accurately. If a standard instrument transformer is used for *B* loading can be so arranged as to get practically zero phase between *A* and *B* at no load on *A*. This is evident from the diagram, Fig. 9, where the impedance volts is in line with the volts e''. The closing voltage *E* will also be along the same line and be in phase with e''. This is the condition where the power factor of the secondary load is the same as that of the impedance triangle of the transformer. Such a condition may be secured in practice by having the load on the transformer *B* reactive or by connecting reactive coils on to load transformer *B* in parallel with its non-inductive load.

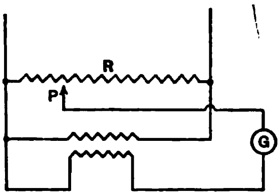

Fig. b.—Arrangement for low voltage, 2,200 and below

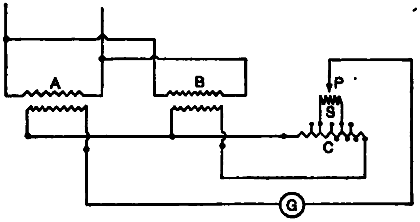

Fig. c.—Arrangement for voltages of 110 to 60,000 or more

For low voltages the resistance *R* may be of any desired amount (about 5 or 10 ohms per volt) and may be used with any suitable detector, (*G*).

For use on 110 to 220- or 550-volt secondaries it would be possible to provide a small auxiliary auto-transformer of known constants with or without the slides, that Professor Shane has shown, refer to Fig. *c*. It would then be easy to get regulation on any transformer of 110, 220 or 550 volts secondary if another transformer to be used as *B* having anywhere near a similar ratio was available without the necessity of getting two transformers alike. For regulation test the constants of transformer *B* need not be accurately known and both ratio and regulation may be obtained if the constants of transformer *B* are known but still *A* and *B* need not be alike. Also with the constants of B accurately known proper loading of its secondary can produce zero phase angle. (Zero phase angle is not always present in transformers at no load.) In either case the low reading voltmeter for reading regulation is not required.

If zero phase angle is produced on B then the reading of E_{min} where A is loaded is also a measure of the phase angle for

$$\text{Sin}\left\{\begin{array}{c}\gamma \text{ in potential transformer}\\ \\ \beta \text{ in current transformer}\end{array}\right\} = \frac{E_{min}}{e''}$$

Quite good accuracy, on account of the very small angle usually found, may be obtained in this way with any suitable means of determining the point f and of reading E_{min}. Professor Shane has found that commercial alternating-current voltmeters may be used; also he has employed a special indicator for the purpose. An indicator similar to that described might be used to measure E_{min} as well as to determine the point of, but perhaps some form of dynamometer, separately excited, if need be, and with or without iron might be used, or any thermo galvanometer scheme, or commutator device, in fact any of the special devices referred to at the Convention last year[*] and this year[†] in connection with ratio and phase angle testing of instrument transformers.

To me the greatest value of Professor Shane's paper is in showing that the somewhat refined methods by which exact regulation, ratio, etc., may be determined for instrument transformers are useful for, and may be easily applied, to the more general problem of the commercial testing, of lighting and power transformers.

Ralph W. Atkinson: Professor Shane has thrown much light on some complexities of transformer theory. Much of the transformer theory is such that to the ordinary engineer, practical proof is necessary for entire confidence in the results.

It is well known that the effective resistance of a transformer as measured by the wattmeter on short circuit is greater than the effective resistance obtained by measurements with direct current. To determine the correct impedance triangle, the resistance as determined by the wattmeter must be used. Otherwise it is quite possible to make a large error in the determination of the reactance. If there is a difference in the case in point, it would tend to bring the results obtained by ordinary methods nearer to those of Professor Shane. If the results given in Table 2 line 9 be taken as correct for short circuit conditions we may obtain a value of regulation only about $\frac{2}{3}$ as far from curve A Fig. 6 as is curve B.

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[*] L. T. Robinson, Electrical Measurements on Circuits Requiring Current and Potential Transformers, A.I.E.E., TRANSACTIONS, **1909**.

[†] Sharp & Crawford, Recent Progress in Alternating-current Measurements A.I.E.E., 1910.

The additional loss as measured by the wattmeter may be of very considerable importance, though generally small in small transformers. It may be calculated by a not very complicated formula while the general explanation of the cause is very simple. The loss may be regarded as due to circulating or eddy currents induced by the field in the coil space due to the load current of the transformer. The field due to the magnetising current is very small and hence causes no loss in the copper. Therefore this copper loss is the same at full voltage as at no voltage. However, Professor Shane's tests show the total copper loss to be greater at the full voltage of the transformer. It would be interesting to know the cause. A possible explanation is the copper loss in the primary due to the exciting current. However the 4 per cent difference in copper loss at full voltage and no voltage can not be accounted for by less than about 4 per cent core loss; moreover this does not account for the reactance on full voltage.

Another point; with transformers connected for a heat run by the ordinary loading-back method, the copper losses are the same as under the short circuit conditions and hence there might be considerable error in the temperature rise obtained on transformers where the "load losses" are large.

It is probable that tests on a transformer having greater proportionate "load losess" would settle definitely their nature. The writer hopes the discussion will bring out the cause of these "load losses"

Adolph Shane: With reference to the errors liable to result in the use of Method I for transformers having large reactance values, as referred to by Mr. Fortescue, I may say that this matter has been given some consideration. The leakage reactance at the worst is always small as compared to the value of normal voltage. Therefore, though I frankly admit that the method is theoretically an approximate one, it affords in nearly every case a truely negligible error. The assumption made is, that the base of a narrow wedge-shaped triangle is equal to the hypotenuse. As long as the angle between these two sides is very small this approximation is legitimate. It would take a leakage reactance of considerable value (third side of triangle) to cause an error of practical importance in the above assumption. By examining the vector diagram of the transformer it will be noticed that this error is a maximum at unity power factor and begins to disappear as the power factor lowers. At one point on the regulation curve the error is theoretically absent, namely when e_{imp} is the value of the regulation. But, excepting near-unity power factor, this error can never be suspected of being important, because the $I\ R$ value is the only other quantity to ever tend to widen out (at very low power factors) the small angle referred to above, and this value is always small as compared to normal voltage.

Therefore, let us consider the worst possible condition, namely at unity power factor, and further let us choose three times the reactance value as observed in the tests. We will consider 12.75 volts as $X\ I$ instead of 4.25, the other values remaining as before. Under these circumstances the regulation volts is really 7.47. By solving the wedge-shaped triangle e_{reg} is found to be 7.82. The error is thus about 4.7 per cent. This is caused by a phase angle of a little more than 3 degrees between the line and secondary voltages. This displacement is usually considerably less in fairly small capacity transformers.

A word about the galvanometer used in these tests. It was a small piece of iron suspended on a thread. A coil surrounded the iron. Such a detector may be made as sensitive as one pleases and is not intended to indicate quantitative results, but a definite minimum point only. Criticism was made of the lack of sensitive adjustment in the method. Figs. 5 and 6 of the paper seem to show a sufficient degree of accuracy and necessarily assume some precision of adjustment. Indeed, where e_{min} had some value, as at unity power factor, a low reading voltmeter was used at times to secure adjustment more quickly and with good results. Of course, the detector must be well damped. Great accuracy of adjustment is only imperative when e_{min} has some considerable value. Fortunately an alternating current instrument (indicator) is sensitive upon the scale. It is not so sensitive near zero, but neither is extreme accuracy of adjustment necessary when e_{min} is quite small. The accuracy of adjustment may always be checked by the equation $e_{imp} = \sqrt{e_{reg}^2 + e_{min}^2}$. Such checks are often desirable and insure correct results.

The error due to current consumption of instruments is negligible and is of no greater magnitude than might be caused by a voltmeter connection for any test.

As to the use of three transformers in Method I, some may consider such an undesirable complication. If so, I would suggest to them Method II, the calculated method. The work at the desk is the same as in the method now popularly used; only the method of obtaining the data is modified.

As for the present methods of obtaining transformer regulation being sufficiently accurate, it would seem from curves 5 and 6, that the primitive method of reading no-load and full-load voltages, and obtaining the difference may give more accurate results. If we desire the truth, then we should find some scheme for ascertaining the *accurate* value of transformer regulation. Of course, I do not think for a moment that the methods presented here are the only ones feasible for arriving at more accurate results. I merely submitted these two proposed methods for discussion, so as to pave the way toward truth.

A paper presented at the 27th Annual Convention of the American Institute of Electrical Engineers, Jefferson, N. H., June 29, 1910.

AMERICAN TELEGRAPH ENGINEERING—NOTES ON HISTORY AND PRACTICE

BY WILLIAM MAVER, JR., AND DONALD MCNICOL

Although there may not be any startling technical announcements to make relative to recent progress in American telegraph engineering practice, yet within the twenty-five years past, in common with the progress in other lines of engineering, substantial developments have been also made in the telegraphic art along numerous lines, such as the standardization of equipment, and the adoption of improved apparatus and methods of operation which have generally resulted in increased efficiency of the plant, greater reliability of operation, a more rapid handling of the traffic, and consequent improvement in the service rendered the public; and which developments have, in fact, been adequate to meet the demands made upon the telegraph.

The time has been deemed opportune to record some of the salient features of present telegraph engineering practice in this country, but first in order more clearly to illustrate the differences between past and modern practice a resumé of the early history of telegraph practice in this country will be essayed in which resumé certain more or less interesting items of information relating to that history perhaps not hitherto published, or in any event not readily available, may be recounted.

The first electric telegraph line in this country was constructed by Morse in 1844 between Washington and Baltimore. The progress of this art into public favor was slow; due mainly to the high rates for service and to more or less imperfect service, the latter due mainly to poorly constructed lines and the former largely to heavy legal expense incurred in the effort to maintain for the Morse interests a monopoly of the telegraphic art. Morse endeavored to obtain a British patent for his electro-magnetic telegraph, but failed on the score of previous publication. Bain of Edinburgh came to the United States in 1848 to obtain a patent covering his chemical telegraph which was refused on the allegation that his device infringed the patents of Morse. Bain's telegraph consisted of a device for perforating long and short holes in a strip of paper, which were used to transmit long and short impulses of current over a wire. At the receiving end he used a sheet or strip of paper saturated with a chemical solution consisting of nitric acid 2 parts, prussiate of potash 20 parts and pure liquid ammonia 2 parts, which solution was decomposed by an electric current from the sending station thereby leaving long and short marks on the receiving paper sheet or strip. Bain pressed his claims in the United States Supreme Court and in the year 1849 a patent was finally allowed. A British patent to Morse would have been of doubtful value at that time, as during the life of the United States patent the Morse telegraph was but sparingly used in Great Britain, various needle and dial telegraph systems having obtained a strong foot-hold in that country.

The maximum speed claimed for the Bain system was about 1000 words per minute, but as a writer of that day remarked:[1] " The process of preparing the message to be transmitted, took quite as long as to transmit it " by the Morse method, and while " Mr. Bain's plan was entirely successful as far as it went it was found that after the quick receipt of a long dispatch, it would take about as long to copy it into manuscript as it would have taken to transmit it in the ordinary manner in the first place." Following the granting of the U. S. patent to Bain, numerous telegraph companies were organized and lines built on which the Bain automatic chemical system was employed, in opposition to the Morse Companies, but in 1850 an injunction was obtained, based on the charge that Bain's apparatus infringed the Morse telegraph patent of 1840. A consolidation of many of the chemical automatic companies with the existing Morse lines soon followed, and subsequently the Morse manual system (in which the Morse stylus recorder, or register was used) went into almost general use.[2] The Morse register was

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[1] "Electric Telegraph," (1852) Jones, pp. 110-150.

[2] In a personal letter to Mr. Maver dated August 22, 1890, Mr. D. H. Craig who was a prominent figure in the early annals of American telegraphy, writes: " I used Bain's system on lines between New York,

gradually displaced by the reading sounder, but not without opposition on the part of the superintendents of telegraph who were apprehensive, needlessly as experience proved, of the introduction of errors thereby. The first printing telegraph was that due to Royal E. House[3] the use of which was begun in 1847–1848 and continued for many years in this country. This system employed a key-board the depression of a key of which resulted in the printing of a given letter on a strip of paper at the receiving station. The speed of transmission by this system was about 50 words per minute. It was operated on lines 1000 miles in length. The Morse interests endeavored to bring this telegraph printer within the scope of the Morse patents but were overruled by the courts.

In the early days of the electric telegraph the methods of line construction were naturally crude, but every year saw improvements in the direction of workmanship and materials used. Wooden poles were used from the first in this country, but the forms of insulators and the materials used in their construction were multitudinous, and it was not until much bitter experience was had with various " improvements " in insulators that practice converged on the glass petticoat form now universally employed in overhead electric telegraph work in this country. One of the so-called improvements termed the "brimstone" insulator was especially defective and nearly ruined several of the competing companies that employed it. This insulator consisted of an iron arm which screwed into an augur hole in the pole, the outer end of the arm carried a hollow pendant filled with sulphur into which an iron hook that upheld the line wire was inserted.

Boston and Portland between 1850 and 1853 and was able often in stormy weather to send to the Boston press columns of news when the Morse lines would not telegraph a word. We frequently, however, had trouble with " tailings " when the dots and dashes all ran together and made the record partially or wholly unreliable, so that in a message or series of messages of 500 or 1000 words there would be yards of record that would have to be discarded and the messages repeated. The later use of artificial resistances or magnets largely eliminated this trouble. Bain used on his early lines (for his chemical solution) nitrate of ammonia, 2 pounds to a gallon of water, and muriate of ammonia one pound to a gallon of water, and one-half ounce of yellow prussiate of potassia. This makes a fair solution, but we discarded it, (date not given) and substituted one half ounce red prussiate of ammonia and one pound of muriate of ammonia dissolved in one gallon of pure rain, or distilled water—iron pins were used with this."

[3] Described in "Manual of the Telegraph," Shaffner, p. 391.

The civil war in this country, 1861–1865, again directed the attention of the world to the great utility of the electric telegraph in war and while its use at this time did not perhaps materially aid in the advancement of telegraph engineering it emphasized the value of the Morse telegraph system for this purpose because of its simplicity and reliability in operation.

The source of electromotive force for telegraph purposes in the United States up to the year 1855 was the Grove cell, which was displaced by a modification of the Smee cell known as the Chester battery, and this battery in turn gave way to the Callaud or gravity battery, of which up to the introduction of the dynamo machine in the year 1882, many thousands were in use. In some of the main telegraph offices 5,000 to 15,000 such cells were employed; entire floors of large office buildings being set aside for their occupation.

To meet the increasing demand for additional telegraph facilities in the decade 1870–1880, without resorting to the continual construction of additional line wires, the thoughts of inventors were directed to means for increasing the capacity of existing wires. To this end the chemical automatic telegraph, and the duplex and quadruplex systems of telegraphy were called into service. Thus in 1870 a compound wire of steel core and copper was erected between New York and Washington a distance of 275 miles on which a chemical automatic system due to Mr. George Little was employed. This system was a modification of the Bain chemical telegraph previously mentioned herein. Originally, adequate means were not provided in the Little system for diminishing the " tailings," or prolonged currents, due to the static capacity of the line, at the receiving instrument, in consequence of which the speed of signaling was low. Subsequently Little introduced a plain resistance in shunt around the receiver with beneficial results.

The Varley devices consisting of electro magnets in shunt with the receiver, and of condensers in series with the receiver[4] for the purpose of eliminating the tailings were subsequently employed, (the electro-magnets probably first by H. Grace,) to great advantage in this and certain other later automatic chemical systems in which a single row of holes in the perforated paper (and a uni-directional current) was employed; the condenser as thus employed virtually giving the equivalent of the double current method. Still later the speed of

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[4] British patent No. 3543. 1862. U. S. Patent 78495. 1868.

transmission on this New York–Washington line was increased to 900 words per minute by the substitution of an iodine solution and by using a platinum needle in place of a nitric acid solution and iron needle.

An important contribution to the art of chemical automatic telegraphy at this stage was the Edison key-board perforator, which by the depression of a key perforated in a moving paper tape the characters necessary for any given letter. By the Little method of preparing the perforated tape not more than 7 or 8 words per minute was feasible, while with the Edison key-board perforator the tape could be prepared at a maximum rate of 40 words per minute, the average being about 25 words per minute. This key-board perforator while highly ingenious from a mechanical point of view was somewhat cumbersome in operation. The key board was about 18 inches in length, and the keys had a drop of about 2 inches requiring strong pressure to carry them down. As a writer of the period remarked " An hours work on one of these punches is a severe strain on the muscles of a strong man."[5] An important test of this system was made between Washington and New York, January 27, 1874 when the President's message on the Spanish " Protocol" consisting of 11,130 words was transmitted. This matter was prepared for transmission by ten perforators in 45½ minutes. The message was transmitted in 59 minutes. Time from the beginning of perforation until message received at distant end of the wire, 53 minutes. The time consumed in translating the characters by ten operators in New York was about 45 minutes, or roughly it required 72 minutes for the entire operation. Four Morse operators on 4 single wires, it may be remarked, are capable of transmitting a message of this length in 55 minutes. In the practical operation of this system by the Automatic Telegraph Company on its single wire from New York to Washington, D. C., during 1873–1874 business was frequently badly delayed by the breaking of the wire, there being no emergency wire, or alternate route. This fact undoubtedly detrimentally affected the commercial success of this system, a result that must obviously follow in all cases where but one route or only a limited number of wires between the important business centers are available. This automatic system[6] was subsequently employed, more or less in combination with the Morse

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[6] (Described in " The Electric Telegraph ", Prescott, Vol. 11, p. 727.)

[5] " The Telegrapher," 1875, p. 109.

manual system, on the lines of the Atlantic and Pacific Telegraph Company until the year 1876, when it was gradually displaced by the Morse manual method of transmission.[7]

From about 1880 to 1884 the American Rapid Telegraph Company and its successors the Banker's and Merchants, and United Lines Telegraph Companies, operated a chemical automatic system known as the Foote & Randall system. These companies lines (compound copper coated wires) extended from Boston and New York to Washington, Pittsburgh, Buffalo, Cleveland and intermediate points. In this systemt he double-current method was employed. The prepared paper was perforated in two rows as indicated in Fig. 1.

Dots were represented by one hole on either side of the strip, the dashes by two holes. Consecutive dots, and dashes, were perforated diagonally on alternate sides of the paper strip as shown in the figure. Two metal drums *d*, *d'* connected with the positive and negative poles, respectively, of the battery were placed side by side in such a manner that one drum came under the holes on one side of the paper, the other under the holes on the other side. Transmitting needles or brushes *n*, *n'* connected jointly to the line wire were arranged so that each was in line with one row of holes on the paper. By the arrangement of the holes as shown each consecutive character of a letter, and the first character of a following letter were made by a different polarity to that making the preceding character and consequently all letters containing more than one character were represented by dots and dashes on alternate sides of the received paper strip.

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[7] About the years 1875-77, the widely advertised claims of the Atlantic and Pacific Telegraph Company relative to the advantages of the chemical automatic and Wheatstone automatic telegraph systems controlled by that company were having a depressing effect on the stock of the Western Union Telegraph Company. Presumably to offset this effect President Orton of the last named company contracted with Messrs. Craig, Randall and Foote to pay $500,000 for a chemical automatic telegraph system that would be superior in every respect to that operated by the rival company. Tests were made of the new automatic system and the experts reported that all the technical conditions of the contract were fully met. Upon the sudden death of President Orton shortly thereafter however complications arose, a compromise offer of $250,000 being declined, whereupon the contract was abrogated and the inventors' interests in this system were turned over to the American Rapid Telegraph Company. It may be added on the authority of Mr. C. A. Randall that the inventors finally received about $15,000 as their portion of the amount received for the patents covering the automatic system bearing their name (W. M. Jr.)

At the receiving station needles n, n' were arranged in series in the line circuit as outlined, and rested on the sensitized receiving paper p. As the chemical solution is decomposed only by a current of positive direction, marks were made by the needle n with currents from battery E, and by needle n' with currents due to battery E'. In this system advantage was taken of the retardation of current due to the static capacity of the line in forming the dashes; the short perforations, all of uniform length, also limiting the time of contact of battery with the line, and thereby limiting the charge imparted to the line at each contact. The records thus produced were easily read by copyists. This system was capable of transmitting clear, legible characters between New York and Boston at the rate of 1000 words per minute, and 500 words per minute were ordinarily so transmitted. Messages were prepared by operators using the Anderson keyboard by means of which 30 to 50 words per minute could be perforated, the machine operating with the ease of an ordinary typewriter. In June 1883, the American Rapid Company had in operation over 2,400 miles of pole line and 14,000 miles of wire. As already intimated this company began operations with the use of compound wires (6 ohms per mile) consisting of a steel core covered with a copper strip each weighing 200 lb. to the mile. This compound wire proved unsatisfactory, owing it was claimed to imperfections in manufacture which led to breaks or openings in the copper strips admitting moisture and ultimately causing the copper to peel off in long lengths. Subsequently No. 6 iron wire was employed as line wires by this company. The rates charged by this company in 1881 for transmitting messages was $1.00 for 195 words between New York and Boston, but experience showed this rate to be unprofitable and it was increased to 15 cents for 20 words. The Foote and Randall automatic system was set aside in 1884 upon the financial failure of the company.

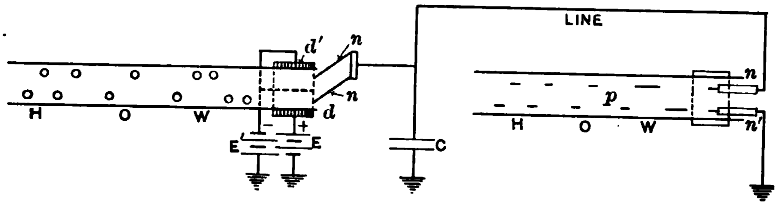

Fig. 1.—Foote and Randall chemical automatic telegraph

In 1881 the "Leggo" chemical automatic system was installed by the Postal Telegraph Company between New York and Chicago (1,000 miles) on its two 1.7-ohm-per-mile wires (compound steel and copper) on which by the Leggo system 1000 words per minute were commonly transmitted. Taylor found by experiments on these wires that up to 400 miles, a speed of 400 words per minute was possible by the old Bain method; that is without compensating for line static,[8] but at a distance of 700 miles the signals arrived in a continuous black line. To remedy this defect Taylor introduced an extra battery *E'*, Fig. 2 at the receiver *R* in opposition to the transmitting battery *E*. The e.m.f. of battery *E'* was one third of that of *E*. *r*, *r'* were adjustable resistances. With this arrangement a speed of 1200 words per minute was possible on this New York-Chicago circuit.

The method of preparing the messages for transmission by the Leggo automatic system consisted in depositing an insulating ink spirally on a revolving metallic cylinder by means of a spout attached to the armature of an electro magnet operated by a relay or Morse key in a main or local circuit. The dots and dashes thus recorded were transmitted from the metallic cylinder at high rates of speed over the line circuit. An advantage claimed for this method of recording signals for re-transmission by Morse telegraphy was that the business originating at branch offices and way offices could be transmitted over through wires automatically without further preparation. The extra battery *E'* was kept constantly to the line during operation and at the instant when the transmitter needle or brush passed onto the insulated ink on the drum this negative polarity cut short the tailings.[9] The Leggo automatic

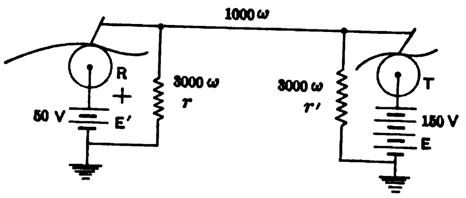

FIG. 2.—Taylor arrangement of Leggo's automatic telegraph

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[8] See article of Theodore F. Taylor, *Electrical World*, May 24, 1884.

[9] This arrangement of batteries for this purpose is perhaps suggested in Prescott's "Electric Telegraph," 1866, p. 137.

system was abandoned for lack of patronage after a comparatively short period of operation.[10]

Since the discontinuance of the American Rapid and the Leggo systems there has been no extensive employment of automatic chemical telegraphs in this country or elsewhere although workers in this field like Anderson and Delany have devised certain features designed to be conducive to greater reliability of operation and speed of translation of the received characters, notably perhaps the Anderson page method of recording the message which enables the attendant to observe the condition of the incoming signals as they arrive, and simplifies the reading of the characters by the copyist[11]. It also lends itself readily to means for drying the paper speedily as received, thus obviating, or minimizing an objection to " wet " strip, namely the tearing of the strip.

The well known Wheatstone system of automatic telegraphy was introduced on certain circuits of the Western Union Telegraph Company in 1883, and its use was continued thereon up to a comparatively recent period when it was[12] to a considerable extent displaced by the Buckingham-Barclay printer. Further reference will subsequently be made to this subject.

As previously stated the employment of duplex telegraphy began about the year 1868, and on short lines was practiced with a certain degree of success without any device to compensate for the static discharge from the main line. Stearns, however, applied the condenser to the artificial line for this purpose in 1872, whereupon the general use of the duplex ensued. Subsequently in 1873–74 the Edison quadruplex was placed in operation on the Western Union Telegraph Company's lines and after numerous modifications of apparatus and circuits finally reached its maximum efficiency about 1884. In the year 1886 there were about two hundred quadruplex sets in operation in the United States, these, it was estimated, providing additional, or " phantom " wire facilities equivalent to 150,000 miles of line wire, the value of which was approximately eleven million dollars.

Much of the success of the quadruplex system between the years 1885–1895 is no doubt properly ascribed to the extensive employment of hard drawn copper wire for telegraph purposes, beginning in 1885. The period indicated was also prior to the

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[10] See TRANSACTIONS A. I. E. E., 1897, p. 139.

[11] See " American Telegraphy and Encyclopedia of the Telegraph," Maver, p. 294.

[12] *Ibid*, Chap. XXVII.

advent of high tension power transmission lines in proximity to telegraph circuits, the inductive disturbances from which undoubtedly have had a very detrimental effect upon quadruplex operation, and to which subject also further reference will be made.

As an instance of the extent to which duplex and quadruplex operation has been utilized in this country in proportion to existing wire mileage, it may be noted that in the case of the Baltimore & Ohio Telegraph Company which had a total of 50,978 miles of wire in operation in 1887, (reaching from Portland, Maine to Galveston, Texas, *via* New York, Washington, Chicago, St. Louis, etc.,) 23,482 miles thereof were assigned to the aforesaid duplex and quadruplex service, producing 56,553 miles of phantom circuits. Of the total miles of wire mentioned there were approximately 4,655 miles of No. 12 and 3,605 miles of No. 14 hard drawn copper;[13] 12,726 miles of No. 6 iron, 25,345 miles of No. 8 iron, 3,944 miles of No. 9 iron, and 252 miles of No. 12 iron wire.

In the years 1885–86 the Delany synchronous multiplex system[14] was in experimental operation on a circuit of the Baltimore & Ohio Telegraph Company's lines. On short lines this system gave the equivalent of six transmissions simultaneously, but owing largely to difficulties introduced by the static capacity of the line, its employment on long lines was not available at that time.

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13. This was doubtless the first extensive employment of hard drawn wire in telegraphy. At this time quite conflicting views were held as to the utility of this metal for overhead telegraph circuits; the advocates of silicon-bronze and phosphor-bronze wire claiming superiority for those materials. The experience of twenty-five years has, however, fully justified the favorable opinions of the pioneer users of hard drawn copper wire regarding its many advantages.

It may be further noted as an interesting item of telegraph history that owing to the expiration in 1880, through inadvertence, of the Canadian patent No. 4608, of April 10, 1875, covering the Edison quadruplex, that system was unprotected by patents in this country after the first mentioned date. A legal contest was, however, waged by the Western Union Company against the Baltimore & Ohio Telegraph Company for infringement of Stern's patent No. 126,847, of 1872, covering the application of the condenser to duplex and quadruplex telegraphy. An injunction *pendente lite* was denied by the courts on the ground that the original Stearns patent had been so broadened by successive re-issues as to raise reasonable doubt as to its validity. The matter was still in litigation when the defendent company was merged with the Western Union Company in October, 1887.

14. Described in "American Telegraphy," Maver, Chap. XXI.

SOURCES OF ELECTROMOTIVE FORCE IN TELEGRAPHY

As already noted herein gravity batteries as a source of e.m.f. for telegraph service have been almost entirely displaced in this country by machine generators. The type of generators used and the arrangement of equipment vary according to the local requirements.

In some instances the generators are driven by gas or steam power developed on the premises, but as a rule public service mains are utilized to operate the machines, either as motor-generators, or by means of separate.electric motors. At points where the only commercial current available is alternating, it is customary to operate from this source an induction motor-driven direct-current generator which in turn furnishes power for the operation of direct-current motor-generators. In numerous cases where driving power to operate the motor generators is derived from public service mains, emergency gas or gasoline engines are installed to insure continuity of service in the event of prolonged interruption of the commercial power circuits. One method of arranging these machines in large terminal offices consists in arranging a certain number of them of equal voltage in series, thereby furnishing a range of e.m.f. from, say 40 to 400 volts, the machines being tapped by the various main line or local wires as required, the local and single wires taking from 40 to 150 volts, respectively, the duplex circuits taking current at 200 volts and the quadruplex circuits at about 350 volts. As currents of both polarities are employed in these systems, two sets or gangs of machines in series, as stated, are employed. Another method of arranging dynamos in terminal offices is to employ from 7 to 14 machines which deliver e.m.f.s ranging from 40 to 400 volts the lower voltage supplying current for the operation of sounder circuits, automatic repeaters, duplex and quadruplex pole changers, transmitters etc. An e.m.f. of 125 volts is used for main line simplex operation, generally way wires having a number of offices on the circuit. Machines supplying respectively 200 volts of positive and negative polarity are allotted to duplex operation, while 385 volt machines of positive and negative polarity, respectively, provide current for quadruplex circuit operation. The general arrangement and appearance of these machines are shown in the accompanying illustration.[15]

Storage batteries also have been utilized quite largely in telegraph service as sources of current for the operation of main line

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[15] Described in "American Telegraphy," Maver, pp. 47-227.

and local circuits. In general these batteries are charged from public service direct-current mains, or by locally operated direct-current motor-generators. The comparatively large loss in transformation of power, from the mains to, and in the storage battery itself, together with the cost of attendance and maintenance of the motor-generators and the battery have acted as a deterrent to its extensive use in telegraph work, notwithstanding certain advantages in the way of constancy and reliability of current that such batteries may possess. The engineering departments of the commercial telegraph companies and of the larger railroad companies have therefore followed closely those developments in the electrical art which aim to procure equally efficient and more economical transformation of electric power for telegraphic purposes, and the claimed advantages of various alternating-current rectifiers—vapor, electro-mechanical, and electrolytic—have been considered and tested. At the present time, for example, quite an extensive application of the electrolytic rectifier is being made by the telegraph companies here, in order to determine what dependance may be placed upon these methods of obtaining practically constant direct-current potentials

FIG. 2a.—Typical arrangement of motor dynamos in telegraph work

from alternating-current sources. One of these rectifiers (the "Hickley") consists of a solution or electrolyte, say, phosphate of soda, and electrodes of carbon and aluminum, contained in a vessel *V*, Fig. 3, to which are attached radiator loops *R* which permit circulation of the solution (necessary on account of the heat developed in the electrolytic cell) thereby preventing the weakening of any portion of the electrolyte more than another. The direct current supplied by the rectifier is of course, pulsating, but owing to the condenser effect of the cells whereby a portion of the negative current is recovered, currents are derived which are sufficiently steady for average telegraph requirements. With this rectifier 80 volts direct current are procurable from 110 volts alternating current mains. The durability of the solution and electrodes of this rectifier depends largely upon the amount of energy delivered, but if not overworked the rectifier will not require renewal oftener than once each year; assuming daily operation of the device. A suitable transformer *T* is utilized to give either higher or lower voltage than that supplied by the available alternating-current mains, the rectifier being constructed to supply e.m.fs. ranging from 6 to 1000 volts. It may be noted also that some use is being made of small step down transformers of the bell-ringing type for the purpose of obtaining low voltages to operate call circuits, etc., operated in connection with telegraph systems.

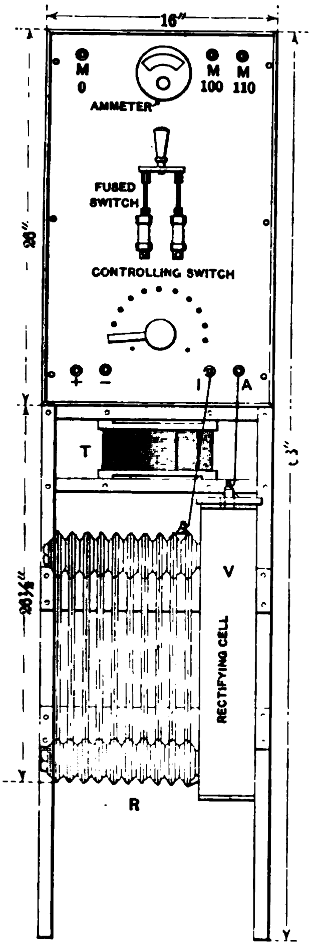

Fig. 3.—The Hickley rectifier

Telegraph Printers

It has long been recognized by certain telegraph authorities, that an ideal system of telegraphy would be a simple and reliable page printer, capable of transmitting and receiving say from 600 to 1000 words per minute on circuits of from 200 to 1000 miles in length. To the inventor of such a system will ensue wealth and fame. It is hardly conceivable, however, that a telegraph printer can be devised that will not possess a number of prominent defects that will act against its general employment; for example, the necessity of preparation of the message for transmission, and its comparative expensiveness and complexity. The first defect would preclude its use on hundreds of stock exchanges and "broker" circuits; the second would debar it from thousands of small way wires. These disadvantages are inherent also in all automatic machine telegraph systems, electro-magnetic or electro-chemical. The superiority of the Morse manual system above all other systems in the foregoing respects is universally admitted.

Reference has already been made in the opening remarks of this paper to the "House" printer. This printer was followed in America by the so-called "Combination" printer, and by the Phelps printer,[16] and in Europe by the Hughes and the Baudot systems, all of which retain the objectionable features of printing the received characters on a strip of paper. Moreover these systems are comparatively slow in operation, not attaining a speed of more than 60 words per minute in one direction, or in each direction if duplexed, although the Baudot system when operated on the synchronous multiplex plan increases quite materially the carrying capacity of a circuit. For some time past in America efforts have been made to obtain higher speed page printing telegraph systems; that is, systems by which the received message will be printed on a regulation telegraph blank ready for delivery. Several different systems of this kind have been recently placed in operation in the United States, namely the Buckingham-Barclay[17] printer on the lines of the Western Union Telegraph Company, the Rowland multiplex printer,[18] experimentally on some of the lines of the Postal Telegraph Cable Company and the Wright printer, to be briefly described presently. The capacity of the Buckingham-Barclay printer is about 100 words per minute in each direction on a circuit 1,000 miles in length with repeaters midway. The capacity of the Rowland printer worked octoplex would be about

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[16] See "Electricity and Electric Telegraph," Prescott, Vol. II, p. 652.

[17] Described in "American Telegraphy," Maver, Chap. XXVII.

[18] Ibid.

280 words per minute on a circuit of moderate length, say 250 miles. The Buckingham-Barclay printer is quite extensively used at present and has been shown to possess marked advantages over its predecessors in printing telegraphy, and as previously noted has supplanted quite largely the Wheatstone automatic system in this country. It is possible, however, that a critical analysis now under way of the respective merits of these systems as regards rapidity, reliability, accuracy, and economy of operation may disclose results somewhat favorable to the Wheatstone system. It is not unlikely that, for the handling of the increased business due to public appreciation of the night " letter-gram " service recently inaugurated by the large telegraph companies in this country, resort may be had to the Wheatstone system or to one or other of the freely available rapid atuomatic telegraph systems mentioned herein, or to others that may be developed.* The merits of the Wheatstone system for service of this general nature has long been recognized in Europe especially in the British Postal Telegraph department where it has attained a speed of from 400 to 600 words per minute on the shorter circuits.

One notable advantage over printing telegraph systems possessed by the Wheatstone or other automatic systems, in which the received messages are translated by a copyist (in common with the Morse manual method, but not by any means to the same degree), is that signals mutilated in transmission that would be beyond recognition in the printed record, may often be deciphered correctly from the tape by an expert operator or copyist. Another important advantage of the Wheatstone system is that its main line apparatus is adaptable either to manual Morse or to high speed transmission by the simple movement of a small switch.

It must be noted, however, that the conditions now surrounding telegraph circuits (referred to elsewhere in this paper), such as high-tension inductive disturbances, and excessive retardation due to the presence of stretches of underground cable, were

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*Under this " night letter " service the companies receive not later than midnight fifty word messages (or less) to be transmitted for delivery on the morning of the next ensuing business day at the standard day rate for ten words, one-fifth of the standard day rate for ten words being charged for each additional ten words or less in excess of fifty words in the night message. The companies reserve the option to mail these night telegrams at destination to the addressee. The messages must be written in plain English.

non-existent when the high speed automatic systems referred to were in practical operation, and these conditions, it may be anticipated, will reduce the speed efficiency in at least direct proportion to the sensitiveness of the respective systems. The night operation of such circuits, would, however, have the advantage of a minimum disturbance from parallel circuits, the exciting cause of which, except the stretches of underground cables, would be less in evidence. Unfortunately this does not apply to static inductive disturbances from adjacent high-potential transmission lines, which are in constant operation.

The Wright printer due to Mr. John E. Wright may be operated by ordinary typists unfamiliar with the Morse code, as the transmitter is equipped with a standard typewriter keyboard which may be operated at typewriter speed, and the depression of a key of which selects a combination of positive and negative impulses, which, passing to line select a corresponding letter for printing at the distant receiving typewriter. The electromechanism of the transmitter prints a tell tale duplicate of the outgoing message in page form. The transmitting potential is 385 volts of each polarity. The line instrument is a polar relay of the duplex type that operates locally a magnet which in response to given combinations of incoming currents is designed to control the movements of a type-wheel, capable in operation of selecting and printing a given letter, of revolving around its axis, moving perpendicularly in the line of its axis, and laterally across the message blank at right angles to its axis, all of which movements are reversible. The receiving typewriter prints directly in message form the received telegram, the blanks being fed to the machine by an attendant who watches the copy during the printing to guard against errors. The disposition of the letters of the alphabet the numerals and punctuation marks on the periphery of the type-wheel is such that in practice it is found that regardless of the position of the wheel any letter may be selected and printed with an average of three and one half current impulses from the transmitter. The speed of this printer in operation on lines up to 300 miles in length is about 40 words per minute in each direction.

It may be noted that in America, telegraph operators during recent years have adopted extensively a keyboard, and other semi-automatic devices for the transmission of the Morse alphabet, which devices quite largely increase the rapidity and facility of transmission over the regulation key method. American operators have also very generally adopted the typewriter for transcribing received messages. Primarily these instruments were adopted as labor saving devices, greatly reducing the mental and physical strain on the operator, and making it possible for operators who had " lost their grip " of key or pen, to return to the ranks of first class operators. The public appreciation of the typewritten copy was such also that the telegraph companies encouraged the use of the machine by increasing the compensation of typewriter telegraphers. Further, the use of the typewriter in combination with the marvelous abbreviations employed in the transmission of press matter, by code[19] considerably diminished the demand for rapid automatic or printing telegraphs, at least for that service, by bringing the performance of Morse working well up to what might be expected from printing telegraph systems. The semi-automatic transmitting key termed the Martin mecograph or modifications thereof is used by perhaps four-fifths of the operators of this country. Briefly, it consists of a contact, which when moved to one side manually by the operator makes a dash, and of a vibrating rod or pendulum, that when moved to the other side automatically vibrates (until stopped by the operator) in the act of so doing making any desired number of dots. It is estimated that 60 per cent more movements are required in sending by the ordinary Morse key than by this device, shown in the accompanying illustration, Fig. 3a.

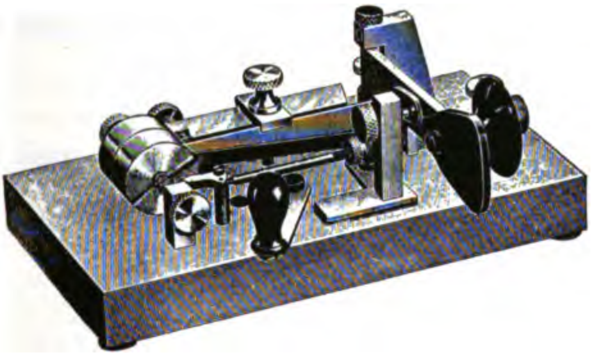

Fig. 3a.—The mecograph

DIRECT POINT REPEATERS

During recent years a demand has grown up for fast duplex telegraph service, in order to provide direct communication

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[19] See " Phillips Code," W. P. Phillips.

between large centres remotely separated. For instance, the vast amount of traffic which arrives at, and which originates at the large eastern cities of this country destined for China, Japan, the Philippines and other Asiatic countries requires that these cities shall have direct communication with the Pacific cable office in San Francisco. Formerly the arrangement of apparatus used in repeating from one multiplex set into another was that whereby the receiving relay controlled the sending transmitter through local connections, but the mechanical inertia of these instruments and the increased number of local contact points through which the operation was controlled did not conduce to high efficiency. The duplex repeater now used on both the Western Union and on the Postal Telegraph lines is known as the " direct point " repeater, and is similar in operation to the Wheatstone duplex repeater. By referring to Fig. 4 it will be seen that the arriving signal from the east will actuate the right hand polar relay *P R*, thus placing for instance the armature of that instrument in contact with the 200-volt negative, e.m.f. which is given an outlet through the left hand polar relay to the line west, and signals arriving from the west are relayed to the line east by a reverse operation. It is now customary to wire up polar duplex and the polar side of quadruplex sets so that this efficient method of repeating may be utilized. Inasmuch as the local contact points of the polar relays are in this case employed to deliver line currents, special devices are provided to control local circuits for operating the reading sounders. For instance, in the Western Union type of duplex repeater the polar relays are equipped with double armatures, mechanically jointed together, but separated electrically, one contact controlling the line potentials, and the other the local circuit. The method employed by the Postal Telegraph Company is the well known " leak " arrangement. A single

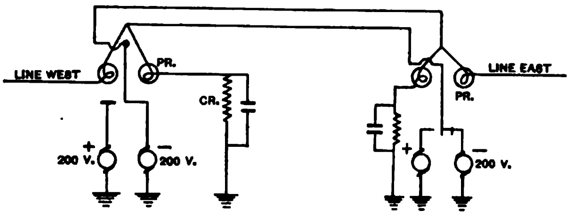

FIG. 4.—Direct point repeater

tap is taken off the armature contact of each polar relay and led to ground through a polar relay and a 20,000-ohm coil. Another method of accomplishing the same result is to substitute a 0.5-m.f. condenser for the 20,000-ohm coil thus obtaining the same response in the polar relay without any loss of current through the leak coil to ground. Indeed when the condenser is used in place of the leak resistance, the polar relay may be done away with, the circuit leading directly from condenser through a sounder and to ground. In this latter case the armature and stop adjustments of the sounder are set so that the signals are all made on the upper stop screw.

The type of duplex telegraphy now universally employed in this country is that in which the well known double-current principle is employed, and by means of the direct repeating relays mentioned, very long distances are spanned, for instance across the continent from New York to San Francisco, by many diverse routes. Ordinarily from four to six repeaters are used in these transcontinental circuits, and the speed of transmission is at least equal to the ability of the operator to manipulate the key. Ordinarily the differentially-wound polarized relay is employed.

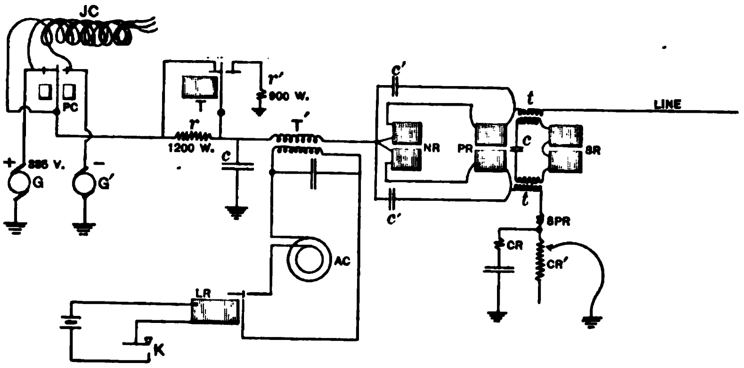

Fig. 5.—Phantoplex on quadruplex circuit

SUPERIMPOSED SYSTEMS. "PHANTOPLEX" AND VAN RYSSELBERGHE

Since Varley[20] there have been many workers whose aim it has been to increase the capacity of a single wire or a wire already in operation as a duplex or a quadruplex by superimposing thereon one or more pulsatory phantom circuits.

In the accompanying diagram (Fig. 5) is shown an arrange-

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[20] Varley's British patent, No. 1044, 1870.

ment of a " phantoplex " circuit on a quadruplex circuit that is in actual operation in many places in this country and by means of which a " sextuplex " is obtained.

In the figure one station only is shown. *G*, *G'* are the sources of e.m.f., for the quadruplex. *P C* represents the pole changer, *T* the transmitter with its shunt and leak resistances; *N R* indicates the neutral relay, *P R* the polar relay, and *C R*, *C R'* the compensating resistance of the quadruplex system, the local circuits of which are omitted in the drawing for the sake of clearness. As the operation of the quadruplex is generally understood,[21] it will be necessary only to describe the phantoplex portion of the system. *A C* is a high frequency generator, the circuit of which is controlled by a local relay *L R* and a key *K*. In the circuit of *A C* is a transformer *T'* the secondary coil of which is in the transmitting portion of the quadruplex system. Condensers *C* and *C'* provide a path for the high frequency currents past the quadruplex relays. *t* and *t'* are small transformers, the primary of *t* being in the main line, the primary of *t'* in the artificial line; and in the secondary circuit of which transformers is the phantoplex polar relay, which in turn operates a reading sounder not shown. This arrangement of transformers *t*, *t'* obviously renders relay *S R* irresponsive to the outgoing currents of *A C*, but still permits it to respond to the high-frequency currents from the distant station. An unretarded path for the pulsatory currents is provided by a grounded condenser *C* at each station. The high-frequency currents of the phantoplex circuit are of a strength below that necessary to operate the quadruplex relays, but the armature of the phantoplex relay *S R* being properly biased-by spring tension responds to the high frequency currents. Incidentally there is shown in this figure at pole changer *P C* a " coil " condenser *J C* known as the " Johnson " coil consisting of three separate coils of German silver wire wound on a wooden bobbin with an air core, the spool being about seven inches long and an inch in diameter. The coils are thoroughly insulated from one another by a double covering of cotton saturated with paraffine. One end of each winding is left open, the other end being connected as shown in the diagram. This device is efficacious in eliminating the sparks at the contact points of the pole changer.

In many cases Morse duplex circuits or portions of them are used simultaneously as telephone circuits, the wires of two such

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[21] See " American Telegraphy," Maver, p. 217.

duplex telegraph circuits being employed as one metallic circuit for telephonic purposes. One such arrangement is depicted in Fig. 7. Here *P C*, *P C* may represent the pole changers at a terminal (or a repeating station as shown in Fig. 4) of two duplex circuits, furnished with e.m.f. by generators *G*. The Wheatstone bridge method of rendering the polar relays irresponsive to the home pole changers is used, the arms of the bridge being formed of a double retardation coil *R C* which is found to be an efficient, practical device. In some cases the armatures of the polar relays *P R* are equipped with retractile springs so that the polar duplex apparatus may be availed of for simplex operation when desired, which result is accomplished by disconnecting one contact *b b* of the pole changer from a generator. These relays also have double local contact points on the armature levers *a*, *a'* shown theoretically in the figure, one of which controls the local reading sounder *S*, the other sounder *S'* in a branch office. The telephone apparatus utilizing the two duplex circuits *D C*, *D C* is shown at *T*. *c*, *c*, *c*, *c*, represent 4 m.f. condensers; *i*, *i* are 30-ohm retardation coils. This arrangement of the telephone, in one instance, is used successfully on duplex telegraph circuits to a distance of 360 miles, the entire length of the duplex circuits being 1000 miles without repeaters.

Composite circuits (originally the Van Rysselberghe simultaneous telegraph and telephone system)[22] are employed in this country and Canada very extensively; notably by the American Telephone & Telegraph Company, also by the telegraph departments of several large railway companies. Between New York and Boston alone at least fifty leased telegraph wires are in daily operation on long distance telephone circuits, and this dual use of circuits is being rapidly extended in telegraph practice, all new line construction being designed with this end in view as noted elsewhere herein, the increased earning capacity of the wires thereby gained being the obvious incentive thereto.

INDUCTIVE DISTURBANCES ON TELEGRAPH CIRCUITS

In the pioneer days of telegraphy when routes were being sought for pole lines, the rights-of-way of the existing steam rail-

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22. For an account of the first experiments with this system (which has now grown to such large proportions) by Prof. F. Van Rysselberghe in this country (1885-1886), see article in *Electrical World*, October 6, 1888, by William Maver Jr., by whom also it may be of interest to note the first set of Van Rysselberghe's apparatus for simultaneous telegraphy and telephony was by request installed experimentally on a circuit of the American Telegraph and Telephone Company between New York and Philadelphia in the Spring of 1890. (March 1-5.)

roads were utilized wherever possible for the obvious reason that, as the proper movement of trains required the constant use of the telegraph, the questions of construction, maintenance, and prompt repairs were thus solved to the best advantage of the railroad and the telegraph companies. The growth of telegraph traffic was however, rapid, and between the larger centres, at least, additional pole lines on highways were soon built to meet the constantly increasing demand for wires. In the course of events also the time arrived when the displacement of the steam locomotive by the trolley car and electric locomotive for train haulage introduced the high-tension transmission circuit, which, being naturally erected along the railroad tracks, at once menaced the value of a railroad right-of-way for telegraph purposes. It developed, also, that long distance transmission lines carrying high-tension alternating currents in numerous instances began to parallel the railroad rights-of-way as generally affording the most direct and favorable routes between cities, thereby adding another disturbing factor to the operation of telegraph lines following the same routes.

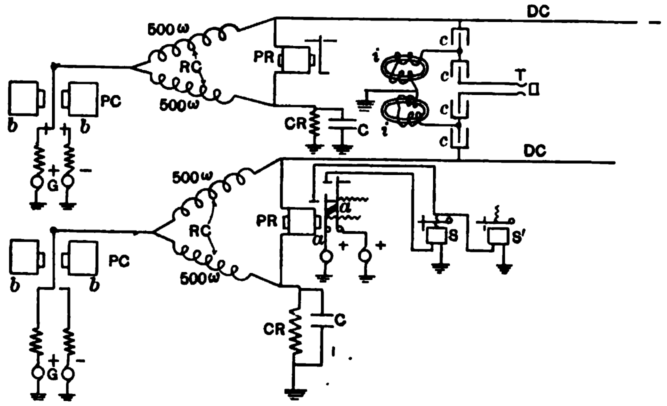

FIG. 6.—Simultaneous (duplex) telegraph and telephone

Apart, however, from the serious inductive disturbances due to the close proximity of such high-tension transmission lines, the subject of inductive disturbances on telegraph lines is not a new one, for mutual inductive disturbances between telegraph circuits were encountered as remotely as 1876 in the dry climate of some of the western states, on lines operated as simplex Morse circuits extending from Omaha, Nebraska to Salt Lake City, Utah.

Upon the introduction of the quadruplex shortly thereafter mutual induction between parallel wires manifested itself as a disturbing element at numerous points, due to the comparatively high e.m.f.s then used on quadruplex circuits, about 300 volts; and as, in the ordinary operation of telegraphy, single wires grounded at each end are employed, the well known method of transposing the wires at intervals to obviate mutual induction effects was not available as a remedy. Fortunately the reduction of efficiency due to this source of inductive disturbance was not very marked, and could, generally speaking, be overcome by an increase of e.m.f. at the terminal stations to 375 or 400 volts.

One of the first methods suggested to eliminate, or ameliorate the disturbances due to mutual induction was devised and tested by Mr. Chas. H. Wilson in 1876, in the western part of this country. The method is indicated in Fig. 7 as applied to single wires*. The object of the arrangement is to set up by means of small transformers *C*, currents in wire *A*, opposite to those induced in wire *A*, by wire *B*, and contrariwise. *R*, *R'* are adjustable resistances, *a*, *a'*, *b*, *b'* are small choke coils. This arrangement was subsequently used on quadruplex lines between Chicago, Buffalo, and Pittsburg, but not very successfully owing to the lag caused by the employment of the transformers *C* in the circuit which augmented the period of reversal to such an extent that the No. 2 side of the quadruplex systems was detrimentally affected thereby.

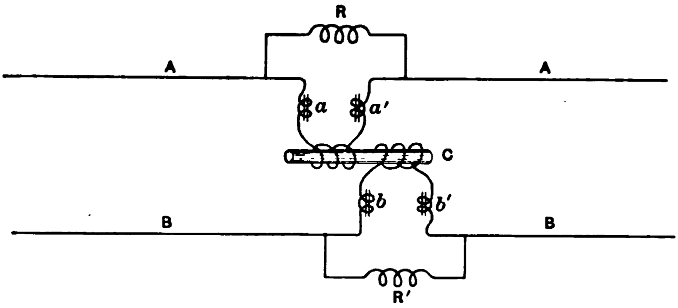

Fig. 7.—Wilson mutual induction neutralizing device

The continual extension of power transmission and other high potential circuits in close proximity to telegraph circuits however created inductive disturbances so inimical to the operation of the telegraph that further means were sought to effect a remedy,

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*See "The Speaking Telephone," Prescott, 1878, p. 362.

short of changing the route of the telegraph pole lines, and a number of corrective devices have been suggested some of which in practice have been fairly successful under certain conditions and in certain localities, but have not always met the requirements elsewhere.

One of these means of obviating harmful induction from high tension power circuits on single Morse wires, due to Mr. E. W. Applegate is shown in Fig. 8 in which a resistance *R*, consisting of a carbon stick is connected across the main line contacts of the relay *M L*. By means of this shunt the rapid induced currents from neighboring alternating current circuits are given a path past the relay, and chattering of the armature is further avoided by increasing the tension of the retractile spring *S*. It was found that these devices tended to impede the action of the armature *a*, to overcome which tendency an extra battery *B*, of six cells are added, which by partly magnetizing the relay cores when the armature is on its back stop, effects this result. This device which is termed a " static pick-up " has been successfully used on a number of telegraph circuits where metallic circuits had been resorted to owing to the inductive disturbances from a frequently unbalanced 60,000-volt three phase system that parallels the telegraph circuits for a distance of eleven miles. The employment of this arrangement made it possible to resume single wire operation.

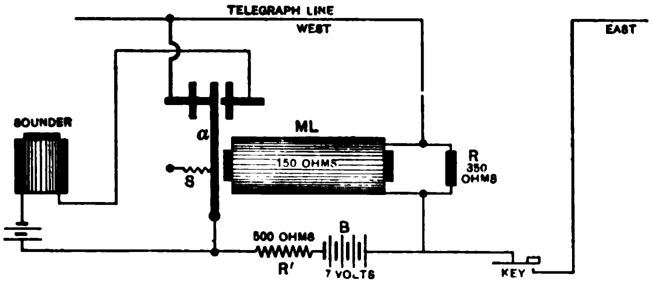

FIG. 8.—Applegate " Static pick-up."

Another plan for obviating inductive disturbances on telegraph wires, due to Messrs. Blakeney and Chetwood, is shown diagrammatically in Fig. 9. *A C* is the disturbing line. When key *K* is open the induced currents oscillate harmlessly to earth via *i' c'*, and *n'*, while the regular Morse signals traverse the relay coils *via* the inductive resistance *n*, and non-inductive resistance *n'*, when key *K* is closed.

A brief description will now be given of one of the more recent methods put into practice for the purpose of offsetting inductive disturbances on telegraph circuits due to the close proximity of high tension electric traction circuits resulting from the electrification of the New York, New Haven and Hartford Railway. To nullify electro-magnetic induction, current transformers *C T* with a 1:1 winding, Fig. 10, are inserted in the telegraph lines at intervals of two miles. To neutralize electrostatic induction the secondaries of potential transformers *P T* are used in connection with condensers *C* as outlined in the figure. The primaries of the transformer are placed in a special neutralizing wire or in the disturbing wire itself. By placing a number of secondary coils in multiple, one neutralizing wire may suffice for a number of telegraph wires. As the neutralizing wire is subject to the same inductive effects as the telegraph wires, the currents developed in the former may be arranged to oppose those due to the disturbing wire.[23]

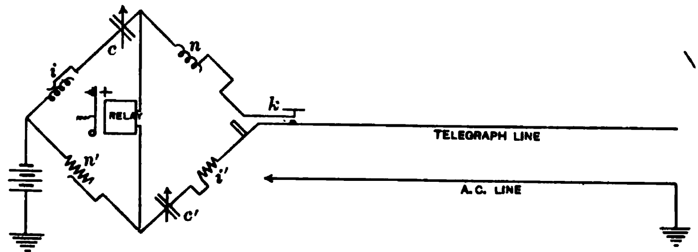

FIG. 9.—Blakeney and Chetwood inductive disturbance diverting device

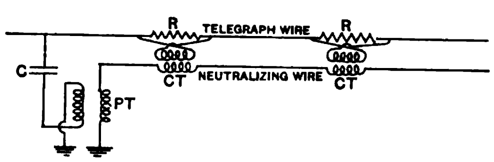

FIG. 10.—Inductive disturbance neutralizing device

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[23] For further details of this general subject see " Telegraph and Telephone Systems as Affected by Alternating Current Lines ", J. B. Taylor, Trans. A. I. E. E., Oct. 1909.

It has been found in practice that the neutralizing of inductive effects by the foregoing arrangement is seriously interferred with by escapes from direct current trolley lines which enter and energize the transformers. Variations in load on the alternating current line, phase distortion, etc., also add materially in preventing anything more satisfactory than an amelioration of the harmful inductive effects. Furthermore, in this particular case, the slight improvement noted is obtained at the loss of three copper neutralizing wires, in addition to the first cost and maintenance of the additional apparatus required. In general it may be stated that the various devices offered hitherto as inductive disturbance correctors have been rather of a palliative than of a positive remedial nature, and inasmuch as the tendency is to increase the use and the potentials of high tension transmission circuits, it appears evident that to meet or evade this situation successfully constitutes one of the most serious problems now confronting telegraph engineers. The basis of a solution of the problem may possibly be found in subsequent remarks herein.

Main Line Relays

The ohmic resistance of relays used in Morse telegraphy has undergone numerous variations during the past forty years in this country. Relays wound to 1200 and 1500 ohms were not uncommon. At one time the resistance of main line relays was calculated on the assumption that for the best results the total resistance of the relays in a circuit should be equal to the resistance of the line wire.[24] Thus on a circuit 300 miles in length, measuring, say 15 ohms per mile, with fifteen stations on the line, the relays would be wound to 300 ohms. There was, however, little or no uniformity in the winding of the relays and but little supervision of the quality of the copper used in the winding, which in the early sixties of the last century varied in commercial copper from 14 to 85 per cent that of pure copper. Measuring instruments of accuracy were at the time referred to a rarity in this country and no proper methods of ascertaining the condition of the lines as regards electrical resistance and insulation were in vogue. In 1867 the late Mr. C. F. Varley, the well known English electrician, was retained by the Western Union Telegraph Company to visit the United States for the purpose of making a thorough investigation of the electrical conditions of the lines and apparatus of that company.

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[24] " Modern Practice of the Telegraph ", Pope, 1869 p. 125.

Following a thorough study of the subject supplemented by hundreds of tests of the lines, insulators, relays, batteries, etc., Mr. Varley presented a voluminous report to Mr. William Orton, President of the Company, December 20, 1867.[25]

The report detailed in extenso, the condition of the equipment as disclosed by the tests, and made numerous recommendations for the improvement of the general service, such as the making of soldered joints, a reduction in the resistance of the relays used, and their re-winding to a uniform resistance of 130 ohms, the wire used to be the best copper obtainable. He also recommended that fewer poles per mile be used in line construction and that a smaller number of wires be worked from one main battery—in fact that a separate battery be provided, for each wire.

Prompt action was taken upon Mr. Varley's report and recommendations, and very marked improvements followed thereafter. Mr. Madison Buell, for instance, in an article on " Low Resistance Relays ",[26] recounts that on the important circuit on which the Atlantic cable traffic between New York and Plaister Cove, N. S., was transmitted the repeaters were found to have relays ranging in resistance from 500 to 1,500 ohms. The relay of the " Milliken " repeater at St. John, N. B., had a resistance of 1,500 ohm. The relays at Boston, Portland, and Bangor had an average resistance of 1,200 ohms. All of these relays were rewound to 80 ohms. Also, many improvements were made in wire jointing, insulation, and leading-in wires at all offices, with the result that whereas on this circuit before these changes were introduced six repeaters were necessary in bad weather and in clear weather three to four repeaters, after the aforesaid improvements were made but two repeaters were required in bad weather, and only one in clear weather to operate the circuit at top speed.

In the course of time, however, relays of 150 ohms were adopted as the standard for simplex Morse circuits. For duplex and quadruplex service the neutral relays were wound to 200 ohms, the polar relays to 400 ohms, (each coil of the differential windings) and for many years these resistances have been the standard. But within the past 8 or 10 years, there has been a still further reduction of the

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25. Report of Cromwell F. Varley, Esq., " On the Condition of the Lines of the Western Union Telegraph Company." Mss. by Mr. J. D. Reid, lithographed. Copies in Wheeler Library, also in Mr. Maver's library and probably in that of the Western Union Telegraph Co.

26. *Telegraph Age*, Jan. 1, 1903.

resistance of main line relays (to 37½ ohms) on many of the commercial and railway telegraph way wires with a very pronounced improvement in the operation of the circuits, especially in bad weather. At the present time the tendency of American practice is to the employment of lower e.m.f.s at the terminals of the circuit and to lower resistances in the relays for multiplex working. During the period when No. 9 iron wire was the standard for telegraph purposes, and when the insulation resistance of the lines, was far below present day requirements, a high e.m.f. was necessary in order to maintain proper current values, but by the substitution of low resistance copper conductors in place of iron wire and with improved line construction, the way has been paved for the employment of lower voltages, and relays of much reduced resistance in multiplex operation. Thus some very satisfactory results have been obtained recently in different parts of the country on quadruplex circuits using e.m.fs. as low as 200 volts on well insulated lines of comparatively low resistance (2 ohms per mile) and with polar relays wound to 100 ohms and neutral relays to 50 ohms. The length of the cores of these relays has been somewhat increased. The "potential" resistance of 600 ohms (usually inserted between the current generators and the multiplex apparatus) in these instances has also been reduced to 300 ohms, and the "proportion" resistance and "leak" shunt in the Field key system from 1200 to 600 ohms, and from 900 to 450 ohms, respectively. The objective in these modifications of the prevailing practice is to reduce the mutuul induction between parallel circuits and to render the relays less sensitive to inductive disturbances from any source.

SOME TELEGRAPH ENGINEERING DETAILS

It might be supposed that telegraph engineering has to do mainly with purely physical and technical questions, but the close relationship existing between the handling of traffic (telegrams, leased wires, etc.) and the machinery employed in handling it, is such that the telegraph engineer, perforce, finds himself involved in the study of traffic details which he cannot well omit without loss to the economies of operation. This for example obviously requires keeping in the engineer's department an accurate record of existing wire facilities, data as to the daily efficiency of operation of all circuits (especially multiplex and automatic circuits) and information as to their electrical condition, together with carefully prepared tabulated records of details pertaining to methods of traffic movement and the amount of traffic handled on the respective circuits throughout the system, in order at once to enable the engineers to determine whether existing facilities are being utilized to the best advantage, or whether additional facilities, or modifications of the arrangement of present facilities may be deemed advisable. Information of this kind is especially important as a guide in the matter of underground construction and cable work extension. Thorough engineering organization results, amongst other things, in placing the engineer's department in a position to intelligently and promptly decide all strictly engineering and related traffic questions that are continually arising in the operation of a large telegraph system.

The graphic method of mapping circuits indicated in the accompanying diagram Fig. 11 to show at a glance the routes of the various wires, their allotted numbers, how operated, offices entered, material of wire, by whom owned, etc., has been found of great utility wherever used. The scheme which is clearly susceptible of many amplifications was probably first employed in the engineering department of the Baltimore and Ohio Telegraph Company in 1885–88 by one of the present writers and it may be of interest to note that details of the nature indicated relating to over 50,000 miles of actual wire were shown on a map four feet long by 3 feet wide. The accompanying specimens of blank forms for certain reports were also used in the operation of the same company, the information derived therefrom enabling the engineer's department to maintain an intelligent supervision of the circuits that resulted in a clearly perceptible enhanced earning capacity in the case of numerous circuits. Somewhat contrary to

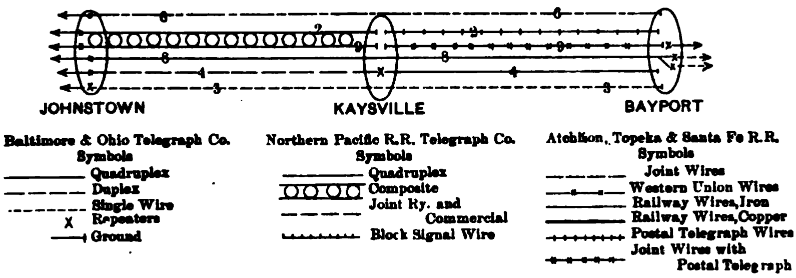

FIG. 11.—Graphic method of mapping telegraph circuits

TRAFFIC BLANK

To...Supt. CLEVELAND, O., FEBRUARY 15, 1886

Statement of Messages Handled in this Office For the Week Ending..

No. of Circuit	From	To	Single	Duplex	Quadraplex		Dates. Messages Sent and Received.						
					A Side	B Side	1	2	3	4	5	6	7

To...Supt. INDIANAPOLIS, IND., FEBRUARY 13, 1886

Report of the Working of the Single and Multiplex Systems in this Office, Week Ending Sat., Feb. 20

Date	Name of Circuit	How Assigned	Commencement of Delay	Termination of Delay	Nature of Delay

expectations these reports were prepared by chief operators or clerks at no additional expense. As will be readily understood the knowledge that the operation of all circuits was under constant impartial supervision was not overlooked by those directly in charge of the operation of the circuits.

A comprehension of the condition of the insulation resistance and conductivity of every circuit, open or in cables is manifestly of great importance to the engineering department and reports of the tests of conductors for these properties are promptly forwarded to the engineer's department periodically.

THE TELEPHONE IN ELECTRICAL TESTING

In America the tangent galvanometer has long since been set aside and simpler and quicker methods of circuit testing and fault localizing have been adopted. Many tests, such as those for insulation resistance and conductivity are now made with high resistance voltmeters, especially where earth currents from adjacent grounded trolley circuits (which frequently indicate an e.m.f. of 15 to 20 volts) are not troublesome. The milliammeter is also used for making insulation resistance measurements not exceeding one megohm and for other electrical tests. The telephone receiver is used as an indicator in many tests. This instrument in connection with an "exploring" coil is largely utilized for localizing faults in aerial cables and in underground cables, especially where the latter are laid in conduits. In making these tests a high frequency current is established in the defective conductor and the exploring coil, a semi-circular coil of fine wire in circuit with the telephone, is moved from point to point along the cable sheath, the indications in the telephone increasing or diminishing as the defect is reached. The telephone receiver as a testing device is particularly advantageous for practical purposes as it places in the hands of the electrical worker or "trouble hunter", an instrument at once portable, and easily understood, and one that is not readily deranged by rough handling. Where a head-band is used to support the receiver the hands of the workman are free.

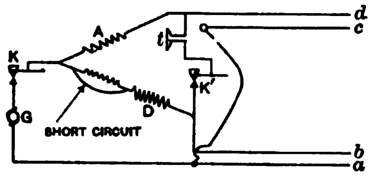

FIG. 12

For quickly determining by means of the telephone as an indicator the distance of a break in a cable conductor when the insulation is normal, one method is as follows: Select three conductors similar electrically to the open conductor *b* and adjacent to each other, *a*, being next to *b*; *c*, being next to *d* and connect as shown in Fig. 12. *G*, is a source of alternating current. For cables approximating 1000 feet in length the generator should give from 40 to 130 volts. The resistance of arm *A* may require to be 100, or 1,000 ohms. To make this test the four wires should be opened at the distant end. Keys *K*, *K'* are then closed and the resistance of arm *D* or rheostat is varied until minimum sound is heard in the telephone receiver, when:

$$\frac{L\,R}{R'} = F$$

where *L* is the length of the cable in feet, *R*, the resistance of arm *A*, *R'* the resistance of rheostat *D*, and *F* is distance to break in feet.

The Varley and Murray tests are still the standards for making accurate measurements for faults in conductors, and the Wheatstone bridge method for accurate resistance measurements.

POLE LINE CONSTRUCTION—AERIAL VERSUS UNDERGROUND CONDUCTORS—NOTES ON DUPLEX AND QUADRUPLEX OPERATION

Owing to the confusion and general disarrangement of business that usually follows the prostration of the telegraph wires by severe sleet or wind storms in this and other countries, every notable occasion of this kind has been followed by insistent demands on the part of the interested business communities that measures be taken to prevent a recurrence of these disarrangments. So much has this been the case that in Great Britain, at least, where such storms are quite frequent, and where owing to the geographical shape of the country the loss of telegraphic communication due to the effects of such storms has been felt with peculiar force, these demands have been met by the British government in the laying of an emergency telegraph cable between London and North Britain. The fact that such unanimous demands are made for the prevention of even a temporary loss of the telegraph between important centers is, it may be remarked, a rather notable acknowledgement of the indispensibility of this public utility as a part of the commercial and social structure of a country.

Apart from the very important matter of maintaining uninterrupted telegraphic communication regardless of weather conditions in the interests of the general public it may safely be assumed that the various telegraph authorities in this country have not been unmindful of the financial losses sustained by the telegraph upon the occasion of each recurring collapse of poles and wires, and that every possible remedy therefor has been most carefully considered. Furthermore, telegraph lines are not only subject to widespread damage from abnormally severe sleet and snow storms, but are also in many places exposed to the ravages of forest fires, avalanches of snow, washouts due to floods, and to destruction by lightning. Again the average life of a pole line in all parts of the country probably does not much exceed ten years. Consequently, if the financial and engineering difficulties in the way of placing telegraph wires underground on a large scale had not been practically insurmountable, that solution of the problem, unquestionably, would have been long ago adopted. But it is well known, for instance, that the increased static capacity and mutual induction of the conductors carried in cables tend to reduce very materially the length of circuit that may be used in satisfactory telegraph operation. Already indeed the presence of a comparatively limited amount of underground cable in the circuits passing through the principal cities of this country has reduced very preceptibly the speed of signaling and the general efficiency of automatic and multiplex telegraph circuits in this country. Being therefore aware of the great technical and financial difficulties that would attend the placing of wires underground generally between cities and towns over the expansive territory of this country, the question of building stronger pole lines, and of employing larger and stronger wires has been frequently proposed by telegraph engineers. The well known " A " and " H " methods of setting wooden poles of course have received due consideration, and in trials have been found to add considerably to the stability of lines. In addition however to doubling the expense for poles, further objection to the use of these methods, especially where the telegraph lines are on a railroad right of way, is the extra space required for setting, which very often is not obtainable. Another plan tested was that of using worn out track rails, set up in " H " form and braced one foot apart. The cost of setting these rails is, however, rather high, being about eleven dollars per unit. In especially exposed places the plan of doubling the number of poles from say 50 to 100 per mile, has been adopted with considerable success. A reduction of the height of poles and an increase of their girth has also been advocated and there is now a tendency in that direction. It is very probable that pole lines built in the future will when possible be built of poles considerably less than 35 feet in height (the present general practice) with head and side guys located about every half mile regardless of the contour of the line. On heavy loaded lines with the poles set about 100 feet apart reduction of the leverage obviously increases the efficiency of guying. In the construction of a thirty-wire line by using ten-pin cross arms a 25-foot pole would generally leave sufficient clearance.

The employment of re-inforced concrete poles for telegraph purposes has been suggested as offering a solution of the problem as regards durability and reliability[27] but has not gained much headway hitherto, principally owing to the present high cost of such poles and also to the excessive cost of transportation. Even, however, if experience should show that cement poles will possess the ability to withstand the strains brought to bear on them by wires heavily coated with sleet, there still remains the unfortunate fact that the wires themselves may break under the strain. It would of course, be a decided gain to avoid the total loss of miles of pole line by the collapse of the poles like bricks in a row—a not infrequent occurrence under present conditions.

In relation to the immediately foregoing remarks, it may not be amiss to digress here to suggest that since the telegraph lines are not put up merely for a day or a year, that a combination of concrete poles, or towers of equal strength and durability with perhaps some form of housing for the wires along permanent and isolated rights of way may be among the possibilities of future telegraph engineering, since such a plan offers promise of reliability of operation without the detrimental accompaniment of impaired efficiency of the telegraph service that follows the placing of telegraph conductors underground. In view of the importance of the subject further reference may here be made to the reduced efficiency of quadruplex telegraph operation within recent years, in some cases amount-

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27. (See paper by Mr. G. A. Cellar, " Experiments with Concrete Poles'" Proceedings, Association of Railway Telegraph Superintendents, 1907, p. 144)

ing to 50 per cent, due to the increased amount of telegraph conductors placed underground in cables in cities. In other cases certain quadruplex circuits have been abandoned because of inductive disturbances from parallel high tension transmission lines. It is a well established fact that prior to the introduction of these disturbing factors, duplex and quadruplex telegraphy in this country had attained a high degree of efficiency. Thus, for instance, it was formerly common practice to operate four, six or more quadruplex circuits between New York and Boston on open parallel lines, each with an efficiency equivalent to four wires worked simplex, and certain quadruplex circuits between New York and Chicago were operated as a rule with an efficiency of at least 90 per cent.

In the equipment of the quadruplex circuits to which special reference is now made, the ordinary horse-shoe polarized relay, with flat armature, and short cored neutral relay were employed without any devices to aid the operation of the No. 2 side excepting the Edison device of the back contact and repeating sounder attachment to the neutral relay. It is well known also that in isolated sections at the present time quadruplex circuits are still operative at high efficiency. It would appear evident therefore that a restoration of the original efficiency of this exceedingly important arm of the telegraph service would be alone an aim worth the best effort and thoughts of telegraph engineers and executives. A return to the former or greater freedom from inductive disturbances would also vastly enhance the opportunities for the utilization of some of the readily available rapid automatic telegraph systems, which as previously intimated the introduction of night letter telegram service may render imperatively necessary in the very near future.

Returning briefly to a consideration of the matter of obtaining a permanent, non-inductive, non-retarding system of telegraph routes, it is clear that utilizing the suggested towers or reinforced concrete poles, with housed wires to afford mechanical protection against storms, incidentally thereby guarding against undue variations of insulation resistance, (a great desideratum for numerous reasons) and by the proper selection of routes at a suitable distance from high-tension lines thus evading their disturbing inductive currents, an immediate improvement in the operation of circuits would be obtained. There would, however, still remain to be dealt with, the detrimental effects due to the presence of conductors in underground cables leading into and out of cities and towns. This difficulty could, however, be obviated by placing the main operating departments of telegraph offices on the outskirts of such cities, from which offices loops might be run from duplex and quadruplex circuits to the various branch and brokers officers without detriment to the operation of the multiplex main circuits. All wires not required for the actual handling of traffic in a given town would in such cases enter the main operating room on the outskirts of the city and pass on without entering the city proper. In many small towns the telegraph lines following the highways enter at one end of the town and pass out at the other end, a custom that has frequently involved placing a comparatively large amount of cable in an unimportant locality considered from a telegraphic standpoint. By the plan suggested, only wires needed locally would enter the place and that by the shortest route to the business center, thereby minimizing the amount of cable required for the proper transaction of telegraph business at that point.

It is unnecessary here to comment on the economies and improvement of operation that could be rendered possible by even a partial adoption of the foregoing suggestions, further than to remark that a proper consideration of the subject will show them to be manifold and of great value.

It had been intended to include in this paper a general reference to recent improvements in the interior equipments of telegraph offices and also to describe the methods and materials now employed in aerial and underground telegraph cable work in this country, but owing to the brief time available for the preparation of the paper it has not been practicable to carry out that intention.

DISCUSSION ON "AMERICAN TELEGRAPH ENGINEERING—NOTES ON HISTORY AND PRACTICE." JEFFERSON, N. H., JUNE 29, 1910.

W. Maver Jr.: I should like to say that this resume is not by any means a full account of the history of American Telegraph Engineering. For instance, in the paper nothing whatever is said about lightning arresters, the forerunners of the switches of which we heard so much this morning. The early telegraph engineers had their troubles with lightning, and the methods adopted to overcome these troubles were numerous; finally coming to the method which is in universal operation to-day, that is, the short path to earth for the lightning current.

About twenty-five or thirty years ago the electric light was inaugurated, following which very quickly telegraph companies began to be troubled a good deal with crosses between the wires of the two systems, with the result that the telegraph switchboards were often burned out, and not the switchboards only, but the buildings of the telegraph companies also. To obviate these troubles as much as possible, the method was employed of coiling up fine German silver wire into coils the size of a pencil, consisting of ten or fifteen turns termed the spider wire. This was put in series with these telegraph circuits at the switchboard, in addition to the short air gap arrester. I do not think the engineers had any thought at the time that the coiling of the wire would have any effect in retarding the progress of the oscillating current towards the instruments.

Ralph W. Pope: The introduction of the Morse telegraph system was followed by what purported to be improvements, and many of these improvements have practically passed out of existence. I refer more especially to the House and Hughes, and the "combination" printers, which followed, leading off with the House printer in 1847 and 1848. I was familiar with the work of that printing instrument, although I did not operate it. My printing telegraph work was confined to the Hughes printer, which was introduced, as you may say, experimentally in 1858, although it did not come into general service. The "combination" printer, so-called from the combining of certain features of the House and Hughes printers by the late George M. Phelps, was, however, used on important circuits by the American Telegraph Company a little later.

One of the defects of the House printer, which was an ingenious machine, was the limited distance over which it would operate, and I would call the attention of the author of the paper presented to the possibility of an error in regard to this having been operated on lines 1,000 miles in length. While that might be true, in a sense, as a matter of fact it was not usually operated between New York and Boston a distance of perhaps 225 miles, except in very fine weather. The ordinary practice was to repeat at Springfield, which was about half way.

One of the difficulties of the early printers in regard to their general adoption was their failure to meet the requirements for way-station work. This was met in the case of the House printer, as is not generally known, by the use of a simplified form of the printer. As the type wheel stopped, the exposed letters could be followed by an expert operator without the use of the printing device. A simpler form was introduced which operated as a dial printer, the operator reading from the wheel, instead of the printing mechanism being used to print on the tape. That was one of the reasons why these earlier types of printers were not successful commercially, for the reason that they could not be used in many stations on account of the expensive equipment.

The question of high speed and the use of the chemical telegraph created considerable interest in telegraph circles at the stage referred to by the author. It is interesting to note that in one of the important experiments made, which is referred to in this paper, that the time consumed in perforating, in transmitting and translating, was more than would have been required by four Morse operators in transmitting the President's message referred to, a difference between seventy-two minutes as against fifty-two minutes. The use of the chemical system raised so many objections that it is not strange it went out of use, but it was at one time quite successfully established in New England, but not using the perforated tape, simply hand transmission, the same as with the Morse system.

The improvements in the Morse telegraph have been largely due to the increased skill of the operators. The use of the typewriter, which has been referred to, brings to mind a rather peculiar relation between the rapidity of transmission by hand and the rapidity with which the operator could receive the same message with a pen. They kept hand and hand, or rather neck and neck, for years, until by the introduction of the typewriter, the receiving operator could copy much faster than the sending operator could send by hand, and this has led to the use of a code for press dispatches, which standardized abbreviations, but the use of the code is not permissible in ordinary private messages, and for this reason the typewriter is still ahead. When we consider the adoption of the mecograph, as it is called here, by the Morse operator for improving the rapidity of his sending, it appears quite possible that the introduction of the Continental code may be brought about some day, as it would require less time, perhaps, to learn to operate by the Continental code used in the wireless system, than it does to learn to operate by these mechanical devices.

The improvements in insulation to my mind have not been so great as the improvements in the conductivity of the line. The early lines, as I recall, used No. 8 iron wire, and then No. 9, and with the introduction of the duplex and quadruplex, as referred to by the author, wires of greater conductivity were introduced. The form of glass insulator now used has persisted for about thirty or forty years.

The possibility of the utilization of a more rapid system, with the introduction of the night lettergram practice, appears to be quite possible. I have talked with some of the telegraph men about that, but they do not see any probability of it yet. It must, however, take the form, in order to be practicable, of some system of perforation like the Barclay printer which transmits with only one repetition, that is, the perforation producing at the other end a page printed telegraph blank. It is rather remarkable that, although the objections to the form of printing tape were so well known in the early days, there appears to have been no attempt to bring about the introduction of a page printing system. When we consider the ingenuity of those early inventors, House and Hughes, it seems to-day as though, if their attention had been directed to this defect, that they might have invented a page printer, and thus perhaps prolonged the life of the printing telegraph system, which has practically gone out of use.

John B. Taylor: Delivering a telegraph message from a person in one part of the country to a person in another part of the country involves something more than getting a code of signals over a given wire. It involves "readiness to serve" at all hours of the day and night, frequently in small places only during certain hours of the day, and also a system of collecting and delivering messages. This, as far as I can see, is the main reason why automatic systems, which can send signals over the wire at a phenomenal rate of speed, sufficient to give a thousand or more words per minute have gone into use only in very limited cases. Mr. Maver can, I hope, enlarge on this point. We see frequently the statement that the telegraph people are not alive to the possibilities of sending messages at a great rate of speed over a single wire, and while a number of messages over a single wire is a good thing, perhaps, between two large cities, it is of practically no use at all to the small towns, of which there are a great many in the country.

The telegraph line is rather apart from the work of many of the members of the Institute, so we are fortunate in having a paper giving an up-to-date resume of present practice. It is difficult for a man out of the field to know just what is being done. The old books give descriptions of duplex systems, quadruplex systems, repeater systems, etc., which are all interesting, but help little towards a knowledge of present practice in the majority of cases.

My own renewed interest in telegraph and telephone matters has been due to the disturbance feature from power lines, and one or two points occurred to me as Mr. Maver was abstracting his paper. It is plainly brought out by him that the practice of quadruplexing, (which means four messages over a single wire at the same time), was not worked to an extent, which, at first sight, it would seem that it should be. This is due to a number of reasons, possibly divided up between poor insulation, variable weather conditions, etc., and to a large extent due to inductive disturbances and to circuits of the same class on the same pole line. This raises the question whether the telegraph companies could not afford to use metallic circuits, in which case the matter of inductive disturbances from their own wires, as well as foreign wires, would be obviated. The matter of insulation would still, perhaps, be troublesome, but this could be improved without an investment which would be very great, in comparison with the investment in poles, wires, etc.

There is also the possibility of obtaining greater capacity from present wires by the combined telephone and telegraph systems. If the demand for telegraph wires and the demand for telephone wires comes out in a certain ratio, we might have metallic circuits between all the important points working as telephone wires and also perhaps a sufficient number to take care of telegraph service, some as grounded lines and some as metallic lines phantomed between two pairs of telephone wires. The curve of demand probably varies to a great extent, the telegraph business of a certain sort going out in the daytime, probably at the peak of the telephone load. With the introduction of the night lettergram, at day rate at a time when the wires are probably not very busy for telephone work, (at any rate since the night telephone rate has been abolished) it is to be hoped a more economical working of the conductors will result.

I did not have time to look the paper over very carefully, and do not know just what Mr. Maver said about the Rowland system, which a few years ago was written up in an Institute paper by Mr. Potts, I believe, where an octoplex capacity was claimed for it. This system used the page printing device direct from keyboard to the message blank for delivery at the other end. I have not heard lately of any extensions made with it, and if Mr. Maver can say a word or two as to the general reasons for the apparent inactivity, I should like to hear from him.

Incidentally, my name has perhaps been taken in a way to give me more credit than is due. In the paper reference is made to the New York, New Haven and Hartford Railroad Company, and also to Fig. 10 which carries my name. Although interested in the work on the New York, New Haven and Hartford Railroad, for the Western Union Telegraph Company, I did not originate the general scheme of neutralizing induction action. This arrangement used was devised by engineers of the Westinghouse Co.

Gano Dunn: I heard Mr. Maver say that four-fifths of the operators in this country use the Martin mecograph. Is this really so?

My observation as I travel around the country is that we do not see many of them, although I do not get into the central offices.

I have found them imperfect, probably because of my own lack of skill, but there seemed also to be certain inherent difficulties such as difficulty of adjustment and not enough certainty of action to cause all the dots to go through on a long and variable line.

It is also difficult constantly to change the adjustment of the mecograph to follow the rising and falling inductive and leakage changes that are found on a long and poorly constructed line, with many stations.

The wireless telegraph is introducing a greater than ever conflict between the Continental and American Morse alphabet. I should like to know whether there is any attempt towards a more general introduction of Continental Morse into this country, and if so, what Mr. Maver thinks of its probable success.

William B. Hale: Perhaps a few remarks on the telegraph system of the Republic of Mexico may not be amiss. The system there is an extensive one, considering the comparatively few large centers of population. The telegraph lines extend to even the smallest towns and villages, because, being a telegraph controlled by the Government, its operation is not based upon the question of profit. The Government is ready and anxious to install a telegraph office in any town which has any need for such service, whether it will pay or not. The idea is to supply reliable telegraph service to the entire people at cost.

The general equipment of the system is practically that of the United States of a few years ago. The Morse manual system, with simplex, duplex and quadruplex operation, is in use; and the lines are mainly constructed with No. 8 galvanized iron wire and a European type of porcelain insulator. Wooden poles are chiefly used, but some of the trunk lines have iron poles. There are a few Hughes printers in service in the Capital for communication between the central office and its branches. In the larger cities of the country duplex and quadruplex instruments are used, and in all other offices the Morse simplex is employed. The American closed-circuit system of operation is in use; also the regular Morse alphabet, with a few changes to adapt it to the Spanish language.

The telegraph is used very extensively in Mexico, not only for business purposes, but for social and personal matters as well. To a very considerable degree the Mexican makes use of the telegram where you would the mail, or a messenger service. He sends telegrams from his place of business to his home, messages of congratulation to friends on their birthdays and telegrams of felicitation on such days as Christmas and New Year's. In the City of Mexico one finds a very convenient form of service for such social messages; we have a card, about the size and shape of your postal card, which can be purchased for five cents, Mexican currency, the equivalent to two and one-half cents in your money. On the front of the card is a space reserved for the address and a number of ruled lines for the message, which must not exceed ten words. These card-telegrams, after being filled out, may be deposited in boxes, similar in appearance to letter-boxes, which are placed at the more important street corners throughout the city, and from which frequent collections are made. The messages thus collected are delivered at the nearest branch office, telegraphed to the office which is within the shortest distance of the person to whom they are addressed, and from there delivered by the regular messengers. This is a prompt and efficient, as well as cheap, means of communication within the limits of the Federal District—in the center of which lies the City of Mexico—and it is very extensively employed for business and social purposes.

The rates for telegraph service in the Republic of Mexico are low. A ten-word telegram may be sent from one end of the country to the other for only one peso, or fifty cents in American currency. The rate for night messages, which are transmitted from 10 o'clock in the evening until midnight, is one-half that of the day rate.

We have been unable to use copper wire for pole lines to any extent, for the reason that it is cut down and stolen by the *peones*—the lower-class natives. Iron wire has so far been employed almost exclusively for the construction of pole lines, but I have suggested the use of a steel core copper-clad wire, which will improve the service and will probably not be stolen, as when cut down it will have very little, if any, value as scrap metal. This copper-clad wire will undoubtedly remain up, and it ought to prove especially valuable in a tropical country like Mexico, where even galvanizing does not protect iron wire from corrosion for any great length of time.

The success of the Federal Telegraph System of Mexico would lead one to favor a government-controlled telegraph. The service is rendered at rates much below those which would be charged by a private corporation; and the dispatch of telegrams is in every respect satisfactory, being prompt, efficient and thoroughly reliable.

G. A. Cellar: The employment of reinforced concrete poles for telegraph purposes has not gained much headway hitherto, in this country. I believe the reason to be principally because of the still comparatively low cost of wooden poles, and the lessened expense of handling the latter as compared with that of handling concrete structures. In Europe, however, reinforced concrete masts are more largely used than in this country. The Deutsche Schleuderrchren-Werke has been making hollow concrete poles by machinery, utilizing centrifugal force, for about five years, and with a great deal of success. The Siegwart company about a year ago completed at its Swiss factory a contract for several thousands of hollow poles, averaging forty feet in height, for power lines, constructed by machinery utilizing centrifugal force. My information is that throughout Western Europe, especially Germany, Switzerland and France, and to perhaps a lesser extent in England, concrete poles are now considerably used in place of timber.

Until the time arrives when a permanent location can be secured for a telegraph line—and a telegraph line of large capacity—it may not pay to build an open line of wires supported by high concrete poles, unless their cost shall but slightly exceed that of wooden poles, for several reasons, among which are; first, possibility that the low voltage signaling systems now in vogue may be forced underground, or somewhere beyond the present up-in-the-air location, by the multiplication of electric transmission lines; and, second, by the discovery of a process through which the elimination of retardation in aerial cables may be effected.

I believe that the increase in price of timber, and the advanced cost of handling concrete poles, will result in a revolution in the heretofore accepted models of pole and wire lines, through which there will be evolved a system of short pole lines of either timber or concrete, where reasonably level ground and policing arrangements permit the maintenance of such lines, and for which proper overhead crossings of highways and private roads encountered can be made without grading up and down from each one. It will not be feasible, however, to use extremely short poles in lines traversing rugged country and especially on railroad lines where the undulations of the surface of the ground are frequent and abrupt and the right of way a succession of deep cuts and high fills. Such lines are better calculated for use on highways where the roadway more nearly follows the form of the ground's surface and the ups and downs are not so abrupt. The objection to the use of the very short poles in the lines above indicated is that the vertical pull on the pins and insulators is certain to loosen the contacts with the supports and foster wire troubles in a degree not comparable with the saving in the lessened cost of the line. There is, however, a very considerable expanse of territory in this country in which the use of the short pole line is certainly feasible and desirable, not only through its lessened cost as compared with a line of high poles, but through its lessened exposure to wind pressure and the lessened strain at the ground line in a short pole as compared with a long pole. I am quite sure that for a comparatively small number of wires, a plan of construction can be evolved which will enable the large utilization of short pole lines with, perhaps, dead ended sections where it is necessary to abruptly raise the line in order to carry the wires over road crossings.

The item set forth in the paper as to the housing of insulators is one which I feel will be beneficial in many storms. No doubt the time will come when the expense incidental to such an installation will be more than warranted by the benefit thus to be derived. However, the driving storms of rain, wet snow and sleet which we experience in our western country preclude the entire protection from such storms by any small roofing protection that I think of at the moment.

Louis M. Potts: The authors make the following statement:

> It has long been recognized by telegraph authorities that an ideal system of telegraphy would be a simple and reliable page printer, capable of transmitting and receiving, say from 500 to 1000 words per minute on circuits of from 200 to 1000 miles in length.

This statement is not in accord with my understanding of the requirements demanded by practical men as far as such statements have been made. While it is possibly desirable in some cases that the ideal printer system should be capable of transmitting from 600 to 1000 words over a circuit yet in the great majority of cases the universal printer system would certainly be used at a very much less capacity than this. I take it that this statement of the authors does not necessarily mean a single mechanism to operate at this speed but apparatus capable of giving this capacity to a circuit. A single printer to operate at such a speed as this would certainly involve complications of construction and adjustment such as to preclude its use on short circuits requiring a speed of not more than 40 to 50 words per minute. I suggest that the ideal printer would not be a single printer capable of transmitting and receiving 300 to 500 words per minute each way, but that it would be a printer mechanism capable of operating at such a speed that the number of telegrams handled by the printer is that number of telegrams which can be economically and efficiently handled by a single operator. In a printing system with automatic transmission this number is determined by the capacity of the receiving operator rather than of the sending operator. Of course how many a single operator can handle depends very largely on the accuracy of the system and the traffic handling methods adopted, but from the present state of development of printing telegraphs it would appear that a printer system, manual or automatic, operating somewhere around 50 to 75 words per minute gives an amount of traffic which can be economically and efficiently handled by a single operator. A manual operator does not require a machine of a speed greater than 50 to 60 words per minute. The average operator could not send faster than this whatever the speed of the machine. In an automatic system a machine speed of 75 words per minute should give a sustained rate of about two telegrams per minute. A receiving operator will be fully occupied with this amount of traffic to care for. The operation of a number of printers of moderate speed on a single wire by some method of multiplex operation appears to meet the conditions imposed by those circuits requiring a high capacity machine better than a single printer of high speed. The use of a moderate speed printer makes possible the construction of a simple, cheap and reliable printer which will be suitable for use on circuits having light traffic. This method of treating the problem results in a universal telegraphic printer, and a variation of the methods of line operation only, to meet the different conditions of traffic.

When a certain rate of transmission is reached on any given circuit, the wire cost is reduced to such a low figure that a further increase of rate is not justified, as the further reduction of wire cost so obtained will be more than offset by the more frequent interruptions and the greater amount of supervision required.

If such a system as the authors suggest, as far as the mechanism is concerned, were in a perfect state of development, I do not believe that it could be successfully operated on the wire plant of to-day on account of the variable electrical state of the wires, the lack of protection against inductive disturbances from foreign sources and a nethod of construction which also lacks protection against the induction between the different wires on the same pole line, which makes impossible the use of extremely high speed telegraph apparatus on more than a few wires, and which materially reduces the efficiency of even the Morse manual system. In order that a printer system operating at a speed even approaching 600 to 1000 words per minute may come into use it is just as important that the wire plant be perfected as the machine itself.

W. J. Camp: I would say that the Canadian Pacific Railway used white porcelain insulators to a considerable extent in the years 1890 to 1898, but the cost increased so much that we reverted entirely to glass until three years ago. We found that the manufacture of glass insulators in Canada had deteriorated so greatly that the insulators turned out were altogether unsatisfactory, apparently they were not properly annealed, with the result that from a week to two months after being placed on the line they would go to pieces without being subjected to any mechanical injury. The price of porcelain insulators had also been so much reduced that for the past three years we have used nothing but white porcelain.

Relative to Wheatstone Automatic operation it may be noted that the British Pacific Cable Board has leased a wire from the Canadian Pacific Railway between Montreal and Vancouver and is now equipping this wire with that system.

The Canadian Pacific Railway method for indicating circuits was adapted from the Japanese system and is by small circles at the ends of straight lines, different markings appearing in these circles as follows:

○ Commercial Simplex.
⦶ Duplex.
⊗ Quad.
● Despatcher Simplex.
◉ Simplex leased.
⧗ Composite, Simplex and Telephone.

I consider a line of 40 poles per mile to be the most satisfactory provided that poles are side guyed varying from every 5th or every 20th poles according to danger from storms, and head guyed every half mile. I do not like increasing the number of poles to more than 40 because, besides costing so much more for construction there is also greater reduction in insulation of the wires.

F. W. Jones: In addition to the historical and descriptive parts of the paper, allusion is made to disadvantages and defects in the construction of lines and in the operation of electrical systems of transmission, and suggestions for their improvement are advanced. Any ideal construction of telegraph lines, and the employment of the most improved and speedy systems for the transmission of telegrams must inevitably be limited in cost to the capital that can be secured therefor, and engineering suggestions of any value must keep within the limits of practicability, which is determined by several considerations, probably better known to the presidents and general managers of telegraph and railroad companies, as those officers are charged with the success and financial results of operation and maintenance, and are de-facto the engineers who decide all questions involved.

That those officers have been able to attain their ideals in these matters is extremely doubtful.

Capital is discouraged by the enormous difficulties encountered in the upkeep and extension of our American telegraph system, such for instance as securing suitable rights-of-way for trunk lines, with their constant demand for added wires; the frequent attempts in Congress to inaugurate a government system; the unfavorable legislation and taxation of the various states; the encroachment of the use of telephones and wireless telegraphy, not to mention the competition of a splendid mail service, besides the increasing cost of labor and materials, and the rigid account to which the proprietors are held by the Courts, for errors and delays which are practically impossible to avoid. Up to the present time the Morse Telegraph system has withstood the inroads of telephone and mail competition, and continues to be favored with an increasing patronage.

The grave situations in which both proprietors and public are placed by the present inability to obviate interruptions to operation between commercial cities, by reason of breakdown of wires and poles, due to storms, fires, floods, snow avalanches falling trees, etc., besides the detrimental effects of electromagnetic and electrostatic induction upon the signals, are not confined to any one company, and their free discussion seems to be well within the purview of the Institute and cannot reasonably be considered gratuitous by telegraph proprietors. In my opinion there are insurmountable financial and engineering obstacles to placing entirely underground the trunk lines between all of the widely separated cities of this continent, except that emergency underground cables may be found an advantage for short distances such as between New York and Philadelphia (90 miles), yet an overhead structure that would be more elastic, built under rigid engineering rules as to strength, number of supports per mile, gauge and number of wires or cables, etc., with reference to the character of the country traversed, and the maximum stresses, (short of cyclones), to which such structure would probably be exposed, could undoubtedly be built at less cost than an adequate and reliable underground system. Upon engineers will devolve the solution of very important questions such as the proper tensile strength of the wires; their ohmic resistance; character of the insulation; and whether open individual wires, or cables be employed. It is obvious that the suggestions in the valuable paper of Messrs. Maver and McNicol, as to the kind and number of poles per mile, are indefinite. As there are great differences of topography and climate to be encountered, different construction is necessary for lines crossing mountains, prairies, mesas of shifting sand, through canyons subject to cloud bursts, and forests where trees are frequently falling, also along the sea coast indented by rivers and bays, and through the latitude where sleet storms frequently visit. A heavy trunk line in northern latitudes would require considerably different construction from a light trunk line in the south. The annual reports of telegraph companies show an expenditure of many millions of dollars for the repair and maintenance of pole lines.

It is open to engineers to calculate what would be the saving in electric operation, if the conductivity, and consequent tensile strength, were very largely increased over that of the wires at present employed overland. I believe that an increase of at least 50 per cent in the conductivity of the largest hard drawn copper wires now in use, would much more than compensate for their additional first cost, but of course they must be supported by the ideal structure above referred to.[1] The average life of a pole line is given as 10 years, this may be true of wooden poles, but not of crossarms, insulators, nor wires.

It has generally been the opinion of engineers, that to secure reliable telegraph lines between the Atlantic and Pacific, over the Rocky Mountains in northern latitudes, that it was necessary to have the protection of the railroad tunnels and snow sheds. The recent construction of a portion of an important trunk line over the summit of the Sierra Nevada Mountains, will be watched by engineers with interest.

A very vital question to be decided in erecting an ideal line, is the kind and gauge of wire best suited for both trunk and side or way lines, also whether iron, or aluminum, or other metals or compounds could be advantageously used instead of hard drawn copper, in case the cost of the latter became excessively high.

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[1] *Elec. World & Engineer*, March 29th, 1902, page 557. *Telegraph Age*, Nov. 1, 1903, page 540.

The voltage of signaling currents at present in use, particularly for quadruplex, duplex, printer and fast Morse key operation, is at its maximum limits, on account of the detrimental sparks at the contact points of transmitters and of the heating of bobbins of relays, and of the serious menace to the insulation of office wires and underground and river cables

The increased speed of signals within the last twenty five years, particularly by the use of mechanical transmitters and by the rapid electrical impulses required for printing and automatic systems on long circuits of comparatively high resistance, has demanded the highest voltages that could be used in order to actuate the relay armatures with sufficient force and celerity.

The mecograph illustrated in the article has a lever that may be moved by a slight motion, from a central or open position, to the right to transmit dots, and to the left for dashes; and is operated by about 30 per cent fewer motions of the hand than is the case with the Morse key, but the motions of the mecograph being lateral instead of vertical, afford relief to the operators muscles that had grown tired from long use of the Morse key.[2]

The Wheatstone automatic system has been employed for several years on the long ocean cables, and on overland wires between London and Persia, and has produced more rapid and reliable signals, increasing the carrying capacity of the cables and wires by obviating the loss of time due to the hesitation of key operators in reading copy, and to other causes. Thus changing the cable transmission of business from ***intermittent***, to ***continuous***.

Repeaters are placed anywhere from 250 miles to 600 miles apart in circuits having very widely separated terminal stations. Such repeaters have their location determined by the convenient position enroute, of a town or city best suited for the maintenance of operators and machinery and not by the object of securing the best conditions for the electrical operation of the wires. The use of quadruplexes is most seriously curtailed by the false signals produced on the neutral relays when the keys on number two sides of several sets in operation on adjacent wires are simultaneously closed, which frequently occurs, the resultant electrostatic induction is then at a maximum.

It is to be hoped that the "ideal system of telegraph authorities in this country" capable of transmitting and printing from 600 to 1000 words per minute on long wires will not lead any of our bright ambitious young engineers to chase an ***ignis fatuus***. I am at a loss to understand why the limit was not placed at at least 5000 words. It is obvious that the time-constant of all known line wires, electromagnets, and their connections, for over 200 miles, when operated by the very highest permissible voltage, would absolutely fail to actuate any page

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[2] *Telegraph Age*, July 16, 1906, page 325.

printing mechanism at such a speed; it is just as sensible for railroad engineers to ask for a locomotive and cars to carry passengers from New York to Chicago in one hour's time, upon present tracks.

This ideal system must be required for press or similar service where the message contains several hundreds of words, and is prepared in some way for continuous transmission, on its being placed in the machine at the sending end. It is impossible for me to imagine how individual telegrams of an average of 30 words each can be prepared in any manner to be continuously transmitted over a wire at the rate of 33 messages per minute. At the time of Mr. C. F. Varleys visit, and of the subsequent modification of relay resistances by Madison Buell, comparatively nothing was known in the United States of farads, and henrys. It seems that our engineers were then trying to secure the maximum magnetic pull on relay armatures with a minimum electromotive force, and overlooked the tardy action of the apparatus due to high inductance. The adoption of a standard of 150 ohms for single relays was due to the impossibility of a large telegraph company regulating the resistance to suit each circuit. The late W. W. Smith in patent No. 106,418 in 1870 claimed the multiple connection of a 150-ohm relay to the reduced resistance of 37½ ohms, he found such relays were not so sluggish in action on a wire equipped with a large number of relays, as were the same number of 150-ohm relays, the improvement was one of better service, and not of decreased cost for current.[3]

Donald McNicol: Mr. Jones questions the likelihood of the development of a printer system capable of transmitting 600 words per mintue over ordinary circuits. That one cannot readily conceive of the probability of such speeds being attained, is probably due to the fact that he confines his speculations regarding mechanical operations and movements, to what it has been possible to accomplish in the past by means of electromagnets.

The KR limitations of circuits (including lines, and windings of instruments) where such circuits are spaced into repeater sections of approximately 500 miles, are in the case of aerial lines, of such consequence, that with ordinary voltages, with lines worked duplex; speeds of 300 words per minute are about as high as is possible where the operations are dependent upon electromagnetic control. There is one printer system in use in Europe for which a speed of 350 words per minute is claimed.

It would be, as Mr. Potts implies, a highly desirable feature of a universal printer telegraph system if its operating capacity were as elastic as is the telegraphic traffic in volume on any given circuit, provided, of course, that its general application to circuits having varying loads at different periods of the day, would permit of economical operation as compared with Morse methods,

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[3] *Telegraph Age*, Sept. 1, 1902, page 382. *Telegraph Age*, Oct. 16, 1902, page 438. *Telegraph Age*, Nov. 16, 1902, page 476.

when the volume of traffic is far below that of the maximum capacity of the machine. Flexibility of operating capacity, with a high maximum rate, would serve to take care of varying loads and of the accumulations of traffic due to temporary loss of wires.

With reference to Mr. Jones remarks dealing with the fate of the engineer's recommendations.

The practical engineer realizes that even in the reconnaisance stage any engineering proposition must be worked out with practicability and economy as factors. Even if for temporary considerations an engineering proposition may not be adopted, it still remains that by virtue of the thought and effort devoted to its development, the proposition will survive as a basis for future undertakings along the same lines. Naturally where the engineer is a traffic economist he has given due thought to the requirement that any proposition he may submit calling for the outlay of comparatively large sums of money for new or for additional equipment, must provide for economical results, or in some manner for enhanced advantages over the methods it is intended to improve, which will insure adequate return on the investment. Although the live engineer is professionally zealous, his conservatism would seem to be well established by virtue of the fact that the major number of the propositions submitted to him for investigation are found to be and reported as impracticable or unprofitable.

W. Maver Jr.: The President is very desirous of getting to the other matters scheduled for the program this evening, and I shall therefore at present only say a few words in reply to the points brought out in the discussion.

Mr. Pope queries the statement that places the distance of transmission by the House printer at 1,000 miles. The statement is traceable to the officers of the original House telegraph company and may be found in "Electric Telegraph," Jones, 1852, page 112, as follows: "The longest line we have is about 1,000 miles—extending from New York to Cincinnati. Messages are transmitted that distance with ease; and no doubt we shall be able to telegraph direct from New York to St. Louis as soon as our line, now building, is completed." Possibly the discrepancy between this statement and Mr. Pope's experience may be explained by a superior conductivity of the newly constructed wires in 1852 as compared with the wires of Mr. Pope's time. It was the common experience of those days, 1865-1870, that, owing to the manner of making joints then in vogue, (a simple twisting of the ends of the wire without solder), the resistance at the joints in a few years almost amounted to a break in the continuity of the wires. For instance, one of the New York-Bridgeport wires tested by Mr. Varley and mentioned in his report (see page 1289) showed it to have a resistance of 241 ohms per mile—normal resistance 13 ohms per mile.

In regard to early attempts to produce a page printing telegraph it may be noted that Charles Wheatstone, about 1840, devised a page printer telegraph system, but it was rather slow and did not get into general operation. Described Sci. Am., May 31, 1884.

Mr. Taylor expresses the opinion that some of the present trouble on multiple telegraph circuits is due to the mutual induction between parallel wires. About twenty years ago I had a very large experience in the practical operation of multiplex telegraph circuits while I was the electrical engineer of a large telegraph company in this country, and the statements on this point in the paper are based upon that experience—we operated circuits between New York and Boston, five or six quadruplex circuits on parallel wires at top speed, obtaining an efficiency virtually of one hundred per cent, except in very bad weather. I found, that when we already had five or six parallel quadruplex circuits, the imposition of additional circuits did not have any detrimental effect upon the operation of the others. Hence, I feel safe in saying what is said in the paper—if it were possible to get rid of the stretches of underground cable and the inductive disturbances from high tension transmission circuits, it would be possible to restore the former conditions of multiplex operation.

The disuse of the Rowland printer in this country is probably due to a number of causes, chiefly perhaps the somewhat complex nature of the apparatus and its unreliability at times. Mr. Taylor himself suggests some of the causes for the present non-use of high speed chemical automatic systems, to which it is assumed he refers, having the phenomenal speed capacity of 1000 words per minute. Numerous other causes have been cited at times without number by those who have had practical experience with such systems. It is pointed out in the paper that automatic systems capable of transmitting at the high speeds mentioned were in operation in this country 30 years ago and are still freely available when desired.

As to the statement relative to the extent of use of the vibroplex, mecograph, and similar instruments to which Mr. Dunn has referred, namely, that four-fifths of the operators now use such instruments, it may be said that investigation will probably confirm that statement. So far as the feasibility of transmitting speedily with this device is concerned, it can be stated that duplex circuits are being operated now between New York and San Francisco, with, I think, three sets of repeaters, by means of semi-automatic transmitters at the highest speed of manual Morse transmission.

Charles F. Scott: Is that repeating done automatically?

Mr. Maver: Yes, regular automatic repeaters, duplex repeaters. The method is described in the paper. The matter of displacing the spaced letter or American Morse alphabet as used in the United States and Canada, by the Continental Morse Alphabet has been proposed frequently within the past

50 years without result. There is no question that for manual sending the American Morse alphabet is the speedier, there being 214 time units in the American to 214 time units in the Continental, exclusive of numerals, and the liability to errors due to the spaced letters of the American Morse alphabet is minimized by the fact that the operators by habit almost universally exercise extra care in the transmission of words containing spaced letters. In automatic transmission, however, as by the Wheatstone system, the use of spaced letters is a source of delay as it is virtually necessary to double space words containing spaced letters in order to avoid errors. Thus the situation stands at present. Possibly the use of the Continental alphabet by wireless telegraph operators may assist in leading to the general disuse of the spaced letter alphabet.

Exception may be taken to Mr. Jones statement that the presidents and general managers of telegraph and railroad companies are de-facto the engineers who decide all questions involved. They may act adversely or favorably upon the reports of their engineers for financial or other reasons, but that does not constitute them the engineers of the company. Apropos of this may be quoted the following sentences from a recent paper by Mr. George Westinghouse* "In view of the fact that there had been no considerable demonstration of the single-phase system by actual use, and that the New Haven trains would be obliged to operate upon twelve miles of lines already equipped with the direct-current third-rail system, it must be conceded that the directors and management of the New York, New Haven and Hartford Railroad showed great courage and confidence in the judgment of their experts." Mr. Jones is quite in accord with the authors of the present paper in expressing his opinion that the financial and engineering obstacles to placing entirely underground the trunk telegraph lines between all of the widely separated cities of this continent, etc.

Mr. Jones statement that the resultant electrostatic induction is a maximum when the keys on the No. 2 sides of several adjacent quadruplex sets are simultaneously closed will bear considerable qualification. For instance, there must be a particular coincidence of polarities to line on the No. 2 sides to bring about this maximum. One can easily conceive of a condition of complete neutralization of ill effects, depending on the polarities to line at a given instant, when all the No. 2 keys are closed. Furthermore, instances are cited in the paper in which many adjacent quadruplex sets have been operated without any impairment due to the cause stated.

Concerning Mr. Jones wonderment that the limit of transmission of an ideal printing telegraph system was not placed at 5000 words per minute, instead of 600 words per minute, the

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*A paper prepared for the joint meeting of the Am. Soc. M. E. and the Inst. M. E., London, July, 1910.

reason may be that the authors were desirous of keeping within limits that are at least eight times nearer attainment than Mr. Jones' system. Mr. Jones' arithmetic is perhaps astray in the computation that a transmission rate of 600 words per minute would involve preparing 30 word messages at the rate of 66 messages per minute. Twenty messages per minute is nearer the mark and twenty operators could easily prepare the messages at that rate. Mr. Jones seemingly bases his dictum that the time constant of all known line wires, electromagnets and their connections for over 200 miles would utterly prevent the operation of a printing telegraph system at the rate of 600 words per minute, upon the assumption that present methods must be strictly adhered to. This was not made a condition of an ideal printing telegraph system by the authors. The Buckingham-Barclay printer to-day has a capacity of 100 words per minute in each direction over circuits 1000 miles in length. In transmitting by this system each letter requires an average of nine time units made up of short and long pulsations of current of opposite polarities. The Murray printer of 150 to 180 words per minute employs five time units for the transmission of each letter. For the Creed printer, employing the Wheatstone alphabet, it is claimed that 225 words per minute may be transmitted.

The Wheatstone automatic telegraph system which employs an electromagnetic ink recorder is capable of transmitting messages over regular telegraph wires at the rate of 600 words per minute, using the continental Morse alphabet, which requires an average of 8 time units per letter; the equivalent of 8 pulsations of minimum duration per letter. It is therefore perhaps not the time constant of the line or apparatus that stands in the way of a 600 word per minute printer so much as the present cumbersome methods of selecting the letter to be printed; together with the more or less cumbersome printing apparatus.

Hence it is conceivable that by the use of a method in which the time units required per letter may be halved or quartered the speed of transmission may be doubled or quadrupled without any change in the line or receiving apparatus, a result that would bring the speed of transmission quite close to if not beyond 600 words per minute. So in this respect as in some others Mr. Jones' railroad analogy is not as apt as at first sight it might appear to be. But the suggestion of an ideal printer telegraph as noted in the paper does not confine the prospective inventor to existing electro-mechanical apparatus. Photography and other physical agents controllable by electrical impulses are open to the ambitious and qualified inventor, who, however, could not say that the context of the paragraph in the paper relating to an ideal telegraph system conveys the impression that the realization of this ideal system is devoid of difficulties.

Mr. Cellar's remark relative to the housing of insulators indicates that he misses the suggestion of the paper that relates to the housing of the wires for mechanical protection against storms. Mr. Cellar's immediately following comment on the destruction of open wires by storms however emphasizes the said suggestion; as does also Mr. Jones mention of the annual expenditure of millions of dollars for the repair and maintenance of pole lines.

With reference to Mr. Pott's remarks concerning the impracticability of operation of high speed printing telegraph systems on wires subjected to severe inductive disturbances, it may be pointed out that a perusal of the paper will show that the authors are in strict accord with Mr. Pott's in this view.

It is noteworthy that many of the important inventions in mechanics and electricity have not been due to men directly engaged in the industrial application of those arts. Watt, for instance, was an astronomical and mathematical instrument maker. Morse was an artist by profession. Stearns, Bell and Pupin were not in the telegraph or telephone service when they produced their notable inventions in telegraphy and telephony respectively. Murray the inventor of the successful printing telegraph that bears his name was a journalist. Creed left the telegraph service to devote his time to the development of his ingenious punching and printing telegraph, and the list might be continued almost indefinitely.

One explanation of this fact may be that in the majority of cases the active engineers in an art are fully occupied with the successful operation of existing apparatus or with problems connected therewith, and are given neither the time nor the financial aid necessary to undertake original research for the advancement and betterment of the art with which they may be associated. Another explanation may be that in many cases the engineers in question are operating engineers, but not inventors. This suggests the question whether men thoroughly familiar with the requirements of telegraphy and of all the conditions to be met with in the technical telegraph service, and largely endowed with the inventive faculty might not be selected to prosecute investigations relative to the improvement of the telegraph service as relates to the transmission of messages, analogously as selected men in the medical and other professions and arts are now exclusively employed in matters relating to the advancement and improvement of those professions and arts.

A paper presented at the 27th Annual Convention of the American Institute of Electrical Engineers, Jefferson, N. H., June 29, 1910.

THE AUTOMATIC TELEPHONE IN RELATION TO CITY SERVICE.

BY ARTHUR BESSEY SMITH

The telephone requirements of a large city differ in certain essential points from those of a city of small or moderate size. The chief of these are as follows:

Measured service.

Private branch exchange service.

Interborough service.

Although these exist to some extent in smaller places, they are peculiarly important considerations in the telephone service of a large and congested city. They are practically the conditions which had to be met by the automatic telephone exchanges installed in Oakland and San Francisco, California. For this reason it is felt that a statement of the chief engineering problems of these cities and how they were solved will be of general interest.

The Setting. The interest in the region of the Golden Gate centers about two cities, San Francisco and Oakland. The former is a thriving seaport of about 350,000 inhabitants. It occupies the rough, hilly, northern end of the small peninsula (see Fig. 1) which separates the southern end of San Francisco bay from the Pacific ocean. The rather sandy region south of the city is thinly populated. The north peninsula across the Golden Gate is more thickly settled. To the eastward across the bay lies the city of Oakland, in the pleasant region between the Berkeley hills and the water. Oakland has a population of over 250,000 while Berkeley, Alameda and other smaller cities have about 60,000 inhabitants. The total population of the region reaches well up to three-quarters of a million.

San Francisco is a cosmopolitan city. There are Chinese, Italian and Latin quarters, each with its distinctive population and language. The wharves lie along the eastern edge of the city, with a great wholesale and manufacturing district south of the business center. Although a large amount of manufacturing is carried on, the harbor and shipping facilities have located the city and made it what it is.

Oakland has had a rapid growth since the earthquake across the bay and is second only to San Francisco in business importance. The cities are very closely bound together by business relations and also because so many business men of San Francisco live in Oakland. North of Oakland is Berkeley, the seat of the State University of California. Oakland also has considerable Chinese population, enough to warrant the serious attention of the telephone engineer.

Main office, San Francisco

The Problem Stated. The requirements to be considered in designing a telephone system for this region may be briefly stated as follows:

1. A system which shall give satisfactory telephone transmission between all points in the whole territory.

2. A system which provides satisfactory accessory conditions such as ease, rapidity and accuracy of completing and controlling connections, methods of charging for service and means for discrimination in the same.

The consideration of these general requirements as applied to the case in hand causes their expansion into ten conditions, *viz.*,

1. Quiet, clear transmission over all talking circuits.

South office, San Francisco

2. Easy, quick and accurate completion of local connections within each exchange district.

3. Provision for the cosmopolitan nature of the population especially regarding the diversity of languages.

4. Measured service.

5. Free service on calls to certain classes of stations.

6. Private branch exchange business.

7 Quick and accurate completion of calls between exchange districts especially between San Francisco and Oakland.

8. Accuracy in charging the accounts of credit toll users.

9. Credit and cash toll work between exchanges.

10. Provision for the harmonious mutual working of different types of apparatus used in the several exchanges.

A Bit of History. In the Spring of 1905 the interest of San Francisco citizens was aroused by a small exhibit of the automatic system. This exhibit was, however, destroyed by the earthquake and fire in the spring of 1906. While the city was recovering from the effects of the disaster the attention of constructionists was diverted to Oakland where an automatic system was installed and completed in May, 1907. It is of the three-wire trunk release common battery type, with Keith type line switches. Three offices are in service, Main East and Berkeley, with two district stations connected to the Main office.

Work was again taken up in San Francisco with the result that a system was installed in 1909. By the time the San Francisco order was placed the two-wire automatic equipment had been perfected and was accordingly used. Four offices are at present operating and are designated as Main, Howard, South and West.

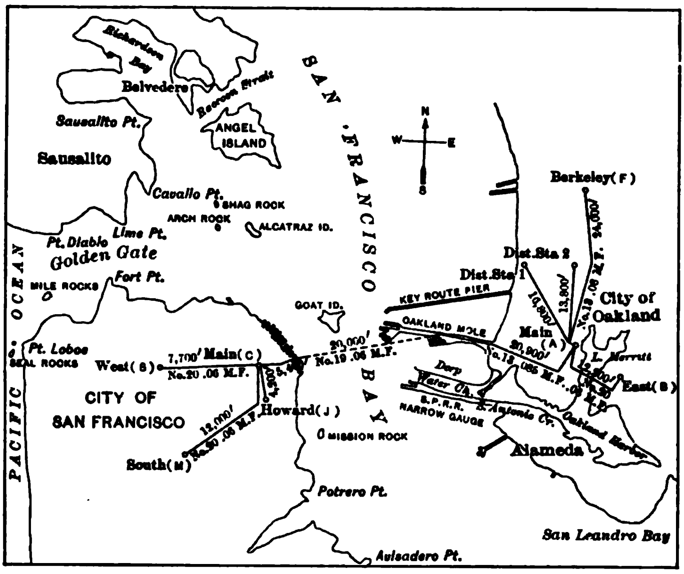


FIG. 1—Map of San Francisco and Oakland

LOCAL EXCHANGE APPARATUS.

Oakland. The locations of the offices in Oakland are shown in Fig. 1. More extended and detailed descriptions of local exchange apparatus have been given from time to time, hence my references will be confined to recalling the types and chief functions of the several switches, in order that the subjects discussed may be more clear.

Each subscriber's line in any office terminates in a line switch (Fig. 2). These line switches are grouped in units (see Figs. 3 and 4) of from 50 to 100 each. All the line switches in a unit have access to a group of ten trunk lines. The general arrangement of switches is shown in Fig. 5. When any subscriber initiates a call, his line is automatically connected to an idle trunk line, *a*. This trunk is preselected, so that there is no loss of time, the connection being practically instantaneous. The various groups of ten trunks each, which come from the banks of the line switch units, terminate in first selector switches.

To the first or bottom level of bank contacts in all first selectors in Oakland are attached trunk lines leading to the Main office. The second level has the trunks leading to the East office and the third level those to the Berkeley office. Taking the East office for example, the trunks from the second level are termed local trunks, *b*, since they run to second selectors in the same office. Those from the first and third levels, however, are outgoing trunks, *c*, for they run to the other offices, Main and Berkeley. These outgoing trunks go through repeaters, which serve the chief purpose of supplying talking current to the calling subscriber from his own office, while still enabling him to send impulses to the distant office to control the switches.

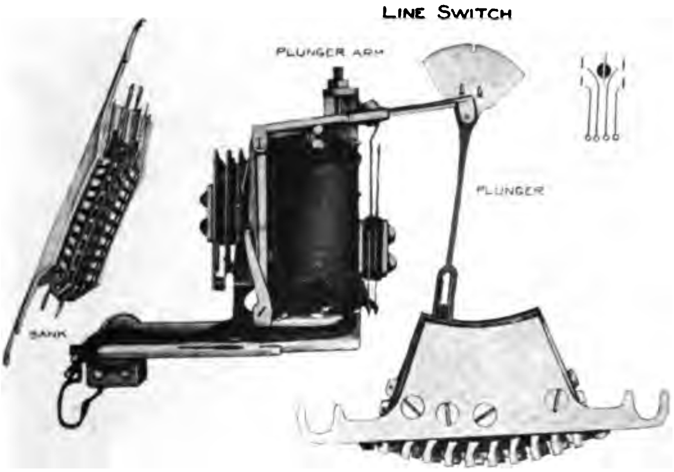


FIG. 2

The second selectors in each office have the duty of picking out the desired thousand group and of selecting an idle third selector in that thousand. The third selector chooses the hundred group and the connector makes the final connection to the line of the called subscriber. In practice the connector switches are mounted on the same frame with the line switches with whose lines they connect. Incoming trunks, *d*, from other offices are wired to second selectors whose banks connect with trunks common to the local apparatus.

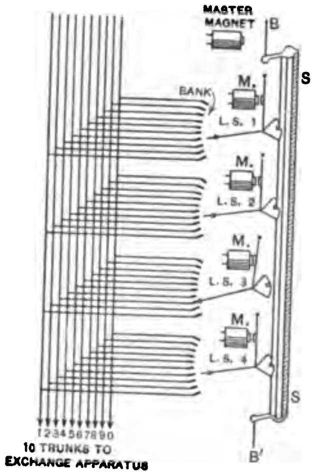


Fig. 3—Grouping of line switches

Fig. 4—Close view of line switch unit

The means by which a subscriber controls the switches is briefly reviewed here to make clearer the operation of the special functions to be described later. The two line wires which extend from any Oakland office to a subscriber's station are termed " vertical " and " rotary " respectively. In the office each is connected to a relay which has its other terminal attached to a battery of storage cells. The other (positive) terminal of the battery is grounded. The dial or calling device at the substation, when operated, grounds each wire in a definite way, operating the relays, and through them the switches.

The vertical wire is the impulse transmitting member, for over it are sent at various times the exact number of impulses required to set the switches according to the digit called. The rotary wire is the switching or circuit-changing member. It determines upon what switch or magnet the vertical impulses shall act. At the close of any series of impulses over the vertical wire, one impulse is always sent over the rotary wire to shift the connections in the switches so that the next series over the vertical line will be effective on the next operation to be performed.

When the called subscriber answers, a relay in the connector is operated which switches the rotary wire from negative to positive battery, thus supplying talking current to the calling subscriber.

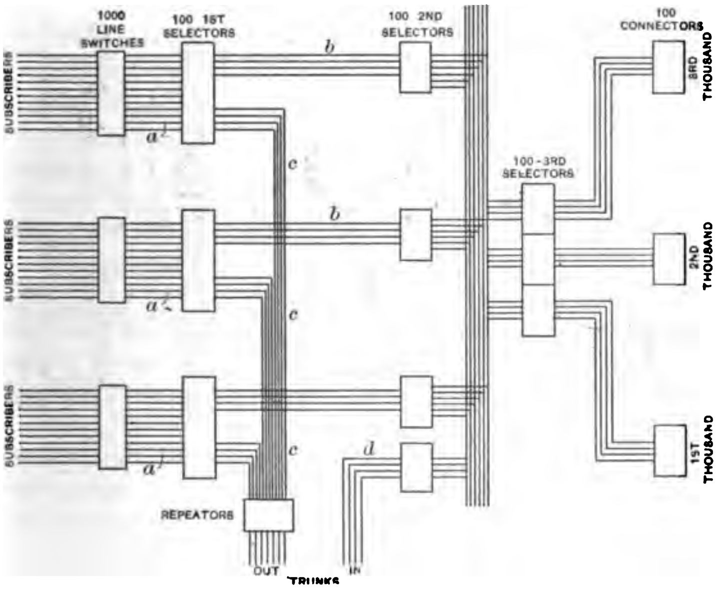


FIG. 5—Trunking in Oakland

The simultaneous grounding and clearing of both vertical and rotary lines causes the switches to be released and restored to normal position.

San Francisco. The relative locations of the four offices are shown in Fig. 1. The grouping of switches is somewhat different from that of Oakland owing to the introduction of secondary line switches. A typical arrangement is shown in Fig. 6.

Each subscriber's line terminates in a primary line switch.

These switches are grouped in units of 50 each, and have access to ten trunks, as described for Oakland. But here the difference begins. The trunks from the primary line switches are carried to secondary line-switch units, where each trunk terminates in a secondary line switch. Each unit group of secondary line switches has access to a group of ten trunks, *d*, each of which ends in a first selector. These secondary line switches are exactly like the primary switches in function, for they pre-select the idle trunks in exactly the same way.

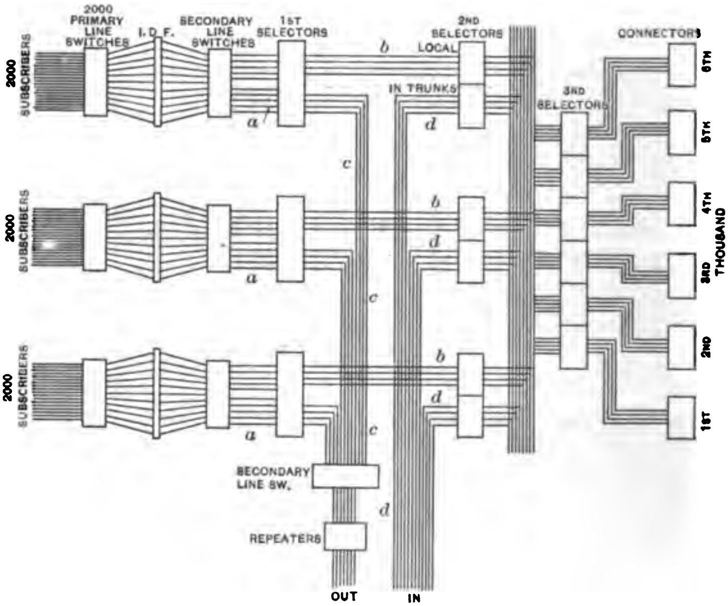


FIG. 6—Trunking in San Francisco

The purpose of using primary and secondary line switches is to enable any subscriber's line to use any first selector switch. This is in the interest of economy. Where only a small number of trunks are available for selection, the efficiency is relatively low. For instance, it has been found in automatic telephone work that ten trunks in one group can be depended upon to handle about 225 busy-hour calls, or 22.5 calls per trunk. Twenty trunks in one group will handle about 575 busy-hour calls or 28.75 calls per trunk. By arranging one hundred first selectors in one group 4,000 busy-hour calls may be successfully handled.

If arranged in groups of ten each it would take about 180 first selectors to carry the same load.

The intermediate distributing frame placed between the primary and secondary line switches is to render more easy the interconnections by means of which the traffic is equalized on all the first selectors.

Since the first selectors select the office in which the called number is located, all levels but one will be connected to trunks to other offices. These outgoing trunks, *c*, are led through secondary line switches so that any inter-office trunk is made available to any first selector. For instance, if we consider a call from Main to South, every trunk leading to the South office from Main will be available for use by every first selector in the latter office. By arranging all the trunks in a common group, considerable saving in trunk cable is secured. Though varying with the local conditions, the saving has in certain cases been as high as 40 per cent.

The incoming trunks, *d*, from other offices terminate in second selectors which have access, in common with local second selectors, to third selectors. The grouping from here on is identical, in general, with that of the Oakland Exchange, and the connectors are mounted on the same frames with the primary line switches, whose lines they are designed to reach.

The exact method of operation differs radically from that used in Oakland, for the San Francisco apparatus is controlled by the subscriber over two wires with no earth return. This greatly sinplifies the subscriber's telephone and gives many structural and operating advantages.

The two subscriber's line wires are known as positive and negative, indicating the terminal of the battery to which each is attached through the windings of the line relay. The series of impulses for stepping up the wipers of the switches is caused by the dial or calling device, which opens and closes a normally closed pair of contacts. The line relay follows these impulses and repeats them to the magnets which move the wiper shaft.

The switching of the circuit to the next switch or operation depends upon the time interval between one series of impulses and the next. During a series, the circuit-changing member is held by a catch, which is released when the impulses cease to come. The release is accomplished by simply opening the line circuit by hanging up the receiver. This momentarily brings into action the release magnets which restore all switches to normal.

1. *Telephone Transmission.* The nature of the completed circuit between two subscribers has a vital effect on the quality and loudness of transmission. Freedom from external disturbances is to be secured by properly transposed wires and perfect electrical balance. The former is secured by a large use of telephone cable, the latter by high insulation and properly designed apparatus. In the telephone switchboards installed in San Francisco and Oakland every talking circuit is balanced from one end to the other. Fig. 7 gives in simplified form the transmission circuit between two subscribers in separate offices. From the calling telephone to the called telephone there are four " bridges " or shunt paths. Each of these is a relay or a pair of relays, all of which are highly inductive, so that little loss is occasioned to telephone current. The impedance of each path from line to earth is made as nearly as possible equal to that of the mate. No extra coils are bridged to one side of the line, and none are inserted in series. All auxiliary circuits are handled by a third wire within each office, leaving the talking circuit clear for its proper functions. The trunks are two-wire with no earth return circuits during conversation. Each subscriber is supplied with talking current from a battery in his own office. No repeating coils are used in any portion of the circuits.

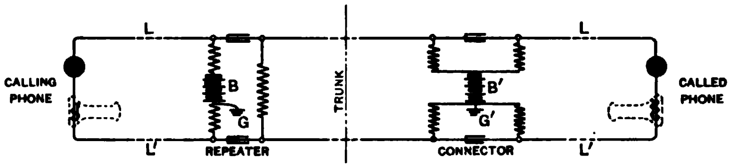


Fig. 7—Simplified talking circuit. Inter-office

2. *Method of Calling.* The method of calling a number on the automatic system has been described by others. Briefly, it consists in rotating a small dial by the finger, making one motion for each digit in the call number. The dial used in San Francisco is shown in Fig. 8. To assist the memory, the offices are designated by letters instead of figures. The code is as follows:

C Main office.
J Howard office.
M South office.
S West office.

Thus, a telephone whose number is 22785, appears in the directory as J-2785. It is served by the Howard office, though this is of little importance to the subscriber.

The manipulation of the dial for an average call number takes about five seconds, after which the bell of the called station begins to ring without further action on the part of the calling subscriber. The ring is intermittent and ceases when the called subscriber answers.

Instantaneous release of the switches is effected by hanging the receiver on the hook. This is of interest chiefly to those who have two or more calls to make in succession.

3. *Diversity of Languages.* The method of calling above described is of special convenience to the many people who speak only foreign languages. The Arabic numerals are common to practically all nationalities represented in San Francisco except the Chinese. For the latter a special lettering has been made which is shown in Fig 9.

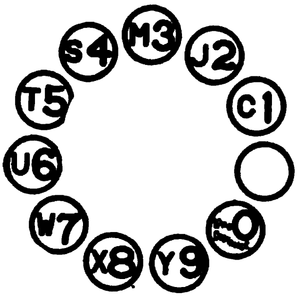


FIG. 8—San Francisco dial

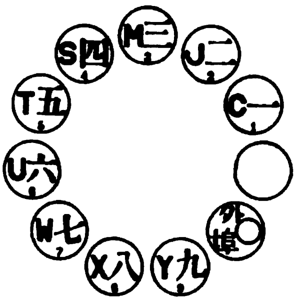


FIG. 9—Chinese dial

4. *Measured Service.* One of the conditions met in managing a telephone system in a large city is the desirability of charging for the service in proportion to the amount of service rendered. This is ordinarily done by attaching a meter to each subscriber's line. The requirements of a meter are as follows:

1. It must register only once for each completed connection, rejecting those in which the called station fails to answer.

2. It must make no charge for connection to certain classes of telephones, such as fire, police, information and complaint desks, etc.

The Oakland exchange is operated on the flat rate basis for all calls originating and terminating within the exchange, which includes the suburb of Berkeley. In San Francisco measured service is required.

The meter in an automatic telephone system is attached to the line switch. As above mentioned, it must not operate until the called station answers. Therefore, the latter act must cause some change in electrical condition at the line switch which will cause the meter to register. The line switch of the calling station and the connector which picks up the called line may be in different offices with 1st, 2nd, and 3rd selectors and a repeater in the circuit between. The called station can control the connector and through it the condition of the line leading back to the line switch. Two changes in condition are available, reversal of current and change of current strength. The latter is undesirable on account of its interfering with conversation to stations set aside for free service. The former seemingly necessitates some form of polarized magnet. As it was desired to avoid the use of permanent magnets, a two-coil meter was devised. It is so arranged that when the called station answers, the current supplied to the latter operates the relay which reverses the current supplied to the calling line. This causes the meter to record one call. Neither coil alone will cause registration, and the apparatus has a range from 0 to 1,500 ohms line resistance. Its line coil is of low resistance and is short-circuited during conversation. The reversal of current for operating the meter is accomplished in such a manner as not to cause inconveniences to the calling subscriber.

5. *Free Service*. Since the connector is the switch in which occurs the reversal of current which operates the meter, the means for giving free service must effect this part of the apparatus. It is done by grouping all free service lines such as information, police, etc , into one or more hundred groups, each group served by a set of connectors. All these connectors are so wired that the current flow to the calling subscriber is not reversed when the called station answers, consequently no register is made.

There is one class of calls for which, strictly speaking, no charge should be made, and that is calls which result in the wrong number being obtained. The meter makes no discrimination here, and if the called station answers, a call will be recorded. However, experience has shown that such a small per cent of wrong numbers are obtained that they may safely be neglected. This is especially true if wrong calls due to carelessness in the use of the dial be omitted. For these it is right to expect the subscriber to pay. The same is true of regular manual practice, for if a subscriber calls for the wrong number and gets it, he is expected to pay for it.

Fig. 10 is a general view of a number of primary line switches. In the space above the switches indicated by the letter *M* the meters may be seen. These are in tight cases which are locked and accessible only to the official who has charge of meter reading.

Cash measured service is furnished by means of coin boxes attached to the line wires at the subscriber's stations. No coin is required to be deposited in order to call. When the called station answers, the reversal of current operates a magnet in the coin box which short circuits the transmitter and places a shunt in parallel with the receiver. This prevents the transmission of speech, but allows the user to hear faintly the voice of the called subscriber. By dropping a coin in the chute, the shunts are removed, so that conversation can take place.

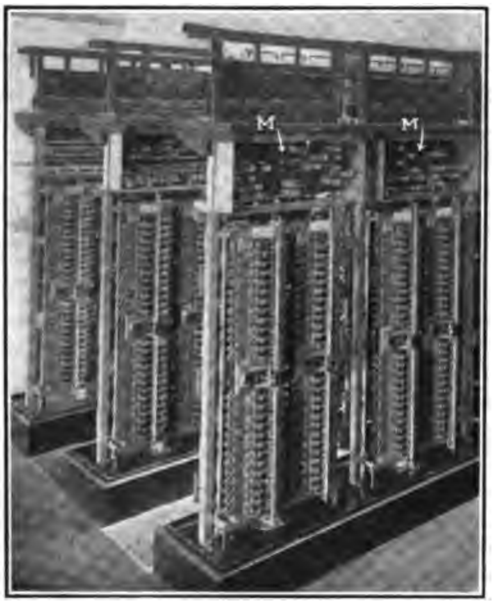


Fig. 10—Primary line switches with meters

When a call is made to a free station as above described, no reversal of current takes place, so that the calling subscriber is not forced to make a payment.

6. *Private Branch Exchanges.* In both Oakland and San Francisco the nature of the business makes quite a large number

of private branch exchanges profitable to the subscriber and to the operating company. These boards are manually operated and have several trunks connecting them with the nearest public exchange office. Each business house is listed under one number in the directory. When a public subscriber selects the call number the connector switch must automatically select an idle trunk to the private branch board. This is done by a special type of switch known as the rotary connector. It responds to the impulses for the tens and units digits of the call number, but immediately thereafter acts as a selector until an idle trunk is found. These rotary connectors are grouped in hundreds so that in providing for this special service the call numbers are set aside in blocks of one hundred each. Thus in the Main office San Francisco, the 1100, 1200, 2100, 2200, 3100, 3200, 4100, and 4200 hundred units are set aside for private branch exchange service and no number in them assigned for individual lines.

Let us suppose that the call number of a certain wholesale house is C-4251 and that four trunks are required for the business. The connector switches in the 4200 group of the Main or C office will serve this board. These four trunks will be multipled to the first four sets of contacts in the fifth level of the connector banks, that is, corresponding to numbers 4251, 4252, 4253, and 4254. Contacts 4255 are connected to the busy tone so that if it happens that all trunks are occupied, the calling subscriber will receive the busy signal and be induced to release. The private contacts 4255 of the several connector switches are not multipled together. If while all four trunks are occupied, more than one called is received for the busy number, the second and later calls will also stop on 4255 and not be forced past to 4256 which might be assigned to other service.

If desired, the remaining four numbers in this same level, 4256, 4257, 4258, 4259 may be given to some other private branch board. In fact any grouping of the trunks of a level may be used, it being only necessary to reserve one set of contacts at the end of each group for busy indication.

The trunks to private branch board are treated exactly like subscriber's lines in the public exchange, each being wired to a line switch for calls to the automatic system. They terminate in jacks and signals on the manual private boards and can be used for establishing connections either to or from the subscriber. The operator is provided with a calling device which may be switched by keys to any cord circuit. With this the operator calls into the automatic exchange and arrangements are made so that complete double supervision is secured on all calls.

In the case of a private branch exchange having sufficient magnitude of business to require it, the trunks leading from connector banks may be made one-way only and reserved for calls to the branch board. There will then be installed as many trunks from the latter to the public exchange as are necessary, these trunks being attached to line switches. The number of trunks is not limited by the number of contacts in a level of the connector bank.

7. *Transbay and Suburban Toll.* We come now to what is perhaps the most interesting feature of the combined telephone exchanges. On account of the relative positions of the two cities, and their close business and social relations, the matter of quick and satisfactory communication between them is of great importance.

The fact that a charge is made for all calls between the two cities makes it necessary to employ operators for putting up these connections, making records of the same.

Long distance toll work is necessarily handled in a different manner from suburban calls. In the former, the telephone company agrees to bring together two persons, in the latter merely two telephones. This is sometimes called the " two number basis " inasmuch as only the two numbers are recorded, no attention being paid to names.

A common method of handling suburban as well as long distance calls is to have each call received by a recording operator, who makes out a ticket. She tells the subscriber that he will be called when the line is ready. The ticket is then passed to a line operator, who calls the distant city and with the coöperation of a similar operator there, establishes the desired circuit. She then calls the station whose number was given by the person originating the call and allows the conversation to take place.

For the suburban work between San Francisco and Oakland it was thought best to abolish this slow procedure and use what is known as the " rapid fire " method. Accordingly provisions were made for allowing the recording operator at San Francisco, for example, to complete the call into the Oakland exchange by a calling device in San Francisco, and to allow the conversation to proceed at once. This virtually makes the recording operator a line operator and entirely dispenses with the services of a line operator to complete the connection in the distant office.

The recording operator is of course obliged to ask the subscriber who originates the call for his telephone number so that the cost of the toll service may be properly charged. It is to be expected that, either by accident or intention, wrong numbers will sometimes be given. To prevent error from this source a system of back checking has been devised, which will be described in detail later.

The operators are divided into two main groups, suburban and long distance. The latter are as usual made up of recording operators and line operators, each with the usual duties assigned.

The suburban operators work in pairs or threes and are termed suburban operators and checking operators. All calls for out of town come to the suburban operators, who act as distributors between the two boards. This is because of the relatively heavy nature of transbay and suburban service as compared to long distance service. The suburban operator puts up suburban connections while the checking operator verifies the correctness of the number given by the calling subscriber. Usually one checking operator verifies the work for two suburban operators, though during periods of light load the latter check for themselves.

The method adopted in making a call is as follows: The subscriber takes his receiver from the hook and calls the digit " 0 " on the dial. This lifts the wipers of a first selector to the top level and selects an idle trunk to the suburban board. Here a lamp attracts the attention of a suburban operator who answers the call by plugging into the jack and throwing the listening key on her cord circuit. She asks whether " suburban " or " long distance " is wanted. If the latter, she momentarily depresses the transfer key button associated with the trunk in use. This automatically transfers the call to the long distance recording board, where multiples of the incoming trunks appear. The proper operator, seeing the burning lamp, answers and cares for the call in the usual way.

If, however, the subscriber replies that he wants " Suburban ", the suburban operator asks him two questions.

" What number do you wish?"

" What is your number?"

This information she writes on a ticket together with the number of the incoming trunk over which the order was received. The pad of tickets bears the suburban operator's position number and is arranged to furnish duplicate copies. Having recorded the information she passes the duplicate ticket to the checking operator who is seated directly in front of her. The two following operations are then performed simultaneously:

The suburban operator selects an idle outgoing trunk leading across the bay and calls the number in the distant exchange by means of her dial. The checking operator upon receiving the ticket plugs into the multiple of the incoming trunk shown thereon. Then by an independent set of apparatus she calls the number of the originating subscriber. If the checking operator finds that the number written on the duplicate ticket is wrong, she passes the ticket back to the suburban operator by dropping it in a special ticket box in plain view. The latter operator at once throws the cut-off key on the cord, thereby severing the connection from the outgoing transbay trunk. She then requests the calling subscriber to repeat his number. If he repeats the number previously given, she informs him that she can not reach him over that number. In most cases the subscriber now corrects his mistake by giving the true number. This is now entered on the tickets and the duplicate again passed to the checking operator for verification. Usually the suburban operator allows the connection to proceed, while the second check is being made, for, as a rule, the second number is found to be correct.

On the suburban operators cord circuit is provided two supervisory lamps which have the usual functions. The calling supervisory lamp burns till the subscriber in the distant office answers. Then the operator stamps the ticket in a calculagraph. At the end of the conversation both subscribers hang up the receivers. This lights both supervisory lamps. The operator then times the ticket and disconnects the circuits.

The completed circuit over which conversation is carried on is shown in simplified form in Fig. 11. It is balanced and quiet in service. The rapid break and make of the calling device in operating the switches through the cable under the bay causes no inconvenience to those using parallel trunks.

When a subscriber has secured connection with the suburban or toll board, it is necessary that he be permitted to signal the operator by moving his receiver hook up and down. This would ordinarily cause the release of his first selector since all automatic switches are arranged to be released by the depressing of the hook lever. To prevent this breaking of the connection a special arrangement is attached to the outgoing toll trunks from each office in place of the regular repeater. This enables the release of the first selector used by the subscriber to be controlled by the operator.

After the subscriber has hung up, the operator pulls out her plug which automatically causes the release of the first selector.

8. *Toll Checking Apparatus.* In the preceding general description of the mode of operation, reference was made to the toll-checking operator and her apparatus. The general plan of checking is to connect to the incoming toll trunk in use a source of alternating current which produces a musical tone. By independent automatic switches the checking operator calls the number given. If correct she will obtain connection to the same line as that over which the call was received by the suburban operator, and by listening can hear the tone. The condition is shown in Fig. 12. The subscriber at the right has called the suburban operator over the incoming toll trunk. The operator has answered and made out the ticket. The checking operator has used a checking trunk to secure connection with the number given. At this point she presses the check tone key which connects to the incoming toll trunk a source of alternating current which produces a sound differing from the regular busy tone of the exchange. If the number is correct, the tone will be carried back over the toll trunk to the connector multiple and thence over the checking trunk to the checking operator.

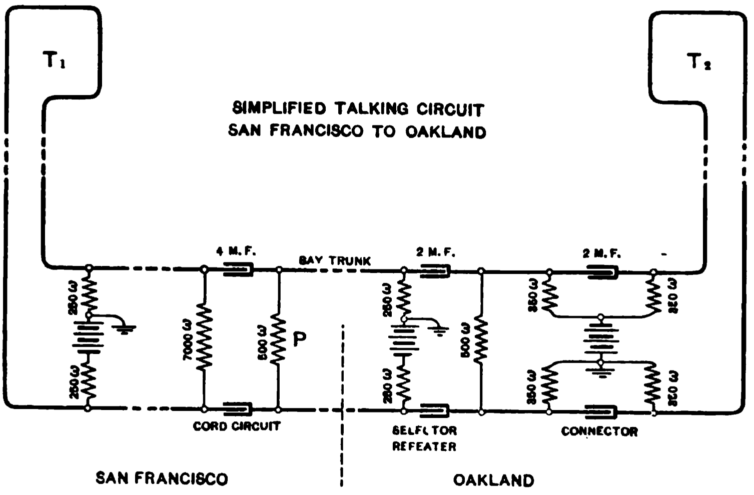


FIG. 11—Simplified transbay talking circuit

The ordinary connector cannot be used by the checking operator in picking up the calling subscriber's line, because the latter is protected by a busy test which will not permit an ordinary connector to establish connection. For this work one check connector is provided in each hundred group. It is devoted exclusively to testing and checking. It is provided with three pairs of wires, one pair (*A* and *B*) for carrying the tone, another pair (+ and –) for operating the magnets for lifting and rotating the wipers and a third pair for auxiliary purposes.

The checking operator secures connection with the check connector in any hundred in any office by a system of first, second and third selectors which is entirely separate from the regular apparatus of the exchange. One first selector repeater is provided for each checking operator, to enable her to select a trunk to any office in the exchange. In each office as many second selectors and third selectors are provided as are necessary for the work, the number varying in the different offices. These are operated by a calling device located at the checking operator's position.

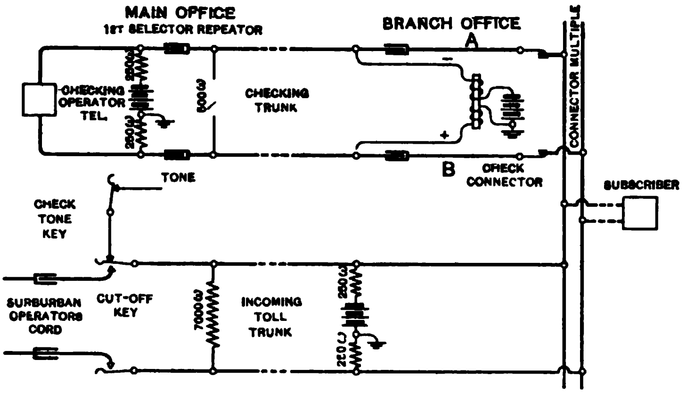


Fig. 12—Simplified toll checking circuit

When the checking operator plugs into a connection it lights a red lamp associated with the suburban operator's cord circuit. This shows that the checking operator has picked up the trunk. When the checking operator has verified the number and withdrawn her plug the red lamp is extinguished, thus notifying the suburban operator that the number has been checked and is correct.

As a guard, tending to prevent the checking of wrong trunks, the checking operator's cord circuit is provided with a lamp. This lamp will light when plugged in on a trunk which is waiting for the completion of a connection. If, however, the checking operator by mistake plugs in on a non-busy trunk, or one over which a connection has been completely established the lamp will not burn.

9. *Credit and Cash Tolls.* The larger proportion of the calls between the two cities are handled on the credit basis. From the records of the toll tickets, statements are made out at regular intervals and sent to the subscribers for payment. For such public places at which it is desirable to collect cash for suburban and long distance service, a regular coin box is attached to the telephone. The dropping of the coin gives a signal which reveals its denomination to the operator.

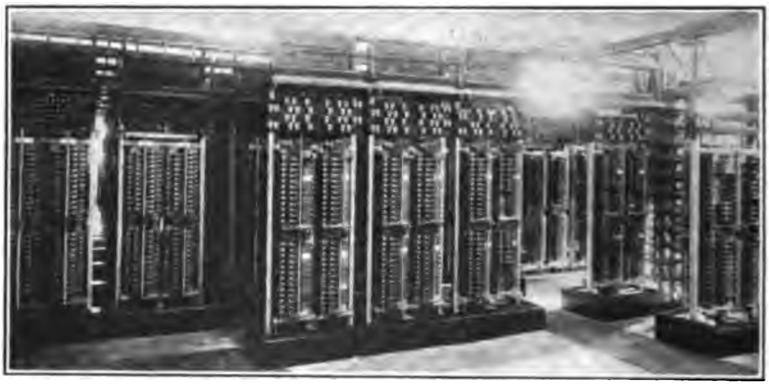


FIG. 13—Secondary line switches

10. *Two Three-wire Operation.* In the general description of suburban toll operation a short reference was made to the trunk lines connecting the two cities. For the purpose of giving a better idea of the arrangement, a trunk line will be described which handles calls from San Francisco to Oakland.

The work of interconnecting the two exchanges was rendered more difficult by the fact that the Oakland apparatus is three-wire, while that of San Francisco is two-wire. The two-wire system requires only the opening and closing of the line circuit. The three-wire system requires each line wire to be grounded in a certain order. The San Francisco recording operator using a two-wire calling device was required to operate three-wire selectors and connectors in Oakland, in some cases as far as thirteen miles away. This was done by means of repeaters which handle the impulses somewhat like a telegraph-repeater, except that it is necessary to transmit impulses only one way.

Each transbay trunk from San Francisco to Oakland ends in multiple jacks with visual busy signals on the San Francisco suburban board, and in a first selector-repeater in the Main office in Oakland. This switch is a first selector, to pick out trunks to the desired office in Oakland, combined with a repeater arrangement to convert the simple make and break of the two-wire system into the alternate grounding of vertical and rotary lines required by the three-wire system. The release of the connection as well as proper supervision is also provided in the repeater.

The operator is provided with a set of plugs and cords with which to connect incoming trunks from San Francisco subscribers to outgoing trunks to Oakland. A calling device is mounted on the keyboard and arranged to be switched into any cord circuit by keys. When a call comes in over an incoming trunk, it is answered by inserting the answering plug of a cord into the proper jack. An idle outgoing trunk to Oakland is selected by inspection of the visual busy signals, and the calling plug of the cord in use inserted into the jack. The calling device is then switched into the cord circuit and rotated in accordance with the desired number. This operates the switches in Oakland.

The supervision is accomplished as follows: Across each cord circuit of the suburban operator in San Francisco is bridged a polarized relay, *P*, Fig. 11. Normally the current from the first selector repeater in Oakland is in such a direction as to cause the relay to light its associated lamp. In the Oakland exchange the circuits from the first selector through to the connector are three-wire. When the called subscriber answers, it causes the rotary line to be switched from negative battery to ground or positive battery. This energizes a pair of relays in the first selector repeater which reverses the current supplied by the latter to the operator's cord circuit in San Francisco. This reversal causes the bridged polarized relay *P* to operate, extinguishing the supervisory lamp.

The release of the three-wire Oakland apparatus calls for the momentary simultaneous grounding of the vertical and rotary lines. The two-wire first selector repeater at the Oakland end of the transbay trunk requires only the simple opening of its line circuit By a suitable arrangement this is made to cause the release of the three-wire apparatus according to the manner just indicated.

The trunks from Oakland to San Francisco are operated straight two-wire, and hence are simpler than those just described. For the sake of securing sharper, better signals the trunks are wired through the first selector repeaters in the San Francisco main office. Supervision is secured by marginal relays.

DISCUSSION ON "THE AUTOMATIC TELEPHONE IN RELATION TO CITY SERVICE." JEFFERSON, N. H., JUNE 29, 1910.

Frank F. Fowle: Mr. Smith's paper is a very interesting description of the general features of a large automatic installation, from an operating standpoint. The descriptive nature of the paper does not permit of elaborate discussion, but there are several novel features worth emphasizing.

The ingenious method of checking suburban toll calls, with the " rapid fire " or " express " method of operating, is especially interesting. It does away with the drag on the service caused by releasing the calling subscriber and then calling him back when the connection is ready—a procedure which, as Mr. Smith describes, is only necessary to verify his number and prevent mistakes or fraud.

The problem of a meter for measured service seems to have been solved to the same degree that it has been worked out in manual practice, but it is yet lacking from the standpoint of the subscriber. The only satisfactory solution to the subscriber will be an indicating meter at his telephone, which he can read himself. The means for accomplishing this appear to be at hand, both in manual and in automatic service. There seems to be some apathy towards realizing this ideal arrangement on the part of telephone companies, due no doubt in part to the cost of an extensive change in subscribers' equipment, and in part to a belief that the public does not demand it. On the latter score, the public has been discouraged in some cases into believing that this ideal plan is very costly and difficult of achievment.

Coin boxes for prepayment service have long been in use in manual systems. They have been operated under two plans, one requiring the deposit of the coin to signal the operator, and the other requiring the coin to be deposited after the order has been given, when told to do so by the operator. The former plan is used in business districts, the latter in residence districts, where it might occasion some inconvenience to find a coin in an emergency or late at night. Under both plans, the operator controls the disposition of the coin by means of keys in her cord circuit, sending it into the coin box if the call is completed, or returning it to the subscriber if the call is not completed.

Mr. Smith describes a device by means of which the coin box is employed in automatic prepayment measured service. The coin here is not deposited until the called party responds, and then it must be dropped in the box in order to take a short circuit off the transmitter at the calling station.

This form of service admittedly has disadvantages in public places, stores, waiting rooms, etc., but on the other hand it has admittedly several disadvantages for offices and residences. In view of the fact that this class of service is usually charged for at a low minimum, it comprises in some cities a large part of the whole development, and considerations affecting it are therefore important.

The functions now controlled at the subscriber's station could be arranged to operate a meter dial and thus register the call within sight of the calling party, thereby doing away with the objections to the coin box in office and residence service. The costs of reading and collecting might be slightly greater than they are with the present system, but not such as to increase the total cost of operation to any appreciable extent. It is quite conceivable that the meters could be read by calling the subscriber on his telephone and asking him for the reading, although in such a case it would be necessary to have duplicate meters in the exchange, as a check.

A meter situated in the exchange, assuming that to be the only meter, is beyond the control or observation of the subscriber, and theoretically this is not the proper place for it, although such an arrangement is both convenient and economical for the company. There is natural suspicion of such a plan on the part of subscribers, particularly when they are unable to check their bills.

Under the proposed plan, the meter should not cost more than the present coin boxes, and probably less. The maintenance costs should also be no greater.

The writer asks Mr. Smith the following questions in regard to automatic practice in San Francisco and Oakland.

1. In the case of manual private branch exchanges, what arrangements are made for night service when no operator is on duty? That is, is there any practice which corresponds to the plan of connecting certain extensions through the branch board to the exchange for night service, as in full manual systems?

2. In the case of manual private branch exchanges, are the extensions equipped for automatic or manual operation, or both?

3. Are automatic, unattended private branch exchanges in demand or in use?

4. Has party line service been developed, and if so, of what classes. Is selective ringing employed?

5. What standard of transmission in terms of No. 19 B. & S. gauge cable with 0.054 or 0.060 mf. per mile, was employed in laying out the distribution, and the toll trunks, for all service in the automatic zone?

Geo. D. Shepardson (by letter): The telephone exchange systems present an interesting case of the gradual displacement of sentient actions by automatic operations which has been going on in most lines of industry. It is common to distinguish between " manual " and " automatic " exchanges according to whether human effort at the exchange is or is not required for performing the various operations of connecting the calling and the called subscribers. As a matter of fact, manually operated systems use more and more automatically operated devices, and automatic systems require more and more manual operation as they become more and more extensive. The exact stage where a given system shall change from automatic to manual operation or vice versa is a question partly of simplicity of design and of certainty of operation, and partly a question of required investment and of dividend-earning capacity.

The first impulse or judgment regarding automatic telephone systems is that they may be suitable for small towns, but that they are inherently outclassed by manual systems when applied to the multifarious demands of large business communities. It is interesting to learn that practically every service has been met successfully by automatic devices, with the single exception of toll service, where partially manual operation is found desirable. Theoretically the automatic system could take care even of such service, and the probable reason for the introduction of manual operators at this stage is doubtless due to financial rather than to purely theoretical or engineering considerations.

The various checks on measured and toll service are of much interest. The feeling that an automatic apparatus is insentient probably adds greatly to the instinctive desire of customers with weak or perverted moral natures to " beat the company." A somewhat similar tone-test on the line of the subscriber reported as calling for a toll connection might save full-manual systems some trouble from tolls erroneously or viciously charged against an innocent subscriber.

The development of the automatic telephone system has proceeded to a stage that compels admiration. Both the electrical and the mechanical features bear evidence of careful forethought and of fruitful experience. A detail that contributed much to the successful operation of switching devices at a considerable distance from the battery, is the minimizing of friction in the selecting switch by having the plunger move to the chosen position before coming into contact with the fingers or jacks.

An equally ingenious feature of the earlier exchanges was the use of one side of the line for selecting the bank or group, while the individual unit was selected over the other wire. In the later development the successful use of the time element in differentiating between the group and the individual, bears evidence of careful design and development. The elimination of the ground connection doubtless removes a source of considerable stray noise and other trouble. But a question arises as to whether trouble is not experienced in requiring the calling subscriber to observe a certain rapidity in making successive settings of the dial, lest too long an interval result in automatically cutting off the connection before it is complete.

The use of primary and secondary line switches for saving time and trunks seems closely analogous to the development of local automatic exchanges for handling business of a district at some distance from the main exchange, such as are being used as auxiliaries to automatic or manual exchanges.

The mention of difficulties arising from the Chinese method of counting, prompts the suggestion that French girls should make good telephone operators on manual boards having twenty jacks in each row. For, if the French think as they speak, they think in twenties rather than in tens. Thus, instead of thinking of 88 as eight tens plus eight, they apparently think of it as four twenties plus eight, for they call it " quatre-vingts huit." The neophyte French operator would automatically look to or reach for the fifth row of jacks instead of for the ninth row as would be more natural for the ordinary girl.

A point of especial interest in the automatic system as presented in this paper is the simplicity of the talking circuit and its freedom from series impedances and objectionable leakages.

Altogether, the system here presented seems to be a triumph of inventive skill, of engineering research and of financial perseverance and courage.

L. M. Antoine (by letter): The paper is limited to a description of the San Francisco plant and does not touch on the advantages to be derived by the system installed there over other systems originally installed.

A point which appealed to me was the small number of switches used, and the flexible arrangements by which these few switches were made to handle the load. The elimination of all superfluous equipment should carry with it many advantages, such as lower first cost, less floor space, reduced maintenance cost and more efficient service due to less chances for trouble. The latter two points are of paramount importance to an operating company, for a lesser amount of equipment will require fewer switchmen to attend it and can be more carefully watched. At the present time first class switchmen are very hard to get and command good salaries. Practice has shown that equipment in constant use is less subject to trouble than that which is only used occasionally, for dust will collect on contacts and moving parts of idle switches, and make their operation sluggish and uncertain.

Another problem which has confronted operating companies, and which seems to be satisfactorily solved in this system is that of giving good measured service. It is not an easy matter to design a meter that will automatically register completed pay calls only and eliminate incomplete and busy calls, calls to free numbers, etc. It has evidently been accomplished and the device and circuits are so simple that its operation should be positive.

One of the strong points of this system is its efficient private branch exchange service. In Portland, Oregon, nearly 25 per cent of the automatic telephones are stations on private systems of some kind. In the standard private branch exchange the trunks and stations terminate in jacks with lamp signals at a small manual switchboard and each station is equipped with an automatic telephone.

Taking down the receiver signals the operator who connects the calling station with a trunk, or another local station asked for. All local calls are completed manually by the operator, but on trunk calls the station does the calling and releasing automatically. This is a great advantage for when the station has been connected to a trunk the calling party can operate as on a main line telephone, and call as many numbers as he desires without attracting the attention of the operator. Until he hangs up his receiver for a period of time longer than that required to release the call the operator gets no supervision. On incoming calls from the central office the rotary connectors select the idle trunks, as described in the paper under discussion. All are two-way trunks. The board is equipped with a calling device enabling the operator to do the calling if desired.

Automatic intercommunicating service has been perfected to such an extent that it is very desirable in private systems of but a few stations. The operation is the same as that of a manual intercommunicating system, except that the calling is done automatically.

Another kind of service that is growing into favor is that of inter-communicating between extension telephones on a main line. A party on one extension wishing to talk with another on the same line calls an eight on his dial which connects his line to a specially designed switch. This switch sends out generator to ring bells on his own line, and also furnishes talking battery. By using different rings for each extension it makes a very satisfactory office system.

A service which is being extensively used is that of a house system in connection with main lines in apartment houses. The main lines are wired in the regular way except that they are multipled into sets at the vestibules, tradesmen's entrance and janitors' quarters. These sets are equipped with push buttons —one for each apartment—with the name of the occupant opposite. When calling any apartment over one of these sets it is merely necessary to press its respective button to ring. On removing the pressure the push button restores itself part way and remains in a talking position until the receiver is hung up, when the button is restored to normal. All 'phones in apartments are so wired that if a push button is depressed before the dial is rotated the bell at the janitor's station is rung and a drop corresponding to the calling telephone energized. If a subscriber wishes to make a trunk call he makes it in the regular way. As soon as the dial is rotated the janitor signal circuit is open.

Toll service is one of the most essential requisites for the success of any telephone system, for the value of a telephone to the subscriber depends as much on the number of subscribers he can reach as on the quality of the service. When toll traffic is as heavy as it is between San Francisco and Oakland, too much attention cannot be given to the development of an efficient and rapid system. With the system installed at San Francisco and Oakland the service should be very rapid, for the suburban operator dials the required number and the checking is done later.

A. B. Smith: Answering Mr. Fowle's questions in order, I will state as follows:

1. Private branch exchanges, which are used in connection with automatic public exchanges, are given the same night service as is customary in an all manual plant. Such telephones as it is desired to connect up for the night are equipped with automatic calling devices. They are thus enabled, when plugged up to trunk lines for the night, to operate the automatic switches in the public exchange just as if each were on an ordinary subscribers line.

2. As indicated above, only such telephones in the private branch exchange are equipped with calling devices, as are expected to be used for direct calling. Owing to the simple nature of the calling device, it is an easy matter to equip any manual telephone in the branch exchange so that it will be able to operate the automatic switches.

3. Unattended, automatic private branch exchanges are in demand and are in use in a number of places.

4. For many years party line service has been given by automatic exchanges. The four frequency harmonic system is employed, using 16-, 33-, 50- and 66-cycle currents to ring the bells. Both two-party and four-party service are in use.

5. Since the matter of transmission standards falls within the field of the constructing engineer, I will leave the discussion of this point to Mr. S. G. McMeen.

Professor Shepardson's remark regarding the time element necessary in two-wire automatic operations, requires a little explanation. When the subscriber takes his receiver from the hook, a circuit is closed through the telephone in exactly the same way as in any ordinary common battery telephone. When the dial is rotated to send in the impulses for any given digit, it merely opens and closes the circuit as many times as there are units in the digit; that is, if the subscriber pulls the dial for the figure 3 the calling device would open and close the circuit three times, and would come to rest with the circuit closed.

If the subscriber so desires, he may wait several minutes between successive settings of the dial without causing any further inconvenience than to delay the completion of his call. The release is initiated by the opening of the line circuit which is done by the hanging of the receiver on the hook.

A paper presented at the 27th Annual Convention of the American Institute of Electrical Engineers, Jefferson, N. H., June 29, 1910.

INTERACTION OF FLYWHEELS AND MOTORS WHEN DRIVING ROLL TRAINS BY INDUCTION MOTORS

BY F. G. GASCHE, M. E.

Recent innovations in the method of driving roll trains by the induction motor as accompanied by a rotor of considerable inertia effect has compelled the study of a dynamical problem of some complexity. The problem is essentially a commercial one in requiring that the mechanism involved shall exhibit the greatest return on the investment. This unavoidably imposes the consideration of the prime mover as well as the motor and equipment immediately attached to the roll train. While a complete statement of the solution of this commercial problem cannot be evolved at this time, it is the purpose of the following analysis to exhibit the manner of disposition of certain important elements.

The examination of the phenomena of motor and flywheel action by analytical processes is proposed in view of the practical impossibility of establishing the important items by the use of recording wattmeters, tachometers, or other instruments. The time intervals are so short that the inertia and other instrument defects introduce large errors even with perfectly constant voltage. Constancy of voltage with any power plant connected with a rolling mill is yet to be observed, so that direct experimental examination of the actions considered herewith is not an inviting prospect.

Roll train resistances, particularly on the heavier types of mills, are so exceedingly variable that no type of prime mover, gas engine, steam engine, or steam turbine, can withstand the sudden applications of load without the risk of troublesome, if not dangerous, speed variation unless one or more flywheels exist in the system of motor drives. In addition to this there is imposed a high cost of conversion and the extra expense due to peak loads in the absence of flywheels.

More than this, if several large systems of roll trains are operated from a central electric power plant, it will be found, sooner or later, that it is structurally and commercially inexpedient to provide a suitable flywheel effect on the prime movers to meet the load variations on the entire system of power transmission. The shocks on the motor shaft driving a roll train are such that safe dimensions are almost forbiddingly large. Without the presence of a flywheel on the motor shaft, this shock, and the accompanying momentary demand for energy, is instantly transferred to the shaft and flywheel of the prime mover.

The motives for the application of a flywheel to a motor-driven roll train can be thus indicated:

a. Providing reservoirs of energy exterior to the power plant, in excess of the structural and commercial possibilities of flywheels on the prime movers, or of storage batteries.

b. Equipment of the roll trains with an independent means of freeing the rolls of the bars, in case the motor becomes suddenly inoperative.

c. Raising the load factor on the power plant.

d. Reduction of size and costs of installation of motors, particularly with variable roll train loads.

With reference to the first item, it may be said that the flywheel performs functions in the way of instantaneous and precisely measured delivery of energy with an efficiency of practically 98 per cent, and with a cost of installation that would make a storage battery the alternative to be avoided.

The second item is a consideration of the first importance to any practical mill man. The repetition of roll changes, involving loss of operative time, and the removal of "cobbles" or defective bars, could easily impose a financial loss that would lead to the condemnation of a given motor drive.

Item *c* is almost beyond discussion, as the approximation of uniformity of demand on the prime mover is an advantage that can be appreciated by all.

Concerning item *d*, it may be urged that the mill operation, known as a roll "pass", is accompanied by characteristies in the nature of expenditure of energy that are not to be found on any other system of electric power transmission. The nature of these resistances will be explained in what follows, but attention is directed to the consideration of an element of first importance, *viz., the time required for the " pass ", as well as the time between " passes ", is established by operative mill conditions.* These time intervals are generally so short that the frequency of automatic change of controlling devices may be considered as very objectionable, if not physically impossible. The deduction from this requirement is that the " secondary resistance " of a motor cannot in general be changed to make available two forms of " slip curves " during the time required by a pass. The " torque-slip " relations having prevailed up to the instant the bar enters the rolls, these relations must continue in most cases until the " pass " has been completed. Since a certain amount of " slip " is necessary in order to realize a torque incident to the resistance of a roll train, it remains to determine how this " slip " shall be distributed over the time required for the " pass ", or a portion thereof. On first sight it would seem possible to employ the minimum of slip and use a motor exerting a torque equal to the roll train resistance when working at its most economical load. An alternative would be to use a motor of lower rated capacity, operating on a greater amount of " slip " in coming to full torque, and supplement the tardy response of the motor by the action of a suitable flywheel. If this alternative does no violence to the efficiency of power transmission, it at least favors a lower cost of installation. On certain types of small mills the first method of driving may serve a purpose with a slightly higher electrical efficiency, without the palpable exhibit of a flywheel, but the inertia effect of the rotor itself will generally in such cases be a considerable item to the advantage of the construction.

It will be shown in what follows that, *on the assumption* of perfectly rigid roll train connections and a rotor without any inertia effect (if such were possible),. the induction motor is physically incapable of assuming any roll train load above the friction load that by some means may have been imposed on the motor. On the larger sizes of roll trains the shock imposed on the rolls and connections, due to the action of a powerful motor of small slip,. will prove such a destructive agent that the experience will be at least a costly one. The nature of shock arising at the motor shaft can be understood from the following study of the characteristics of a roll pass. (See Fig. 1.) As the bar strikes the rolls at *a* preparatory to entering the groove, there is an increasing resistance to the driving mechanism until the forward extremity reaches *b*, the smallest section of the groove. The resistance at this point *b* becomes a tangential effort at the roll surface remaining constant until the rear end of the bar reaches the point *a* at the rolls, when it diminishes to zero as the rear end of the bar reaches the point *b*. In addition to this resistance there is a constant resistance, due to the light running of the roll train, which must be added to the above in referring the energy requirements to the motor shaft.

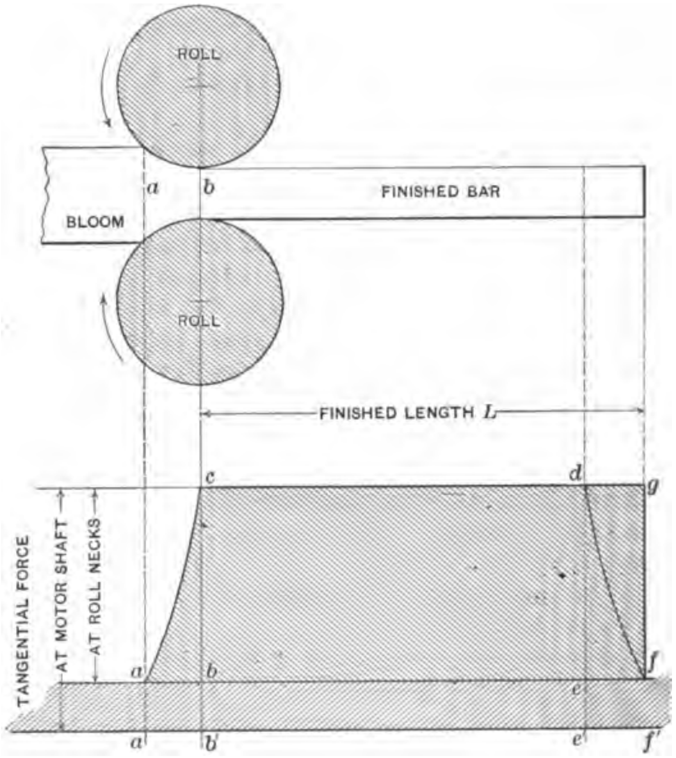
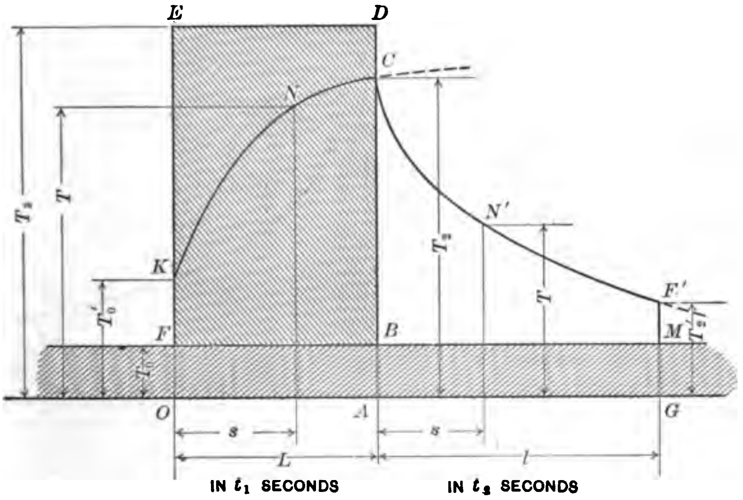


FIG. 1—Energy diagram for a roll pass

The operation of a roll pass may be represented by a diagram of energy *a' a c d f f'*. The "approach load" *a' a c b'* is due to causes above explained, as is also the "terminal load" *e' d f f'*.

In some of the larger mills the portions *a b* and *e f* may be a large percentage of the total distance *a f* for the pass. In many problems of design it is sufficient to consider the diagram of neergy for a pass as the rectangle *b' c g f'*, thus assuming the instantaneous rise of roll train resistance to the full value T_3. For other cases, and particularly for tapered ingots, the " approach load " $a'\ a\ c\ b'$ must be investigated as a special problem. As the necessity for this will seldom arise, the complete solution will not be introduced at this time.

It may occur at this part of the treatment of the subject that an item of leading importance must be assumed or defined before analysis of the complicated phenomena can be undertaken. This item is the tangential force due to the roll pass, which can be obtained in two ways. First, by direct experiment on existing roll trains. Second, by calculation through the use of suitable formulæ and physical constants. Assuming that by some means a definite knowledge of the energy diagram for a given " pass " is available, the considerations governing the proportions of flywheels and motors may be developed from the dynamics of the problem. Energy diagrams for mill operations may be divided into two distinct classes, illustrated by Figs. 2 and 3. The former may characterize all isolated roll trains having individual motors, in which equipment there is no possibility of a simultaneous operation in two or more grooves.

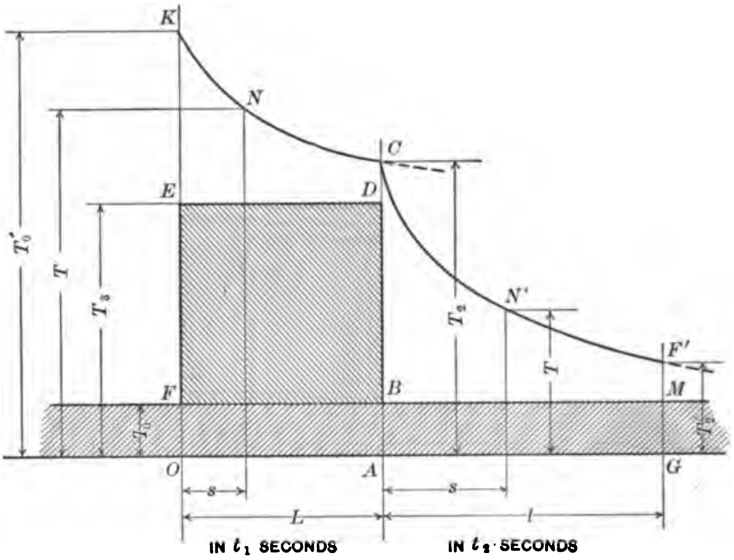


TYPE I—Tangential force at the motor shaft at the instant of full entry of bar into the pass is *less* than the tangential force due to the roll train resistance, *i.e.*, $T_0' < T_3$

FIG. 2—Elementary load. Rigid roll connection.

The roll "passes", so far as time of action is concerned, are completely isolated.

The latter (Fig. 3) may develop in systems of rolls driven from a lay shaft and gearing such that the simultaneous action on two or more "passes" is a possibility. This action results in certain "combination loads". The principal distinction between these energy diagrams consists of the following: The initial tangential force T_0' in Type I is less than T_s, due to the roll train, and generally greater than T_0, due to friction load. The force



TYPE II—Tangential force at the motor shaft at the instant of full entry of bar is *greater* than the tangential force due to the roll train resistance, *i.e.*, $T_0' > T_s$

FIG. 3—Elementary load. Rigid roll connections.

T_0' for Type II is greater than T_s by virtue of the previous history of the motor action, and is invariably the result of combination loads of a certain class. Equations (1) to (36), inclusive, exhibit the dynamical relations for these elementary loads.

CYCLICAL OPERATION OF ROLL TRAINS

With all the apparent variations of load conditions in a given mill, there is for the same class of steel product a well defined cycle of operations into which the mill equipment and its operatives gravitate. The determination of the elements of this cycle, including forces in action, time intervals, etc., is capable of precision within the limits of error of the primary data, by means of equations **(1)** to **(36)** and the particularly important value of the force $_nT'_2$ at the end of the last time interval for a mill cycle. The derivation of the numerical value of this force from the elements of the various loads composing the cycle is shown in equations **(37)** to **(43)** inclusive.

It is seen that all the formulæ are dominated by a particularly important constant A, which embodies all that is characteristic of both motor and wheel, so far as the dynamics of the problem of roll driving are concerned. Its value must be determined with some degree of accuracy, since gross errors will vitiate all of the subsequent calculations.

As an independent check on the numerical value of A the diagram (Fig. 4) has been prepared with explanatory notes, such as to favor a rapid estimate through the use of a straight edge set in two consecutive positions. The positions of the straight edge conform to the fundamental items τ, Δ_τ, v_s, and $M K^2$.

These are constant for any given combination of motor and wheel, irrespective of the nature of mill loads to which they may be subject.

ANALYSIS OF ELEMENTARY LOADS SHOWN AS TYPE I AND TYPE II, ASSUMING RIGID ROLL CONNECTIONS

The energy diagram (Figs. 2 and 3) for the pass is area $O\ A\ D\ E$ of which $O\ A\ B\ F$ is the portion representing the friction load due to light running of the mill. The tangential force T due to motor, never goes below T_0 corresponding to the above friction load.

Area $K\ N\ C\ D\ E$	represents energy from the wheel for Type I load and to the wheel for Type II load.
Area $O\ F\ K\ N\ C\ A$	represents energy from the motor.
Area $B\ C\ N'\ F'\ M$	represents energy from the motor to the wheel during the interval between passes.
Area $A\ B\ M\ G$	represents energy due to friction load during the interval between passes.

Notation. All forces, velocities, lengths, and times are supposed to be reduced to the action at the extremity of the radius of one foot at the motor shaft.

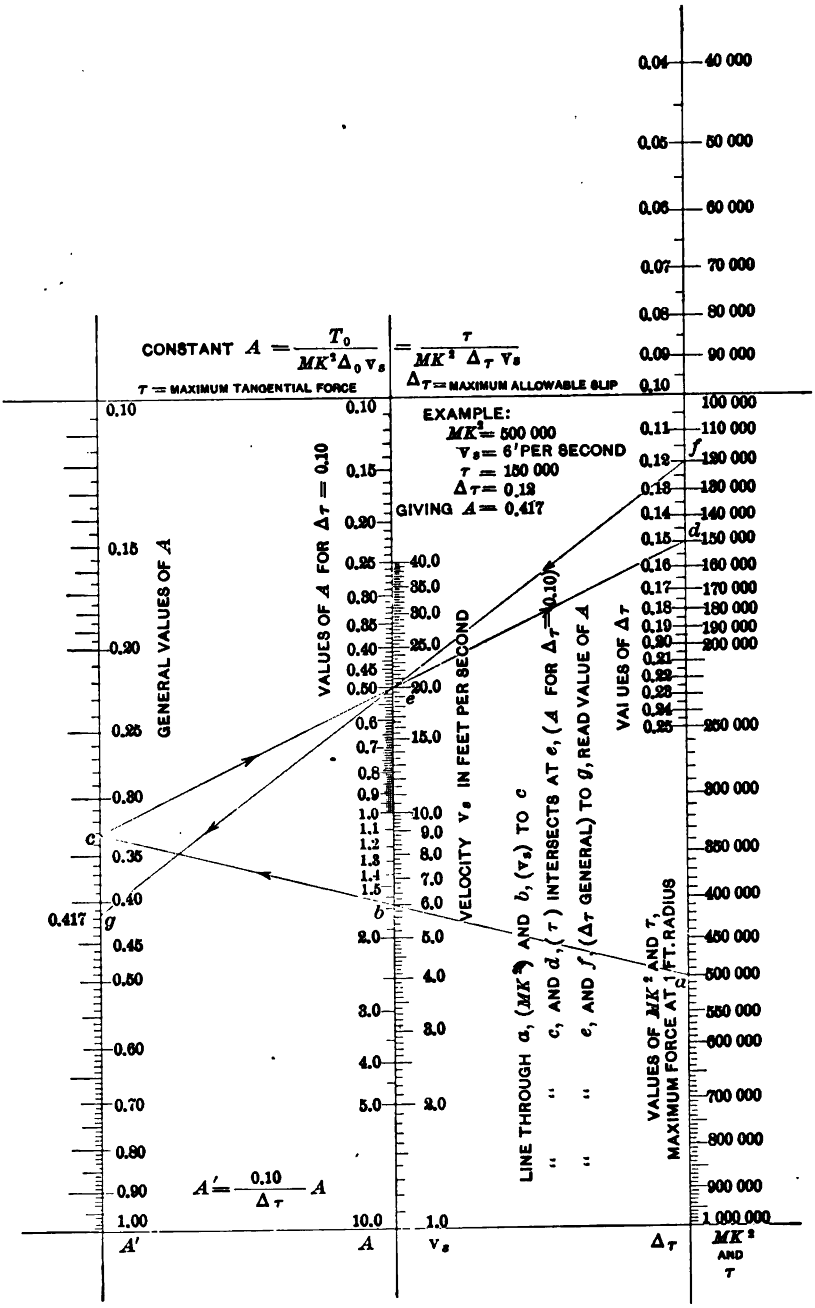


Fig. 4—Diagram for calculating constant *A*

K = Ratio of radius of gyration to unity for the wheel and rotating part of the motor combined.
M = Combined mass of the wheel and rotor.
L = Length of feet corresponding to the pass.
l = Length in feet corresponding to the interval.
t_1 = Time in seconds to complete the pass.
t_2 = Time in seconds to cover the interval.
v_s = Velocity corresponding to synchronous speed, ft. per sec.
v_0 = Velocity at friction load, ft. per sec.
v_2 = Velocity at the end of the pass, ft. per sec.
v_0' = Velocity corresponding to the initial force T_0'.
v = Velocity at any intermediate distance s and time t.
T = Tangential force at any instant t and distance s, pounds
T_0 = Tangential force corresponding to friction load, pounds.
T_0' = Tangential force at start of the pass, pounds.
T_2 = Tangential force at end of the pass, pounds.
T_2 = Tangential force at beginning of the interval, pounds.
T_2' = Tangential force at end of the interval, pounds.
T_3 = Tangential force due to the roll train resistance, pounds.

Type I. Relations for the Pass. From the general assumption that the decrease of velocity of the rotor, *i.e.*, the "slip" is proportional to the tangential force at unit radius, we have

$$T : T_0 :: v_s - v : v_s - v_0$$

or

$$T = \frac{T_0}{v_s - v_0} \left(v_s - \frac{d\,s}{d\,t} \right) \qquad \text{(1)}$$

from this

$$\frac{d\,T}{d\,t} = - \frac{T_0}{v_s - v_0} \cdot \frac{d^2 s}{d\,t^2} \qquad \text{(2)}$$

The force acting on the roll train, due to the change of speed of the fly-wheel, acts in the same direction as the effort of the motor T and has a value $- M K^2 \frac{d^2 s}{d\,t^2}$ whence,

$$T - M K^2 \frac{d^2 s}{d\,t^2} = T_3 \qquad \text{(3)}$$

observing the value in (2) we obtain,

$$\frac{d\,T}{d\,t}+\frac{T_0}{M\,K^2\,(v_s-v_0)}\cdot T=\frac{T_0}{M\,K^2\,(v_s-v_0)}\cdot T_3 \quad \ldots (4)$$

which will be written,

$$\frac{d\,T}{d\,t}+A\,T=A\,T_3 \quad \ldots\ldots\ldots\ldots\ldots (5)$$

The integrating factor of this is ε^{At}, leading to,

$$T=T_3+c\cdot\varepsilon^{-At} \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

when $t=0$, then $T=T_0'$ and $c=T_0'-T_3$..............(7)

i.e.

$$t=\frac{1}{A}\log_e\left(\frac{T_3-T_0'}{T_3-T}\right) \quad \ldots\ldots\ldots\ldots\ldots (8)$$

The time for the pass is therefore,

$$t_1=\frac{1}{A}\log_e\left(\frac{T_3-T_0'}{T_3-T_2}\right)\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

which becomes infinite for $T_2=T_3$.

In practical applications it is frequently convenient to employ the approximate value

$$t_1=\frac{L}{v_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

Returning to (1) and (3) we have,

$$-M\,K^2\frac{d^2\,s}{d\,t^2}+\frac{T_0}{v_s-v_0}\left(v_s-\frac{d\,s}{d\,t}\right)=T_3 \quad \ldots (11)$$

or

$$\frac{d^2\,s}{d\,t^2}+A\,\frac{d\,s}{d\,t}=A\,v_s-\frac{T_3}{M\,K^2} \quad \ldots\ldots\ldots (12)$$

$$=A\left[v_s-\frac{T_3}{T_0}(v_s-v_0)\right]$$

Considering $\frac{ds}{dt}$ as the variable we have,

$$\frac{ds}{dt} = v_s - \frac{T_3}{T_0}(v_s - v_0) + c_1 \cdot \varepsilon^{-At} \quad \ldots\ldots\ldots (13)$$

when $t = 0$, then $\frac{ds}{dt} = v_0' = v_s - \frac{T_0'}{T_0}(v_s - v_0)$

and

$$c_1 = (v_s - v_0)\frac{T_3 - T_0'}{T_0} \quad \ldots\ldots\ldots\ldots\ldots (14)$$

$$\therefore \frac{ds}{dt} = v_s - \frac{T_3}{T_0}(v_s - v_0) + (v_s - v_0)\frac{T_3 - T_0'}{T_0} \cdot \varepsilon^{-At} \quad (15)$$

also

$$s = \left[v_s - \frac{T_3}{T_0}(v_s - v_0)\right] t - (v_s - v_0)\frac{T_3 - T_0'}{A \,.\, T_0} \cdot \varepsilon^{-At} + c_2 \quad (16)$$

when $t = 0$, then $s = 0$, and $c_2 = (v_s - v_0) . \frac{T_3 - T_0'}{A\,T_0}$ .... (17)

Finally:

$$s = \left[v_s - \frac{T_3}{T_0}(v_s - v_0)\right] \cdot t + (v_s - v_0)(1 - \varepsilon^{-At}) \cdot \frac{T_3 - T_0'}{A\,T_0} \quad (18)$$

Substituting the value of t from (8) in equation (18)

$$s = \frac{1}{A}\left\{\left[v_s - \frac{T_3}{T_0}(v_s - v_0)\right]\log_e\left(\frac{T_3 - T_0'}{T_3 - T}\right) + (v_s - v_0)\frac{T - T_0'}{T_0}\right\} \quad (19)$$

Length of pass

$$L = \frac{1}{A}\left\{\left[v_s - \frac{T_3}{T_0}(v_s - v_0)\right]\log_e\left(\frac{T_3 - T_0'}{T_3 - T_2}\right) + (v_s - v_0)\frac{T_2 - T_0'}{T_0}\right\} \quad (20)$$

Types I and II. Relations for the Interval Between Passes. At the point N' with A as origin,

$$T - T_0 - M K^2 \frac{d^2 s}{d t^2} = 0 \quad \ldots\ldots\ldots\ldots\ldots (21)$$

Substituting the value of $\frac{d^2 s}{d t^2}$ from (2)

$$\frac{d T}{d t} + A T = A T_0 \quad \ldots\ldots\ldots\ldots\ldots\ldots (22)$$

leading to,

$$t = \frac{1}{A} \log_\epsilon \left(\frac{T_2 - T_0}{T - T_0}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots (23)$$

and

$$t_2 = \frac{1}{A} \log_\epsilon \left(\frac{T_2 - T_0}{T_2' - T_0}\right) \quad (24)$$

Also from (1) and (21)

$$\frac{d^2 s}{d t^2} + A \frac{d s}{d t} = A v_0 \quad (25)$$

leading to,

$$\frac{d s}{d t} = v_0 - (v_s - v_0) \left(\frac{T_2 - T_0}{T_0}\right) \cdot \epsilon^{-At} \quad \ldots\ldots\ldots (26)$$

$$s = v_0 t + \left(\frac{v_s - v_0}{A}\right) \left(\frac{T_2 - T_0}{T_0}\right) (\epsilon^{-At} - 1) \quad \ldots\ldots (27)$$

Substituting the value of t from (23)

$$s = \frac{1}{A} \left\{ v_0 \log_\epsilon \left(\frac{T_2 - T_0}{T - T_0}\right) - \frac{T_2 - T}{T_0} (v_s - v_0) \right\} \quad \ldots (28)$$

For particular values

$$l = \frac{1}{A}\left\{ v_0 \log_\epsilon \left(\frac{T_2 - T_0}{T_2' - T_2}\right) - (v_s - v_0)\, \frac{T_2 - T_2'}{T_0} \right\} \quad \ldots\ldots(29)$$

Type II. Relations for the Pass. The force acting on the fly-wheel is the excess of effort of the motor T above the resistance of the roll train T_3 and has a value $+ M\, K^2 \frac{d^2 s}{d\, t^2}$ whence,

$$T - T_3 - M\, K^2 \frac{d^2 s}{d\, t^2} = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots(30)$$

The differential equations derivable from (1), (2) and (30) are identical in form with (22) and (25), subject to the same treatment in integration; thus $T_0' > T_3$ we have

$$t = \frac{1}{A} \log_\epsilon \left(\frac{T_0' - T_3}{T - T_3}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots(31)$$

$$t_1 = \frac{1}{A} \log_\epsilon \left(\frac{T_0' - T_3}{T_2 - T_3}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots(32)$$

Similarly:

$$\frac{d\, s}{d\, t} = v_s - \frac{T_3}{T_0} (v_s - v_0) - (v_s - v_0)\, \frac{T_0' - T_3}{T_0} \cdot \epsilon^{-At} \qquad (33)$$

and

$$s = \left[v_s - \frac{T_3}{T_0} (v_s - v_0) \right] \cdot t + (v_s - v_0)\, (\epsilon^{-At} - 1) \left(\frac{T_0' - T_3}{A\, T_0}\right) \qquad (34)$$

$$= \frac{1}{A} \left\{ \left[v_s - \frac{T_3}{T_0} (v_s - v_0) \right] \log_\epsilon \left(\frac{T_0' - T_3}{T - T_3}\right) - (v_s - v_0) \frac{T_0' - T}{T_0} \right\} \qquad (35)$$

also

$$L = \frac{1}{A} \left\{ \left[v_s - \frac{T_3}{T_0} (v_s - v_0) \right] \log_\epsilon \left(\frac{T_0' - T_3}{T_2' - T_3}\right) - (v_s - v_0)\, \frac{T_0' - T_2}{T_0} \right\} \qquad (36)$$

RELATION BETWEEN THE FORCES AND TIME INTERVALS FOR A MILL CYCLE—CYCLICAL ACTION

$$\text{from (9)} \quad T_2 = T_0' \cdot \varepsilon^{-At_1} + T_3\,(1 - \varepsilon^{-At_1}) \quad \ldots\ldots(37)$$

$$\text{from (24)} \quad T_2' = T_0'\,(1 - \varepsilon^{-At_2}) + T_2 \cdot \varepsilon^{-At_2} \quad \ldots\ldots\ldots(38)$$

$$= T_0\,(1 - \varepsilon^{-At_2}) + T_3\,(1 - \varepsilon^{-At_1})\,\varepsilon^{-At_2} + T_0'\,\varepsilon^{-A(t_1+t_2)} \quad (39)$$

This may be transformed into

$$T_2' \cdot \varepsilon^{A(t_1+t_2)} = T_0\,(\varepsilon^{At_2} - 1)\,\varepsilon^{At_1} + T_3\,(\varepsilon^{At_1} - 1) + T_0' \quad (40)$$

For clearness of notation let

$a = A\,t_1$ and $b = A\,t_2$ using a_1, a_2, etc., for the several passes, and b_1, b_2, . . . b_n for the successive intervals.

Then, for the several passes,

$$\left.\begin{aligned}
{}_1T_2' \cdot \varepsilon^{a_1+b_1} &= T_0\,(\varepsilon^{b_1} - 1)\,\varepsilon^{a_1} + {}_1T_3\,(\varepsilon^{a_1} - 1) + {}_1T_0' \\
{}_2T_2' \cdot \varepsilon^{a_2+b_2} &= T_0\,(\varepsilon^{b_2} - 1)\,\varepsilon^{a_2} + {}_2T_3\,(\varepsilon^{a_2} - 1) + {}_2T_0' \\
{}_3T_2' \cdot \varepsilon^{a_3+b_3} &= T_0\,(\varepsilon^{b_3} - 1)\,\varepsilon^{a_3} + {}_3T_3\,(\varepsilon^{a_3} - 1) + {}_3T_0' \\
\ldots\ldots\ldots &= \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\
{}_{n-1}T_2' \cdot \varepsilon^{a_{n-1}+b_{n-1}} &= T_0(\varepsilon^{b_{n-1}} - 1)\varepsilon^{a_{n-1}} + {}_{n-1}T_3(\varepsilon^{a_{n-1}} - 1) + {}_{n-1}T_0' \\
{}_nT_2' \cdot \varepsilon^{a_n+b_n} &= T_0\,(\varepsilon^{b_n} - 1)\,\varepsilon^{a_n} + {}_nT_3\,(\varepsilon^{a_n} - 1) + {}_nT_0'
\end{aligned}\right\} \quad (41)$$

Bearing in mind that ${}_{n-1}T_2' = {}_nT_0'$ and finally ${}_nT_2' = {}_1T_0'$ for cyclical operation we have

$$\left.\begin{aligned}
{}_nT_2' &= \{T_0\,(\varepsilon^{b_n} - 1)\,\varepsilon^{a_n} + {}_nT_3\,(\varepsilon^{a_n} - 1)\} \cdot \varepsilon^{-(a_n+b_n)} \\
&+ \{T_0(\varepsilon^{b_{n-1}} - 1)\varepsilon^{a_{n-1}} + {}_{n-1}T_3(\varepsilon^{a_{n-1}} - 1)\} \cdot \varepsilon^{-(a_n+a_{n-1}+b_n+b_{n-1})} \\
&+ \{T_0(\varepsilon^{b_{n-2}}-1)\varepsilon^{a_{n-2}} + {}_{n-2}T_3(\varepsilon^{a_{n-2}}-1)\} \cdot \varepsilon^{-(a_n+a_{n-1}+a_{n-2}+b_n+b_{n-1}+b_{n-2})} \\
&+ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\
&+ \{T_0(\varepsilon^{b_3}-1)\varepsilon^{a_3} + {}_3T_3(\varepsilon^{a_3} - 1)\} \cdot \varepsilon^{-(a_n+a_{n-1}\ldots+a_3+b_n+b_{n-1}+\ldots b_3)} \\
&+ \{T_0(\varepsilon^{b_2} - 1)\varepsilon^{a_2} + {}_2T_3\,(\varepsilon^{a_2} - 1)\} \cdot \varepsilon^{-(\sum_2^n a + \sum_2^n b)} \\
&+ \{T_0(\varepsilon^{b_1} - 1)\varepsilon^{a_1} + {}_1T_3(\varepsilon^{a_1} - 1)\} \cdot \varepsilon^{-(\sum_1^n a + \sum_1^n b)} \\
&+ {}_1T_0 \cdot \varepsilon^{-(\sum_1^n a + \sum_1^n b)}
\end{aligned}\right\} \quad (42)$$

Multiplying each side by $\varepsilon^{(\sum_1^n a+\sum_1^n b)}$ and transposing ${}_1T_0'={}_nT_2'$ we have

$$
\begin{aligned}
{}_nT_2'\left(\varepsilon^{(\sum_1^n a+\sum_1^n b)}-1\right) = \\
&\left\{T_0(\varepsilon^{b_n}-1)\cdot\varepsilon^{a_n}+{}_nT_3\,(\varepsilon^{a_n}-1)\right\}\cdot\varepsilon^{(\sum_1^{n-1}a+\sum_1^{n-1}b)}\\
&+\left\{T_0(\varepsilon^{b_{n-1}}-1)\cdot\varepsilon^{a_{n-1}}+{}_{n-1}T_3(\varepsilon^{a_{n-1}}-1)\right\}\cdot\varepsilon^{(\sum_1^{n-2}a+\sum_1^{n-2}b)}\\
&+\left\{T_0(\varepsilon^{b_{n-2}}-1)\cdot\varepsilon^{a_{n-2}}+{}_{n-2}T_3(\varepsilon^{a_{n-2}}-1)\right\}\cdot\varepsilon^{(\sum_1^{n-3}a+\sum_1^{n-3}b)}\\
&+\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\\
&+\left\{T_0(\varepsilon^{b_3}-1)\cdot\varepsilon^{a_3}+{}_3T_3\,(\varepsilon^{a_3}-1)\right\}\cdot\varepsilon^{(a_1+a_2+b_1+b_2)}\\
&+\left\{T_0\,(\varepsilon^{b_2}-1)\cdot\varepsilon^{a_2}+{}_2T_3\,(\varepsilon^{a_2}-1)\right\}\cdot\varepsilon^{a_1+b_1}\\
&+\left\{T_0\,(\varepsilon^{b_1}-1)\,\varepsilon^{a_1}+{}_1T_3\,(\varepsilon^{a_1}-1)\right\}
\end{aligned}
\qquad (43)
$$

The above equations (**40**) to (**43**) inclusive, are general for type loads (I) and (II) with any value of the time intervals including t_2 (equation **24**) equal to zero. They, consequently, form the basis of calculating the starting force T_0' for the first pass in a mill cycle; even for combination loads.

Suppose $\varepsilon^a = 10^{\cdot\alpha}$ Then $a \log_{10}\varepsilon = \alpha$

But

$$\log_{10}\varepsilon = 0.4343$$

$$\therefore\ 0.4343\,a = \alpha$$

and we may write

$$\varepsilon^a = 10^{\cdot\alpha} = 10^{\cdot 0\cdot 4343a}$$

Hence, if we multiply each of the above exponents by 0.4343 and replace $\varepsilon = 2.71828$ by 10 we may employ the ordinary system of logarithms in the above calculations. This process may be completed once for all if we say,

$$a = 0.4343\,A\,t_1$$

$$b = 0.4343\,A\,t_2$$

Thus leading to the following system of equations for calculating ${}_nT_2'$ *viz.*,

$${}_nT_2'\left(10^{(\sum_1^n a+\sum_1^n b)}-1\right) =$$

$$\left.\begin{array}{l}
\{T_0\,(10^{\cdot b_n}-1)\cdot 10^{\cdot a_n}+{}_nT_3\,(10^{\cdot a_n}-1)\}\cdot 10^{\cdot(\sum_1^{n-1} a+\sum_1^{n-1} b)} \\
+\{T_0(10^{\cdot b_{n-1}}-1)\cdot 10^{\cdot a_{n-1}}+{}_{n-1}T_3\,(10^{\cdot a_{n-1}}-1)\}\cdot 10^{\cdot(\sum_1^{n-2} a+\sum_1^{n-2} b)} \\
+\{T_0(10^{\cdot b_{n-2}}-1)10^{\cdot a_{n-2}}+{}_{n-2}T_3\,(10^{\cdot a_{n-2}}-1)\}\cdot 10^{\cdot(\sum_1^{n-3} a+\sum_1^{n-3} b)} \\
+\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\
\{T_0\,(10^{\cdot b_3}-1)\;10^{\cdot a_3}+{}_3T_3\,(10^{\cdot a_3}-1)\}\cdot 10^{\cdot(a_1+a_2+b_1+b_2)} \\
\{T_0\,(10^{\cdot b_2}-1)\cdot 10^{\cdot a_2}+{}_2T_3\,(10^{\cdot a_2}-1)\}\cdot 10^{\cdot(a_1+b_1)} \\
\{T_0\,(10^{\cdot b_1}-1)\cdot 10^{\cdot a_1}+{}_1T_3\,(10^{\cdot a_1}-1)\}
\end{array}\right\}\quad(44)$$

The influence of the exponential terms is such that it is usually unnecessary to employ more than the first three or four terms in the series for the calculation of the starting force (${}_nT_2' = {}_1T_0'$).

ENERGY FROM THE MOTOR

From (1)

$$ds = \left(v_s - \frac{T}{T_0}(v_s - v_0)\right)dt \quad\ldots\ldots\ldots\ldots(1a)$$

from (5) or (8)

$$dt = \frac{1}{A}\cdot\frac{dt}{T_3 - T} \quad\ldots\ldots\ldots\ldots\ldots(45)$$

from (22) or (23)

$$dt = \frac{1}{A}\cdot\frac{dT}{T_0 - T} \quad\ldots\ldots\ldots\ldots\ldots(46)$$

from (1a) and 45

$$ds = \frac{1}{A}\left[v_s - \frac{T}{T_0}(v_s - v_0)\right]\cdot\frac{dT}{T_3 - T} \quad\ldots\ldots\ldots(47)$$

The energy from the motor during the pass in foot pounds is,

$$\int_0^L T\,ds = \frac{1}{A}\int_{T_0'}^{T_2}\left[v_s - \frac{T}{T_0}(v_s - v_0)\right]\frac{T\,dT}{T_3 - T} \quad\ldots\ldots(48)$$

$$= \frac{1}{A}\left\{\left[(v_s - v_0)\frac{T_3}{T_0} - v_s\right]\left[T_2 - T_0' + T_3\log_e\frac{T_3 - T_2}{T_3 - T_2}\right] + (v_s - v_0)\frac{T_2^2 - (T_0')^2}{2\,T_0}\right\} \quad\ldots\ldots\ldots(49)$$

Substituting the value of L from (20)

$$\int_0^L T\,d\,s = T_3\,L - \frac{1}{A}\,(T_2 - T_0')\left[v_s - \frac{T_2+T_0'}{2\,T_0}\,(v_s - v_0)\right] \quad (50)$$

Similarly, from (1a), (46) and (29) we obtain:
The energy from the motor during the interval in foot pounds

$$\int_0^l T\,d\,s = T_0\,l + \frac{1}{A}\,(T_2 - T_2')\left[v_s - \frac{T_2+T_2'}{2\,T_0}\,(v_s - v_0)\right] \quad (51)$$

In view of the following statements equations (54) and (55) we may say:

$$\int_0^L T\,d\,s = T_3\,L - \frac{M\,K^2}{\tau}\,\Delta_\tau\,v_s^2\,(T_2 - T_0')\left[1 - \frac{T_2+T_0'}{2\,\tau}\Delta_\tau\right] \quad (50a)$$

$$\int_0^l T\,d\,s = T_0\,l + \frac{M\,K^2}{\tau}\,\Delta_\tau\,v_s^2\,(T_2 - T_2')\left[1 - \frac{T_2+T_2'}{2\,\tau}\Delta_\tau\right] \quad (51a)$$

$$\int_0^L Tds + \int_0^l Tds = T_3\,L + T_0\,l + \frac{M\,K^2}{\tau}\,\Delta_\tau v_s^2\,(T_0' - T_2')$$

$$\left[1 - \frac{T_0'+T_2'}{2\,\tau}\,\Delta_\tau\right] \quad (51b)$$

NOTE ON THE VALUE OF THE CONSTANT A

$$A = \frac{T_0}{MK^2(v_s - v_0)} = \frac{T_0\,\frac{v_s+v_0}{2}}{\frac{1}{2}M(K^2v_s^2 - K^2v_0^2)} = \frac{1}{\theta} \quad \ldots\ldots (52)$$

where θ is a time in seconds.
Thus: θ is time required for the force T_0 acting with a mean velocity $\frac{v_s+v_0}{2}$ to deliver the energy corresponding to that absorbed by the wheel when the velocity v_0 is increased to v_s, *i.e.*,

$$\frac{1}{2}\,M\left[K^2\,v_s^2 - K^2\,v_0^2\right] = T_0\,\theta\,\frac{v_s+v_0}{2} \quad \ldots\ldots\ldots (53)$$

Assuming that the nature of roll train loads gives evidence of the maximum tangential force τ which will be imposed on the motor, and that the corresponding velocity is v_τ, then equation (**1**) gives

$$\tau : T_0 :: v_s - v_\tau : v_s - v_0$$

i.e.,

$$v_s - v_0 = \frac{T_0}{\tau}(v_s - v_\tau) = \frac{T_0}{\tau} \triangle_\tau v_s \qquad \textbf{(54)}$$

where $\triangle_\tau$ is the maximum allowable slip in per cent of synchronous speed corresponding to the maximum force τ whence from (**52**) and (**54**)

$$A = \frac{\tau}{M K^2 \triangle_\tau v_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots \textbf{(55)}$$

While the commercially advisable slip for a given equipment of power plant motors and transmission lines is always a local problem, it seems to be the evidence of recent large installations that $\triangle_\tau$ lies in value between 0.08 and 0.12 and may be accepted in preliminary designs at $\triangle_\tau = 0.10$ whence

$$A = \frac{10\,\tau}{M K^2 v_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots \textbf{(56)}$$

DISCUSSION ON "INTERACTION OF FLYWHEELS AND MOTORS WHEN DRIVING ROLL TRAINS BY INDUCTION MOTORS." JEFFERSON N. H., JUNE 29, 1910.

C. P. Steinmetz: This paper of Mr. Gasche I consider a very valuable and important addition to the records of our Institute dealing as it does with an extremely important problem of motor application, an application, indeed, which I believe represents the most severe service to which electric motors have ever been applied.

When we speak of intermittent load or fluctuating load, usually we immediately think of railway loads. We realize that the load mathematically discussed in this paper, the roll train, is a load in which the fluctuation is vastly more rapid and more violent than in any railway train. I understand that under certain conditions the change from friction load to maximum load, and return to friction load, occurs within less than one revolution of the driving motor. The system which is dealt with in the paper is a system of a power consuming device, the roll train, in which power is consumed at a very fluctuating rate, but with fluctuations which are fairly definite in their nature, a power supply at a rate by which speed and power are related to each other in the well known manner of the induction motor, and the energy storing device, the flywheel. Here we have changes in the condition of the system at such a rate that never during the operation do the conditions, in regard to speed and torque of the motor become constant, that is, the phenomenon with which we have to deal here is not that of stationary operation but is a transient operation, and again here we are in the field of transient phenomena, and if we look at the equations we will recognize immediately the transient function as characterizing the inter-relation of phenomena. Now, transients have one characteristic, that is, the relation of the elements to the system are not determined by their constants alone, but are also determined and dependent on the conditions of the system at the starting moment and at the end of the transition, that is, the so-called terminal conditions enter into the function mathematically as integration constants.

Now, we have two different forms into which the terminal conditions enter, either as independent and fixed conditions, or as relations connecting the conditions of the system, at the starting moment and at the finishing moment of the cycle. For instance, if an electrical circuit is changed by a switch, you have given the previous condition and you have given the final condition, between these two the transient completes its course. A second case is where the terminal condition is related to the starting condition, usually identical therewith, that means where the transient condition recurs as recurrent transient phenomenon. Recurrent transients, as you know are used in the electrical industry to a large extent for circuit control—in the circuit control which cuts resistance in and out of the motor field periodically. Such recurrent transients are the arcing grounds which we have on our transmission lines, etc.

The recurrent transient which Mr. Gasche treats of so interestingly in this paper is a very much more complex one. The cycle completes, not after two or three steps, as we usually find, but after a very great number of steps, during the passing of the roll train, each being characterized by a rapid change, from friction load to maximum load and back to friction load, next passing from friction load to maximum load, possibly smaller or longer duration than the previous one, back again to friction load, and so on, until finally the cycle closes itself by the last terminal condition coinciding with the first starting point.

This is extremely interesting, and as we all realize, it is a very important problem which is here dealt with. Interesting and important also the subject is, as pointed out by Mr. Gasche in his opening remarks, in another respect—by the nature of the load. The loads here consist of the action of forces within that range from which scientists and theoretical investigators usually keep carefully away, while industrially it is the range of greatest importance, that is, the range beyond the elastic limit, where the action of the forces has become irreversible. We have already spent some time at this convention in studying the range of electric forces at those voltages where the action has become irreversible, where we are beyond the elastic limit of the action of electric field.

Here you have the condition before you when you deal with mechanical forces acting beyond the elastic limit.

We cannot expect too much at once, but I hope you will join with me in expressing the wish that Mr. Gasche may find it possible very soon to complete this valuable information by giving us what is referred to, how to calculate that maximum load by the use of suitable formula and physical constants. It is a field which is of extreme importance, not only in the range of mechanical forces, but also in the range of electrical forces, and all other forces, because here we get information on the nature of the forces, where you are beyond the elastic limit. and it is in this field which is being opened up at present, and up to the door of which the present paper leads and, as we hope, the next paper of Mr. Gasche will lead us beyond the door into the field of that development.

Charles F. Scott: We are always interested to see electricity do big things and new things—our interest in connection with the steel mill has been to see the motor take the place of the engine, the engine which has been capable of quick reversing and handling enormous instantaneous loads. The thing which struck me particularly, as Mr. Gasche was giving the introduction to his paper, and indicating some of the conditions which he has to meet, were the features which lead away from what has been done before—he was not simply replacing the engine, which used to do something ponderous and impressive, but he was going into an entirely different field and doing something which had not been done before, and something which could not be done before.

The little electric motor which only a dozen years ago was an average street railway motor of 25 or 50 h.p., doing some auxiliary features about the mill and was looked on as a kind of toy, entirely insignificant compared with the main operations of the mill—that little motor has grown until it has become the central feature of the steel industry. Take the power plant—that has changed, we have a new kind of prime mover, one which is not at all adapted to steel mill work, a gas engine, which is a great big, slow moving, constant running, non-overload machine, just the kind of thing that is not fitted for the intermittent speed and power requirements of steel mills.

Going to the other extreme, the requirements in the way of rolls and performance are, as Mr. Gasche points out, simply enormous in the operations of a steel mill; they have never been met before, and in between this otherwise helpless, big, gas engine and these tremendous requirements in the rolls, comes the electric system with the motor, and with one of the simplest kinds of motors, the induction motor. The alternating current generator and the induction motor, the simplest types of generator and motor, come in to perform this marvelous service which is revolutionizing the whole steel business.

The power problem is, as Dr. Steinmetz pointed out, one of the most severe problems which appears in mechanical work. In one sense the problem is of a very elementary kind, in that it does not go into the unknown and involve mysterious features such as some of these electrical discussions that we have had today, involving ions, gases, and one thing and another, but in the rather long table of the symbols which enter into the formulæ we have simply those which represent the most elemental matters in mechanics. There is mass, and length, and time, the fundamental units, and then there is a little more complexity in the case of velocity, etc., and the problem is simply, we may say, the elementary mechanical problem of supplying the proper constants and working out the mechanical elements, which in turn will give the motor requirements, the speed and torque, or tangential forces to be developed by the motor. It is by this kind of language that the requirements of service can be gotten into the nomenclature of the motor, which is simply torque and speed.

To read a paper and hear explanations of these new large forces and requirements is impressive, but it is still more impressive to see the thing itself. In looking at the reversing motors in the South Chicago works of the Illionois Steel Company some time ago, I was very much impressed in standing and looking at the motor and its great big armature, some five feet in diameter, revolving rapidly in one direction, and then easily and quietly and quickly reversing and running in the other direction, and oscillating back and forth under the control of the little hand lever of the distant operator; and yet that motor and those rolls can reverse, from 4800 kw. in one direction to the same amount in the other direction, in six seconds—and the motor-generator set which supplies the power for variations of that kind, for the loads thrown on and off as the ingot comes in and out of the rolls, is such that the power that is taken from the generator is practically constant within a variation of 25 or 30 per cent. These enormous powers, the ease with which these sudden changes take place, and yet the practical constancy on the circuit, are something to observe, and cause a new wonder and admiration for what electricity has accomplished.

Gano Dunn: Mr. Gasche's work may be regarded in one respect as looking toward the development of a substitute for the storage battery. A few years ago there was brought out, the value of batteries floating on the line to serve as reservoirs of power and to absorb fluctuations. Such batteries enabled large reductions in plant capacity and in line, and enabled great improvements in regulation. Storage batteries, however, are not adapted to the excessively severe service and difficult environment of steel mills for the reason, as Mr. Edison more emphatically than is here permitted, used to put it, that they are wet.

While it is true that we have been familiar with the capacity of a flywheel for storing energy, we have never in the past made such general use of this property as has been recently made in steel mills in Europe and in this country. We have all known that a flywheel running at a constant speed can never deliver or absorb power and that it is only when we slow it down that we can uncover and make it give up the energy stored in it. We have also known the law of the rate at which it gives up its energy or absorbs it, but it has been left for Mr. Gasche to develop and analyze this law when the flywheel is electrically tied to a motor on the one hand, and rolling mill work on the other.

With Mr. Gasche's formulas we have spread out before us, all the necessary relations between motor, wheel and work, that we need to know in making use of the flywheel as a reservoir of energy and as a mechanical substitute for the electrical storage battery.

In sympathy with the paper, I criticize the statement "It will be shown in what follows, that on the assumption of perfectly rigid roll train connections and a rotor without any inertia effect (if such were possible), the induction motor is physically incapable of assuming any roll train load above the friction load that by some means may have been imposed on the motor."

I cannot agree with this. Up to the limit of its break-down torque the motor would accept load even if its rotor had no inertia, and I see no characteristic in the load that would be imposed by the entering of an ingot, that would introduce new conditions that would alter this fact.

The paper also says, " On the larger sizes of roll trains the shock imposed on the rolls and connections due to the action of a powerful motor of small slip, would prove such a destructive agent that the experience would be at least a costly one. The nature of the shock arising at the motor shaft can be understood from the following study of the characteristics of a roll pass."

The shock on the shaft of a big induction motor with small slip can be no greater than the shock on the shaft of the same motor when it has been equipped with a flywheel. The conclusion may follow from the formulas, but the formulas are good only within the scope of their terms, and the ideal case of a rotor with no inertia is probably not properly represented in this case, by the terms.

How much power to take out of a given wheel or how much of a wheel to install for a given power involves a nice consideration of first cost on one hand and annual charges on the other. The key to the problem is the percentage of slow-down.

For moderate slow-downs the energy a wheel will deliver is approximately proportional to twice the slow-down, while the energy wasted by the rotor of the induction motor driving it is roughly proportional to three times the slow-down.

With fixed slip resistance large slips or slow-downs, while involving cheap wheels, mean low efficiencies; and low efficiencies must be charged not only with the power wasted, but with their proportion of the increase in first cost of the plant to supply them. My experience has been that it is really cheaper to put in what at first looks like an expensive wheel and run it at small slip, even where power is cheap. This is dictated by reasons not only of economy but of effective operation, since regulation problems are simpler with small slips and overloads are less disturbing.

Where the flywheel installation absorbs a small proportion of the total output of the power plant of a mill, gradient of load change is of more importance than percentage of fluctuation between maximum and minimum load. For usual mill conditions, which involve relatively long waits between slabs or ingots compared to the waits between the passes of a given slab or ingot, what might be termed the maximum average power consumption is bound to occur almost no matter how big a flywheel is put in.

Even an enormously large flywheel will not continue to absorb power during the whole of the relatively long waits between slabs or ingots, nor will it deliver stored power during the whole of the relatively long time required for the succession of passes of any given slab or ingot. Consequently the main power plant must be installed to supply the maximum average power required by the work.

The flywheel's duty is to prevent fluctuations from this maximum average rather than from the datum line of zero power and if this view is taken, a moderate flywheel outfit, without attempting to smooth out the fluctuations that occur between successive slabs or ingots, will very satisfactorily smooth out the fluctuations occuring between the passes of a given slab or ingot.

In designing such moderate flywheels the gradient of the fluctuation rather than its absolute amount is the feature to which attention should be given. It is too sharp a gradient that causes noticeable change in the brilliancy of lamps. It is too sharp a gradient that causes synchronous apparatus in the neighborhood to drop out of step. It is too sharp a gradient that upsets the stability of governors in the power house and it is too sharp a gradient that prevents a happy and comfortable adjustment of all the apparatus in the mill to such rises and falls of potential as will occur in the everyday working of a steel mill.

If the gradient is properly taken care of, relatively large fluctuations of power may be permitted and in the ordinary large mill, where there are a number of fluctuating loads, these loads will be found to pool their demand for power so that the fluctuation from the power plant will be surprisingly small.

Where there is opportunity for pooling, it is a useless investment to install flywheels larger than just enough to prevent wide departures from the maximum average rolling load.

Selby Haar: Mr Gasche's paper is of great value at the present time, because it deals with a subject on which there are practically no data on record, so that all engineering recommendations on driving motors must be based on laborious calculation. For this reason, any conception which gives one a broader view of the problem is welcome.

The author has assumed that the torque of the motor is proportional to its slip. The same assumption underlies Mr. H. C. Specht's paper which was read at the Frontenac meeting. This does not affect the nature of the conclusions which have been drawn, and is an almost necessary simplification, but since the torque of an induction motor is not exactly proportional to the slip the variation must frequently be considered, especially if the maximum reduction in speed is specified. The writer has selected a set of conditions and drawn the torque curves to show this.

In Fig. 1, the full line shows the actual torque curve of a motor designed to give twice full load torque at 15 per cent slip; the dotted line represents a curve with the same slip at light load as the full line, while the dot and dash line is drawn so as to show the same torque at 15 per cent slip as the full line.

Fig. 2 shows the distribution of the duty between motor and flywheel corresponding to each of the torque curves. The full line curve was calculated by a method which will be described later, but equations 8 and 23 were used for the other two. Attention is called to the shape of the full line curve for the interval between passes. This is due to the departure of the torque curve from a straight line.

The method of calculation to which reference has been made was developed for rapid work without the aid of any tools but a slide rule after the torque curve is drawn. The theoretical basis is as follows:

T_s is the total torque to be delivered.
T_a is the motor torque at the time t_a.
T_b the torque at the time t_b.

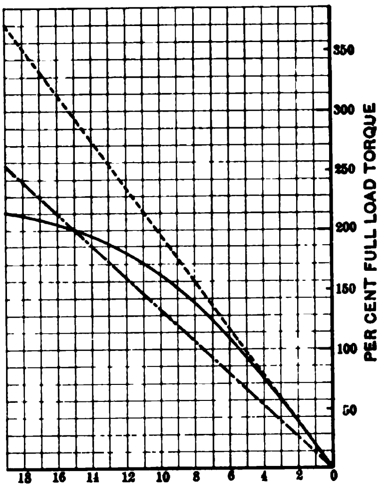


FIG. 1

From the torque curve we get σ_a as the slip corresponding to T_a and σ_b corresponding to T_b. This gives a difference in speed of $(1-\sigma_b)\, v_s - (1-\sigma_a)\, v_s$, and an average acceleration (or retardation) of $-\frac{(\sigma_b-\sigma_a)\, v_s}{t_b-t_a}$. The flywheel torque is

$$\frac{M\,K^2\,(\sigma_b-\sigma_a)\, v_s}{t_b-t_a}.$$

Then

$$\frac{T_a+T_b}{2} = T_s - M\,K^2\,\frac{(\sigma_b-\sigma_a)\, v_s}{t_b-t_a} \text{ for the pass,}$$

and

$$t_b - t_a = \frac{(\sigma_b - \sigma_a)\, v_s\, M K^2}{T_s - \dfrac{T_a + T_b}{2}}$$

Assuming constant intervals for $\sigma_b - \sigma_a$, say one per cent, we obtain $t_b - t_a$ directly. These times need only be summed until the pass is completed. The modification of the formula for the interval between passes is obvious. The attached tabulation shows the method of carrying out the work.

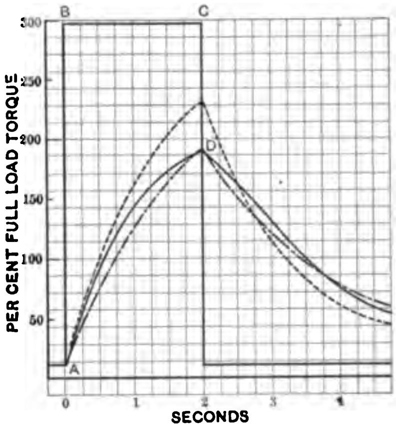


FIG. 2

Another point in this connection: The area A, B, C, D, A in Fig. 2 represents the decrease in momentum of the flywheel.

Pass.

Slip	T_a	T_b	$\frac{T_a+T_b}{2}$	$T_s - \frac{T_a+T_b}{2}$	$t_b - t_a$	Elapsed time
0.0055–0.01	15000	26500	20800	394200	0.042	0.042
0.01 –0.02	26500	53500	40000	375000	0.098	0.140
0.02 –0.03	53500	78500	66000	349000	0.105	0.245
0.03 –0.04	78500	104000	91200	323750	0.113	0.358

etc.

This can be separated into various factors of mass and speed drop until satisfactory division is obtained. It can be used as a check on the other method, or if the point D is fixed and the curve A D drawn in by estimation, the flywheel effect required can be determined directly.

W. W. Crawford (by letter): In discussing Mr. Gasche's paper, it is my purpose to call attention to some of the physical aspects of the interactions covered by his equations, to introduce a short-cut method for deriving the behavior of the apparatus under repeated cyclical loads from its behavior during the first cycle, and to extend the method to cases where regulating devices are used to control the torque of the motor.

The motor operates at constant speed under a constant friction torque until the first bloom reaches the rolls. This applies a sudden, but uniform, load. The motor then approaches a new condition of steady running, which, if the time required for the pass were sufficiently long, the motor would eventually reach. The approach to steady running is retarded by the inertia of the flywheel. The rapidity of the approach is less, the heavier the flywheel, and the greater the necessary increase in slip before the motor will take up the entire torque.

Mr. Gasche's equation 8 shows that the motor torque follows a logarithmic curve which approaches asymptotically to a line representing the uniform load applied. This equation may be put in the following form:

$$\operatorname{Log} \frac{T'}{T} = A\, t$$

where T' = initial unbalanced torque acting to change the velocity of the flywheel.
T = unbalanced torque at a later instant.
t = time interval.
A = a constant inversely proportional to the amount of inertia of the flywheel, and inversely proportional to the amount of slip for a given load.

When the load is removed, the motor is developing a torque in excess of the friction load, and the difference is an unbalanced torque accelerating the flywheel. The law of torque variation is the same (see equation 24) as before, when T' and T are taken to represent the unbalanced torques.

Therefore the calculation of any cycle resolves itself into considering the unbalanced torque at the beginning of each element of the cycle, computing from it the final unbalanced torque by means of the formula, and combining this with the rolling torques to obtain the motor torques. The same formula is used in each element since A is constant throughout.

A table of values of the ratio $\frac{T'}{T}$ corresponding to the different time intervals can be made up for a given set of rolls, and the same table will apply for the calculation of any combination of loads to which the apparatus may be subjected.

Calculation by the above method requires that the conditions at some point, say the beginning of the cycle, are known. Where the mill operation is continuous, conditions at the beginning of a given cycle are not known, being dependent on the previous cycle. The results of continuous operation might be obtained by figuring through cycle after cycle till a uniform condition is reached, in fact, after the first cycle practically uniform conditions will have been reached in most cases. The rigorously correct method given below is however just as simple.

In Fig. 1, the solid and dotted curves apply to the first cycle and a cycle of continuous operation respectively.

Then $Q\ P$ = initial motor torque in addition to friction torque, in a cycle of continuous action.

$Q'\ P'$ = final motor torque in addition to friction torque in the first cycle.

$Q'\ P'$ is known from the computations on the first cycle. $Q\ P$ bears a simple relation to it and is computed as follows.

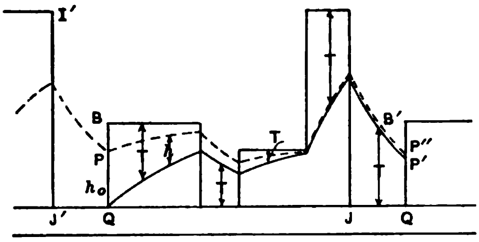


FIG. 1

It may be easily shown that the difference between the solid and dotted curves is represented by a continuous logarithmic curve whose equation is

$$\log \frac{h_0}{h} = A\ t$$

$$\text{Let } \frac{h_0}{h} \text{ for a whole cycle } = x$$

$$\text{Then } P'\ P'' = \frac{Q\ P}{x}$$

$$\text{now } Q\ P = Q'\ P''$$

Hence

$$Q\ P = Q'\ P' + P'\ P''$$

$$= Q'\ P' + \frac{Q\ P}{x}$$

$$\text{or, } Q\ P = Q'\ P' \left(\frac{x}{x-1}\right)$$

That is, to compute the correction to the initial motor torque, multiply the difference in motor torque at the beginning and end of the first cycle by the ratio $\frac{x}{x-1}$

where $\log x = A\, t_c$

t_c being the time for a whole cycle.

In cases where regulating devices are used to increase the slip when a given load is exceeded, we have to deal with sudden changes in the constant A. Referring to Fig. 2, when a certain load represented by the point P is reached, the regulating device acts. Due to its time element the introduction of resistance is delayed to the point P' after which a larger value A' of the constant prevails. The total motor torque is instantaneously reduced in the ratio $\frac{C\,D}{P'D} = \frac{A}{A'}$. The torque then increases along a second curve $C\,E$ with a much slower rise, due to the greater change in speed before a given change in torque takes place.

In computing the constant A (formula 55) the torques being ordinarily expressed in pound feet and $M\,K^2$ being expressed in pounds at one foot radius, it is advisable to introduce the factor G (= 32.16) directly in the formula.

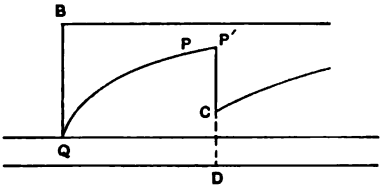


FIG. 2

In the very convenient diagram given by Mr. Gasche for computing A, M is expressed in the "gravitational" unit of mass which is equal to 32.16 pounds.

F. G. Gasche: I might give the assurance that the formulæ have been subjected to numerous applications and checked in many ways, such that the engineer may use them with some confidence.

Several years ago, the U. S. Steel Corporation inaugurated the construction of a large plant involving many features withour precedent—at least in the magnitude of the several installations and the importance of the engineering problems.

It was proposed that, simultaneously, there should be complete motor driving of the rolling mills and that current should be furnished from a station involving a radical departure in the type of prime mover. There is nothing incompatible with these propositions provided the variations of frequency due to the action of the prime mover are negligibly small; but considerable variations introduce problems of great concern when the character of mill loads in the presence of a lowering voltage is understood. Should the prime movers be guilty of erratic control the safety and commercial efficiency of the entire equipment compels the use of flywheels and other safe guards. Many of these mill drives have been equipped with exceptionally large flywheels simply as a precautionary measure. This seeming extravagance has been attended by good fortune in the way of economies in the transmission of power and in the satisfactory service of the mill equipment.

Another complication arose from the ambition to surpass all precedents in the amount and rate of displacement of the metal in many of the roll passes, thus increasing the loads which would ordinarily be imposed on the driving motor. Preceding any other consideration in the power transmission problem, it became necessary to explore in a way that unknown region of the properties of materials which may be called the plastic state.

We have elaborately evolved mathematical theories of elasticity, and the statement of the laws applying to the region of " perfect elasticity ". Similarly, we have access to the theoretical hydro-mechanics, involving the assumption of "perfect mobility" or freedom from internal resistances. There remains to be investigated the " plastic region " promising to exact the best efforts of the physicist and mathematician before the subject is thoroughly understood and placed in the form most suitable for engineering purposes. In lieu of such assistance it becomes necessary not only to exterpolate with reference to our experimental data concerning roll train resistances, but also to investigate the "plastic region" at least, empirically, before we were in a postion to give the electrical designer the necessary load conditions within reasonable limits of error.

Possibly, a preliminary statement of the methods by which these roll-train resistances are estimated could have preceded the subject of the paper, but a subsequent statement of the case for the purpose of the Institute, if it is of sufficient interest will not suffer if suitable time is allotted to its preparation.

With regard to Mr. Dunn's observation concerning a statement in the paper, this is simply an interpretation of the formula (19) bearing in mind the value of the constant A containing MK^2 in the numerator. A zero value of MK' makes S equal to zero, or the motor does not assume the load due to the pass.

It is well within the possibilities that there is enough elasticity of the roll train connections in many cases to give an " approach " load condition as defined for Fig. 1. The allowance for such gradual assumption of the load would complicate the analyses beyond all requirements of practical applications unless the bar is actually a tapered ingot with little or no " draft " at the start of the pass. In this case, however, the statement to which Mr. Dunn refers does not apply when certain critical " torque-slip " relations of the motor have been established.

A paper presented at the 27th Annual Convention of the American Institute of Electrical Engineers, Jefferson, N. H., July 1, 1910.

THE DESIGN OF THE ELECTRIC LOCOMOTIVE

BY N. W. STORER AND G. M. EATON

The features to be embodied in an ideal electric locomotive depend entirely on the point of view. Any electric locomotive, however, must contain certain essential features.

First. Mechanical parts of strength sufficient for the required service;

Second. Motors of capacity sufficient to develop the required power;

Third. A reliable transmission system between the motors and driving wheels;

Fourth. Weight on driving wheels sufficient for adhesion;

Fifth. A complete control system;

Sixth. Riding qualities enabling the locomotive to negotiate the rails without undue damage.

More or less closely associated with these essentials there is an endless variety of detail concerning which no two men will hold identical opinions.

The electric locomotive designer must act as a clearing house for the opinions and ideals of all the men associated with railroad electrification. To prepare himself for this position, he must view the locomotive through the eyes of men connected with every branch of the service.

Locomotive Ideals. The man who is responsible for hauling trains on schedule time sees a perspective that does not include first cost, weight, or mechanical or electrical efficiency, as those terms are generally understood. He sees in the electric locomotive only a means for keeping his trains moving, and on schedule time. His conception of efficiency is represented by the number of trips made on schedule time, divided by the total number of trips. He has had long, hard experience with steam locomotives, and is acquainted with their good and bad points. He accepts an electric locomotive only as a last resort, and then recommends the incorporation of as many as possible of the features of his successful steam locomotives. This on the face of it is a wise plan, but it should be remembered that a locomotive may be successful *because* of a given detail or it may be successful notwithstanding that particular feature. Again, a certain feature may be successful because of interrelation with other features, and a new design of locomotive must be carefully analyzed to see that an old and proven device will have the environment necessary for its best success. Too much emphasis cannot be laid on this point, as the differences in principle between steam and electric locomotives are not always easily recognizable. This point is well illustrated by fundamental differences in the application of cranks and connecting rods on steam and electric locomotives, which will be discussed in detail later.

The eyes of the motive power man see much the same features as those of the operating man, but his eyes magnify details of design in a greater degree. Both will wish to incorporate as many standard parts as can be used, and they will insist on the strength of all parts being ample to withstand every phase of the service such as bumping, speeding, overhauling, etc. They will be interested in the machine involving low maintenance charges, but in this respect they will not fully foresee the effect of the various mechanical features upon the electrical equipment, and they are liable to insist on the adoption of mechanical details, which of themselves have a low cost of maintenance, and yet at the same time will involve an excessive cost for the maintenance of the electrical equipment. Their ideal locomotive will operate safely at high speed, in either direction. It will be able to make up a reasonable amount of lost time, and will always be ready for service. It will not require long lay-overs, and will be in the shop the least possible time. They would like if possible a single type of locomotive which would perform any service that might be required of it, from making up and hauling a 2,500-ton freight train to making a high speed run with a "limited."

The amount of power consumed and the excessive weight involved in an interchangeable locomotive of this type are a matter of little importance to them, so long as the locomotive is strong enough to stand every phase of the service, and does not call forth protests from the maintenance-of-way department and bridge engineers. They know that such protests will certainly be forthcoming if damage to track and bridges is greater than that attendant upon the operation of the accepted types of steam locomotives.

Up to within a short time it has been the accepted idea that an electric locomotive would have riding qualities greatly superior to those of the steam locomotive, and that it would cause much less track destruction, due to the perfect balance and the absence of reciprocating parts. Recent experience has demonstrated that these features in themselves are not sufficient to produce a good tracking locomotive, and it is now generally recognized that the proportioning of an electric locomotive which will have ideal riding qualities is one of the most serious problems today confronting the designer.

The ideal locomotive of the general manager or president of the railroad is one that will meet as nearly as possible the ideals of his subordinates, and in addition will be a part of that system which will give the most reliable service, consistent with a reasonable cost of operation; or, in other words, will earn the largest dividends on the investment. The cost of the locomotive will appeal most strongly to him.

It is popularly supposed that the ideals of the electrical engineer concerning electric locomotives embrace only the electrical details of the locomotive, such as motor design, efficiency, temperature, and the control and collecting system, but this is a mistake at the present time, whatever it may have been in the past. It is necessary for him to have the broadest possible ideal. It is his duty in connection with steam locomotive designers to select that combination of details which will be the best compromise of the ideals of all railway people. It must be recognized that every complete design is a compromise, as much so in locomotives as in other machinery, and as long as the ideals of the different departments are conflicting it is certain that an ideal locomotive, from all points of view, will never be secured.

LOCOMOTIVE PROBLEMS

Transmission. At first sight it appears to be a very simple problem to transmit the power from rotating armatures to rotating wheels. This, however, is not the case, there being more or less serious objections and limitations to every type of transmission that has been proposed. Many of the types give excellent service when used in their proper places, but the fact remains that for high speeds and also for maximum powers, the problem of transmission is one of the most serious among the mechanical problems confronting the designer.

It will be helpful to classify the various types of transmission. Some of the objections and limitations of these types will be discussed later:

a. Gearless motor with armature pressed onto driving axle. " New York Central." Fig. 1.

b. Gearless motor with armature carried on a quill surrounding axle, and driving the wheels through flexible connections. " New Haven Passenger." Fig. 2

c. Geared motor with bearings directly on axle and with nose supported on spring borne parts of locomotive. " St. Clair Tunnel." Fig. 3.

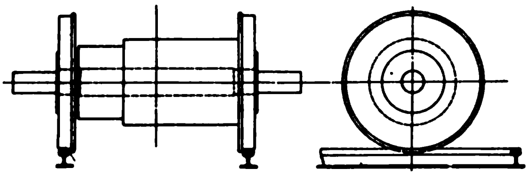


FIG. 1

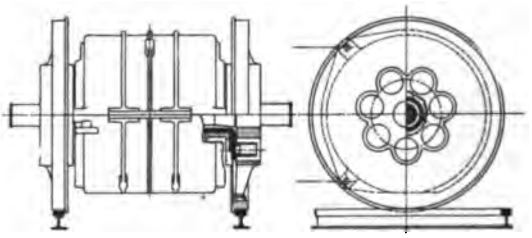


FIG. 2

d. Geared motor with bearings on a quill surrounding axle, and (1) nose supported on spring borne parts of machine (New Haven Car Fig. 4) and (2) motor, rigidly bolted to spring-borne parts of machine, the quill having sufficient clearance for axle movements. " Four-motor New Haven Freight." Fig. 5.

e. Motor mounted rigidly on spring-borne parts, armature rotating at same rate as drivers, power transmitted to drivers through cranks, connecting rods and countershaft on level with driver axles. " Pennsylvania " Fig. 6.

f. Motor mounting and transmission as in (*e*) but motor fitted with double bearings one part for centering motor crank axle and the other for centering the armature quill which surrounds and is flexibly connected to the motor crank axle. "Two-motor New Haven Freight." Fig. 7.

g. Motors mounted on spring borne parts, armature rotating at same rate as drivers, power transmitted to drivers through offset connecting rods and side rods. "Latest Simplon locomotives." Fig. 8.

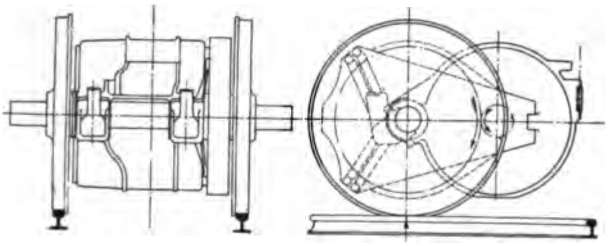


Fig. 3

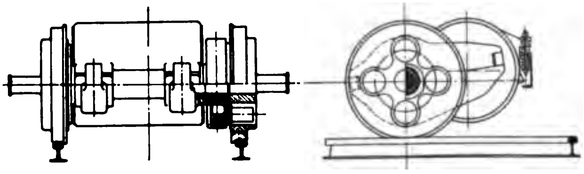


Fig 4

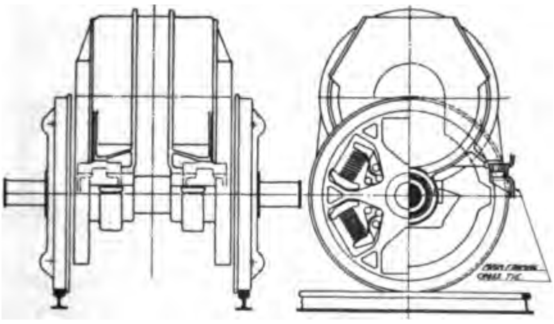


Fig. 5

h. Motors mounted on spring-borne parts, armature rotating at same rate as drivers, power transmitted to drivers through Scotch yokes and side rods. "Valtellina Locomotives." Fig. 9.

j. Motors mounted rigidly on spring-borne parts, power transmitted through gears to counter-shaft, thence to drivers through Scotch yokes and side rods. Fig. 10.

Further classification of electric locomotives on the basis of framing and wheel arrangement is also of assistance in gaining a clear understanding of existing locomotives.

a. Cab and framing an integral structure. All weight carried on drivers. Drivers contained in a single rigid wheel base. " St. Clair Tunnel." Fig. 11.

b. Cab and truck framing separate structures, all weight carried on drivers. Drivers contained in two rigid wheel base trucks. Draw bar pull transmitted through center pins or through truck frames. " Spokane & Inland Empire Ry. Co." Fig. 14. " P. R. R. 10001 and 10002."

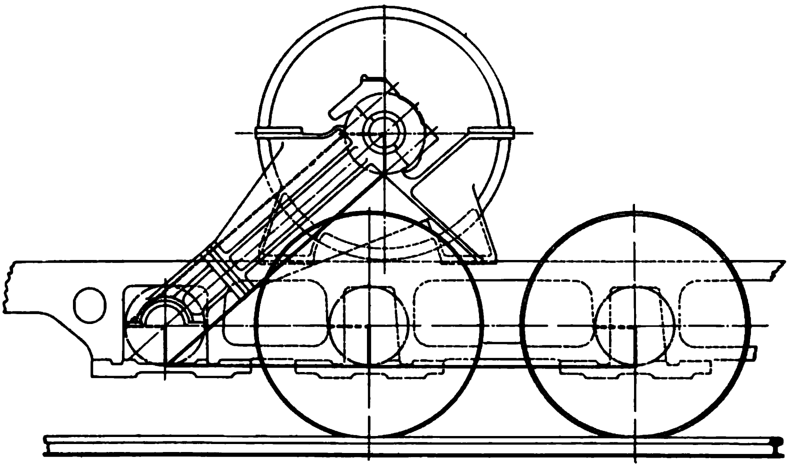


FIG. 6.

c. Same as (*b*) but with added idle wheels for guiding and weight carrying. " Modified New Haven Passenger, and New Haven Freight." Fig. 15.

d. Any of the foregoing forms permanently coupled in pairs or articulated. " Pennsylvania." Fig. 16.

e. Same as (*a*) but with added idle wheels for guiding and weight carrying. " Valtellina or New York Central." Fig. 13.

f. Cab and framing an integral structure. All weight carried on drivers. Driver wheel base partly rigid and partly flexible. " Simplon Tunnel." Fig. 12.

Service Requirements. It has been stated that from an operating standpoint it would be very desirable to have one locomotive which would be capable of handling at the desired speed any train from the heaviest freight to the fastest limited. While such a locomotive can be built, it will be at a prohibitive cost.

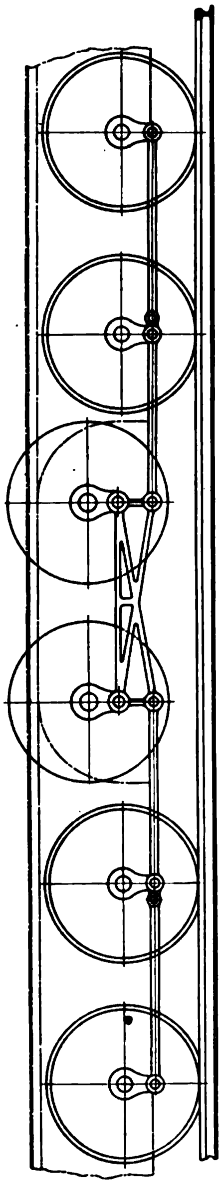


FIG. 8

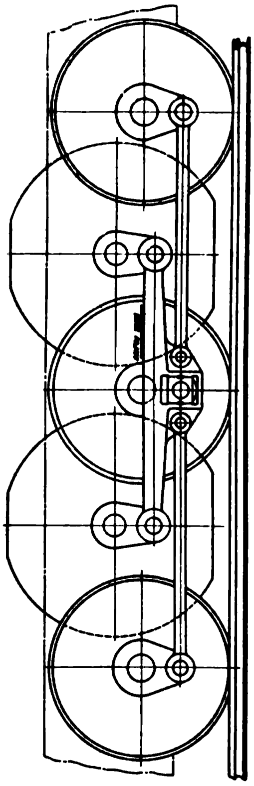


FIG. 9

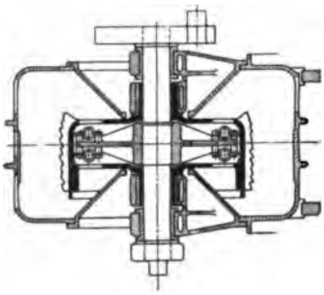


FIG. 7

It is commercially practicable to cover a considerable range of speed and weight of trailing load with one locomotive, and any passenger locomotive may be used to handle on its lower speeds freight trains within its capacity for tractive effort; but where the weights of trains to be handled and the speeds at which they operate vary as widely as they do on most trunk lines, an absolutely interchangeable locomotive is impracticable. This we believe will be shown in the discussion of the requirements for the various classes of service in the following pages.

Switching Service. From the nature of this service the locomotive operates to a great extent over curves and special work. This track construction is expensive and hard to maintain. The locomotive should therefore embody primarily in its design such features as will enable it to negotiate this kind of track with the least effort. We list the chief of such features in approximately the order of their importance.

(*a*) Short rigid wheel base.

(*b*) Minimum dead weight per axle.

(*c*) Minimum total weight per axle needed for adhesion.

(*d*) Concentration of weight near midlength of locomotive, and short cab overhang.

(*e*) Effective equalization perferably of the three point type.

(*f*) Flexibility of framing under longitudinal twist to assist equalizing system.

(*g*) High center of gravity. While this is of helpful tendency it is probably not worth the expenditure of much money or weight on account of the slow speed of operation.

These features may all be summed up as those tending to produce a locomotive whose wheels may be deflected by the rails with the least attendant movement of the mass of the locomotive.

Fig. 17 illustrates a four-wheel steam switcher of a standard type. Attention is called to the extreme overhang and consequent nosing characteristic. This overhang is practically inherent in a steam locomotive of minimum wheel base.

Slow Freight Service. Most of the transcontinental railroads are to day limited in their carrying capacity by long mountain grade divisions. The present practice is to run the heaviest freight trains that can be operated over these divisions. This service is now handled by consolidation or mallet steam engines, which haul 2,000 to 2,500 ton trains at 8 to 10 miles per hour, and electric locomotives are expected to handle the same or heavier trains at higher speeds to increase the capacity on the line.

The latest developments in locomotive design indicate that the type of locomotive best suited for such service, with speeds of 12 to 15 miles per hour is one having a motor geared to each axle. The feature of prime importance in the design of these locomotives is the absence of weight in excess of that necessary for adhesion. Every ton of excess weight in the locomotive means a ton less trailing load. A slow-speed freight locomotive should be designed with all weight on the drivers.

In the slow-speed service, the maximum allowable weight per axle should be used if the total weight of locomotive can be thereby reduced. A greater dead weight per axle can probably be tolerated than is wise in switching service, because being a road engine, a much less amount of special work will be negotiated than in the case of a switch engine, and the damage to the track will not be excessive at the normal operating speeds.

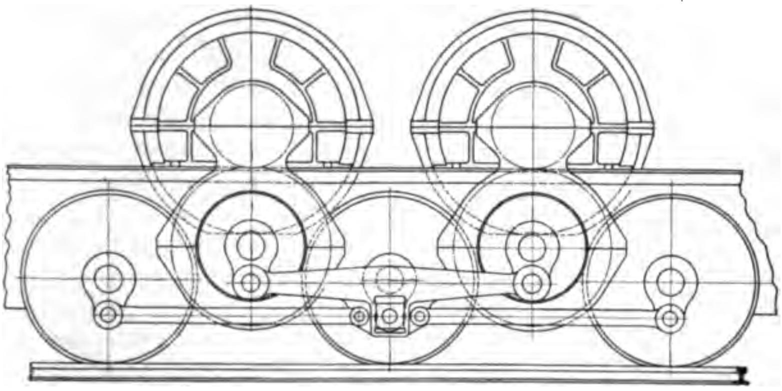


FIG. 10

If, however, complete spring support of the motors can be achieved without excess total weight, and this can usually be done, then the decrease in maintenance charges should much more than offset the increased first cost attendant upon such spring support.

There is a great difference of opinion among railway engineers both in regard to the total weight per axle and the amount of dead weight allowable. Some would keep the total weight per axle below 40,000 lb. and the amount of dead weight equal to that of wheels, axles and journal boxes. Others do not hesitate to put 60,000 lb. on a single pair of wheels with a dead load of 15,000 to 18,000 lb.

The intention here is not to attempt placing strict limits on axle loads, but to call attention to general tendencies, as each actual installation must be settled upon its own merits, or in accordance with the practice on the particular line involved.

The wheel base of the slow-freight engine should be as flexible as possible so as to curve easily and prevent flange wear, and should take switches and turnouts without undue stress on the track. No idle leading or trailing truck axles will be necessary. The remarks on high center of gravity, equalization, concentration of weight at midlength of engine and flexible framing apply almost equally on switching and slow freight services.

Fast Freight Service. Some trunk lines have no heavy grades, and are able to operate their freight trains at speeds of 30 to 40 miles per hour, or even higher. For such roads a locomotive adapted to cover a range of speed from 30 to 60 miles per hour is well suited to handle both freight and all but the highest speed passenger trains.

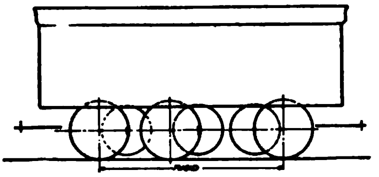


FIG. 11

Two points of departure from switching requirements are worthy of particular attention when the speed runs as high as 50 to 60 miles per hour. One is a requirement of service operation, and another is imposed by the design. These points are interesting in that service requirement and design limitation go hand in hand. First the speed makes it advisable to provide leading wheels of small size and light dead weight to assist in guiding and more particularly to iron the rails down gently to an actual bearing surface on the road bed and thus avoid the knock attendant on hammering the free rail down with the heavy drive wheel. Second, as the speed increases, either the tractive effort decreases with less weight required on drivers or the horse power demanded increases with attendant weight increase and the added wheels are necessary to avoid overloading the drive wheels.

High Speed Passenger Service. The most important requisite of a locomotive designed to operate at 60 miles per hour and over is its ability to run at the highest speeds possible without injury to the track. All the track disturbances mentioned above, except in curves and special work, have been primarily in a vertical plane. When we consider speeds of 50 to 60 miles per hour, however, we are closely approaching the range where even on tangent track serious lateral disturbance is liable to occur. Extensive speed tests have shown that almost any kind of a machine will stay on the track at 40 miles per hour, without serious damage to tangent track. As the speeds increase above this figure, however, the bad riding qualities rapidly appear. The particular features following apply with more and more importance as the speed increases so that we are led naturally to a consideration of the higher speed machines, bearing in mind again that no sharp dividing line exists and individual conditions must govern all concrete cases.

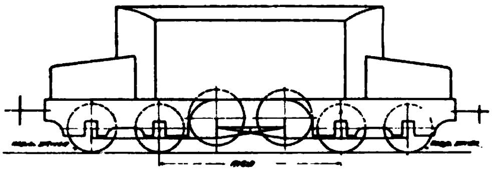


Fig. 12

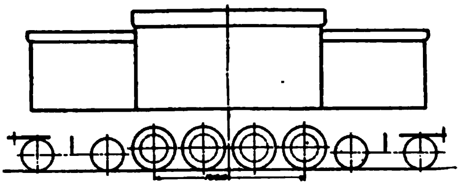


Fig. 13

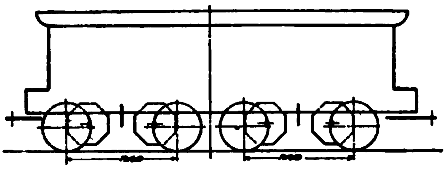


Fig. 14

There are certain features that tend to reduce the intensity of the lateral forces on the track. First of these, and a source of much recent comment, is "high center of gravity." The acceptance of this as a cardinal principle of successful high speeding, however, is not universal. The theory on which the belief in the value of a high center of gravity is based is that the higher the mass of the locomotive is placed above the axles, the less will be its restraining influence against lateral motion on the part of the wheels. The mass of the locomotive may take the general direction of the track while the wheels follow all the little irregularities in its surface and alignment.

Assume for instance, that a locomotive is running at high speed on tangent track and that some rail defect imposes sudden transverse movement upon the wheels. Under these conditions the mass of the wheels and axle and any other masses rigidly associated with them will deliver a shock approximating a hammer blow to the side of the rail head. Evidently therefore these masses should be minimized unless it can be shown that their increase does not involve serious injury to the track and consequent danger in operation.

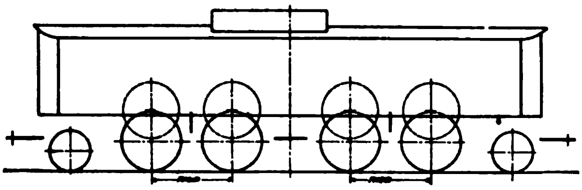


Fig. 15

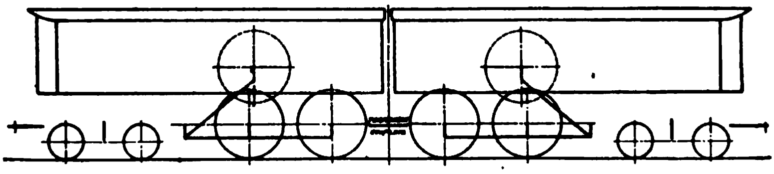


Fig. 16

The blow delivered by the spring borne parts of the locomotive is radically different from this in both low and high center of gravity machines. In the case of a locomotive whose center of gravity of spring borne parts is at the same height as the center of the transverse restraint, *i.e.*, about the center of the axle the transverse movement of the leading driver would impose a rotation of spring borne parts about avertical axis. Fig. 19. The lateral force to impose such a movement would be very great, due to the great moment of inertia about this axis. In the case of a locomotive whose center of gravity is high above the center of transverse restraint the movement imposed upon the spring-borne masses by transverse movement of the leading driver is a composite of two rotations, viz., about a vertical axis and about a horizontal axis parallel to the rails. Fig. 20. As the moment of inertia about the latter axis is much less than that about the former it is evident that the lateral forces involved in the high center of gravity machine will be less. The forces opposing rotation about horizontal axis are provided by the semi-elliptic riding springs, which will transmit their resultants ultimately to the running face of the rail and will not aggravate flange pressures. Were it not for the dampening effect of the friction of the semi-elliptic springs and the detail friction of the machine, this rotation about a horizontal axis would be a simple harmonic vibration. The period and amplitude of this vibration would be functions of the characteristics of the semi-elliptic springs and of the polar moment of inertia of the masses moved.

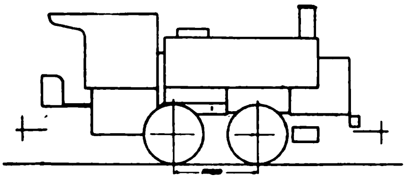
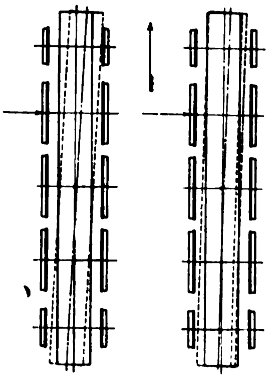


FIG. 17



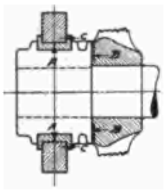


FIG 18

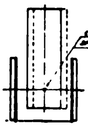


FIG. 19

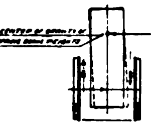


FIG. 20

Suppose for example that with the low center of gravity locomotive first considered, some combination of lateral springs were applied which would impose on the spring-borne weights a vibration about the vertical axis of period and amplitude and dampening action identical with that occurring on the high center of gravity machine. There being no rotation about the horizontal axis, the forces required to control the vibration would be greater than with the high center of gravity machine, because of greater moment of inertia about the vertical axis; and further, the transverse rail stresses would be greater because the reactions of the controlling forces are transverse.

We can formulate an idea of the springs necessary for such transverse restraint by comparing them with the semi-elliptic riding springs which perform the dual function of supporting weight and resisting rotation about the horizontal axis. Probably transverse springs as heavy and with as great amplitude of motion as these semi-elliptic riding springs would be none too powerful to perform the required service, and it should be noted that their friction is almost as important as their spring action.

The foregoing discussion is predicated upon the assumption, that the spring borne masses are an integral unit; and it shows, from perhaps a new point of view, that the production of an ideal high-speed, low center of gravity engine of the type noted, while perhaps theoretically possible, is attended by serious if not insurmountable difficulties.

Considering further this horizontal rotation of the spring-borne masses of a locomotive with medium height of center gravity, we find that there is a zone that is neutral as regards transverse motion relative to the track. If in such a locomotive certain of the lower masses were hung from longitudinal trunnions located on the center line of the locomotive and in this neutral zone, it is evident that the rotation of the spring-borne masses would be more easily accomplished due to the lessening of the masses moved. Possibly gearless concentric motors could be hung in this way, in connection with a drive of sufficient flexibility to allow free wheel play.

This is not a combination that could be recommended solely because of good riding qualities. It is, however, entirely possible for such a machine to have sufficient attendant simplicity to make it a better compromise than an engine where simplicity and mechanical efficiency are directly sacrificed to secure high center of gravity.

It may be mentioned that the New Haven locomotives have a motor mounting that approximates this condition. There is not as great amplitude of springs to allow unrestrained wheel play either vertically or laterally as might be desired, but there is enough to cushion all blows that the track receives from the mass of the motors, and the reports of track maintenance since the addition of the leading wheels eliminated the nosing tendency, are very gratifying.

Almost equally advantageous with the high center of gravity is the concentration of the mass of the locomotive about this center of gravity, both vertically and longitudinally. It is conceivable that if the mass of the locomotive could be so concentrated longitudinally about the center of gravity as to decrease the radius of gyration about the vertical axis to a value well within the rigid wheel base, there would be no more serious lateral disturbance on the track with a low center of gravity machine than with one having higher center of gravity but with a much longer radius of gyration about the vertical axis. Every effort should, therefore, be made to locate the mass of the heavy parts of the locomotive as near the middle as possible.

The action of a low center of gravity locomotive can be very materially improved by locating the point of side restraint below the level of the driving axles. Every inch that this point is lowered is equivalent to raising the center of gravity of the spring-borne parts by an equal amount.

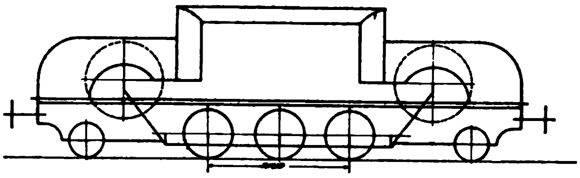


FIG. 21

Wheel Sizes. On a steam locomotive, large wheels are considered essential for high speed service. The primary reasons are to minimize the wear and tear on parts subjected to reciprocating stresses, to maintain the piston speed at a safe figure, and to keep down the blow on the track due to the incorrect counterbalance. An advantage of large wheels in any high speed engine lies in the attendant low surface speed of the journal, and again in the long time elapsing between tire turnings. There is also less distress of metal in both tire and rail, due to the greater area of contact with the large wheel. On the question of the advantage of large wheels for road engines, there is probably a greater unanimity of opinion among railway men than on any other detail of the equipment.

Equalization. The most successful high-speed steam locomotives of to-day are designed with a three-point equalization, having one point ahead and two trailing. This is apparently a very desirable arrangement for any locomotive, and the electric locomotive designer is at once confronted with a new problem in adapting it to a locomotive which must be designed to operate equally well in either direction. The only means by which the actual three-point equalization can be secured on such an engine is to devise some means for shifting the equalization when the engine is reversed. It is possible to arrange air cylinders interlocked to the reverse lever, which will automatically alter the equalization system, so that a single point of equalization will always lead and two-points will always trail. This should, however, be reserved for a last resort, as it does not seem wise to accept such weight and complication unless it proves essential.

A symmetrical arrangement of wheels on the two ends of the locomotive has been criticised by some as lending itself to a nosing tendency in high-speed engines. While there is some evidence to support such contention, it is not regarded as absolutely proven, and there is an open question as to whether the symmetry of equalization rather than symmetry of wheel arrangement is not the irritating cause.

Whatever system of equalization is used, it is very desirable that the springs on an electric locomotive should be very flexible. This in itself will tend to equalize the loads on the drivers without the complete three-point equalization system. It is contended by some of the best engineers that a four-point equalization system with flexible springs is better than the three-point equalization system.

Interchangeable Locomotives. If the accuracy of the foregoing outline of features for various services is accepted, the impracticability of performing all classes of service economically with a single machine, is at once made apparent. The engine for the heavy high speed passenger train will require motors of large capacity. This capacity, however, can be utilized only at the high speeds with a corresponding low tractive effort. The electric locomotive is not so well suited for interchangeable service as the steam locomotive because of the fact that its continuous tractive effort is practically constant regardless of the speed at which it is operated. A steam locomotive, on the other hand, can develop its maximum horse power at almost any speed, and its continuous tractive effort may be anything from its maximum, which is developed at starting, down to that necessary to give its maximum horse power at its maximum speed. An electric locomotive designed to develop its continuous capacity at 60 miles per hour, if operated in freight service at 30 miles per hour will be developing only one-half of its capacity. On account of the necessity of having the best riding qualities at high speed, the locomotive will be very much heavier than one designed especially for freight service having the same continuous tractive effort. The cost also will be much greater. It may be contended that where gearless motors are used, it is simply a matter of winding the motor to develop a given tractive effort at its maximum speed, and it will then be suitable for any service requiring this tractive effort at lower speeds. This is true, but for mechanical reasons the converse is not true; namely, that a freight locomotive can be operated in passenger service by winding the motors for a higher speed. An economical mechanical design for a locomotive, which is thoroughly satisfactory for freight service, will not be at all suitable for the high speed passenger service. Steam locomotives have been used interchangeably to some extent in railway service, but in general this has been found impracticable.

Transmission from Motor to Wheel. At the beginning of the paper it was stated that the transmission of power from the motor to the driving wheels is one of the most serious problems confronting the designer. It is closely allied with the type of framing, wheel base, and location of center of gravity of the locomotive. While many types of transmission are in successful operation, none is above criticism from some point of view.

Gearless Concentric Motors. It is well known that gearless motors in which the armature is carried dead on the axle while having the simplest transmission of all are destructive to roadbed when operated at high speeds. The mounting of the motor on a quill driving the wheels through springs is also objectionable from some standpoints, but it is open to less objection from the fact that its weight is all spring-supported against both vertical and lateral shocks.

There is a definite, though somewhat restricted, field where the gearless concentric motor is most successful. High service speed is essential to allow a rate of revolution sufficient to secure an economical power output per unit weight of motor. The gearless concentric motor for slow-speed operation cannot compete with the geared motor, as the weight and cost will be prohibitive. The power demanded per axle must not be so great as to result in wheel overloads.

TRANSMISSION THROUGH GEARS

Gears are very unpopular in many quarters, and have unquestionably some disadvantages. However, there is probably no part of the standard street car motor equipment which has given less trouble than the gears and pinions. There have been many cases of broken gears and of gears that have had an unduly short life, but all of these cases could be traced to a cause or causes which are now well understood, and can easily be avoided.

We feel perfectly safe in saying that, in the present state of the art, gears can be designed which will perform satisfactorily in any class of railway service. The improvements which have been made in the quality of gears and pinions by the use of high-grade materials having greater strength, higher elastic limits, and improved wearing qualities, are such that there should be no hesitancy on the part of the locomotive designer in recommending gears for service where a reduction from the armature speed is desirable, as in low-speed locomotives.

Gears for very slow-speed work may be pressed on the driving axle as in ordinary street car work. Where the motors are of large capacity, it will be necessary to use twin gears, as in the case of the locomotives for the Cascade Tunnel, and the high-speed freight locomotive No. 071 for the New York, New Haven & Hartford, R. R. The former has the gears pressed directly on the axle, but in the latter, the gears are mounted on quills. This latter design is much to be preferred, and is in fact necessary where the locomotives are to be operated at speeds much above 30 miles per hour. The use of the quill, of course, involves a further connection between the quill and the driving wheels. This is accomplished in the case of the New Haven locomotive by long helical springs, one end of which is clamped to a projection from the quill and the other to the spoke of the driving wheels. These springs have such a large amplitude of motion that the axle is almost entirely unrestrained by the motor which is mounted rigidly on the truck framing. On this locomotive the gears are also provided with a spring connection between the rim of the gear and the center, which removes practically all of the shock due to high pitch line speed, and at the same time divides the load equally between the two gears on the quill.

A further advantage of gearing the motor to a quill having large clearance around the axle is that it enables the motor to be mounted rigidly on the truck, and directly above the axle, thus permitting the greatest economy of space by bringing the driving axles close together. It also raises the center of gravity of the spring-borne parts and brings the motor well above the dust and dirt of the roadbed. And as the motor projects through the floor into the cab, the commutator, brushes and oil boxes are rendered accessible at all times. It also facilitates the use of forced ventilation which greatly increases the capacity of motors of the enclosed type. The limitations of this type of transmission are not yet well defined, as it has been in use but a short time, but the performance thus far has been so satisfactory as to give promise of its success in a wide range of application. It is believed that on account of the extreme flexibility of the drive that the pitch line speed may be raised to a much higher value than has ever before been deemed possible. The flexibility effectually prevents the extreme shocks which are ordinarily received by the gear teeth of a high speed locomotive when the gear is pressed directly on the axle.

The use of gearing which permits the armature to run at a higher speed of rotation than the driving axle, places a limit on the speed of the locomotive which from the point of view of the operating man may be undesirable. It is necessary in designing such a locomotive to consider the maximum speed at which the locomotive is to be operated and leave a margin above this figure before the safe limit of the armature speed is reached. The service conditions will determine the maximum locomotive speed and also the speed at which the motors should develop their continuous rating horse power. These two locomotive speeds and the limiting peripheral speed of the armature, together with the desired horse power output form the mechanical basis for the motor design. For economical designs it is not advisable to allow a maximum armature speed of more than 2 or 2.5 times the continuous rating speed. If a greater ratio than this is required, the armature speed must be reduced. The weight and cost of motor for a given continuous capacity will increase directly with this ratio.

Some of the other limits in a geared motor design are the pressure per inch width of gear face at the continuous rating, and the directly associated limit of the available distance between wheels, which must be divided between the gears and the motor. The available gear reduction is limited, on the one hand, by the diametral pitch necessary to secure a tooth with sufficient strength or life, together with the minimum number of teeth in the pinion consistent with low maintenance; and on the other hand, by the maximum number of teeth in the gear that can be applied with a given diameter of driving wheel with sufficient rail clearance.

With theoretically perfect gears a very high pitch line speed should be operative. In regular interurban mounting of motors, heavy strains are imposed on gear teeth in high speed operation by sudden vertical displacement of wheels due to track irregularities, with attendant acceleration or retardation of armature. In such applications a maximum pitch-line speed of 3,500 to 4,000 ft. per minute is operative. With complete spring support of motor and flexible connection to wheels, or with flexible gears, it is evident that a higher speed will be permissible. There are insufficient data at hand to approximate the limit under these conditions.

The above statements are all based on the use of spur gears and it is confidently expected that even better results can be obtained by the use of helical gears which are now coming into use. The success of this type of gear which is used for the Melville-McAlpin steam turbine drive indicates a sphere of usefulness for gears which has scarcely been touched.

While it is too early in the use of gears for large locomotives, to make an absolute statement of fact in regard to the allowable pressures, experience thus far indicates a pressure of 1,000 lb. per inch width of gear face as a perfectly practicable value for continuous rating of large gears. With special steel pinions and high grade gears it is probably safe to exceed this figure. It is well known that for short hauls pressures far above 1,000 lb. per inch are now in daily successful operation. In the locomotives for the St. Clair Tunnel, for instance, the pressure is carried on a single gear having a 6-in. width of face. The normal loads at which the locomotive operates on the up-grade give a pressure of from 1,500 to 2,000 lb. per inch width of face on the gears. With this pressure the pinions have a life of 40,000 to 50,000 miles, and none of the gears has yet worn out, although the locomotives have been in continuous operation for over two years. With twin gears there is a possibility of further increase in unit pressure as the absence of relative skewing of pinion and gear shafts produces a better application of the tooth load.

Probably the greatest limitation to the use of motors geared to the axles or to quills surrounding the axles is the restricted space between the wheels. As the output of the motor increases the width of the gear face must increase also, and this extra gear space must be deducted from the space ordinarily occupied by the motor. This results in motors having a larger diameter than would ordinarily be designed. In spite of this limitation, however, it is probable that geared motors as large as 500 h.p. continuous rating will be used. This is about as great an output as can be utilized on a single axle.

TRANSMISSION BY SIDE RODS

A desire to secure the good riding qualities of the high-speed steam locomotive, and at the same time to avoid the difficulties and limitations imposed by mounting the motor concentric with the axle, has lead to the adoption of side rods for transmitting the power from the motor to the wheels. There is a very strong tendency in this direction both in Europe and in this country. The general form universally adopted except for the three phase locomotives in Italy and Switzerland, which will be discussed separately, is that of the now familiar Pennsylvania locomotive which is illustrated by Fig. 6. The motor is mounted on top of the locomotive framing, and the armature shaft connected by quartered cranks to a jack-shaft located in the same plane as the driving axles. The power is transmitted from the jack-shaft to the wheels by other parallel rods.

This type possesses some very distinct advantages. It permits the use of a single powerful motor to drive two axles. The motor is mounted in the cab instead of under it so that all parts are readily accessible and are thoroughly protected from the dust, dirt and water from the road bed. The location of the heavy motor so high in the cab raises the center of gravity of the locomotive to a height corresponding to that of high-speed steam locomotives. The side rods form a transmission system that is familiar to all steam locomotive operators. It apparently has all the good points of the steam locomotive rods and is, in addition, susceptible of perfect mechanical balance and gives a uniform tractive effort.

There are, however, certain fundamental differences between the performances of side rods on steam and electric locomotives.

1. The steam locomotive transforms the heat energy of the steam into mechanical work by means of a reciprocating engine. Connecting rods and cranks are therefore essential

features. The electric locomotive on the other hand develops its power by rotation and no single type of transmission can be listed as indispensable.

2. In case of a steam locomotive there are at least two independent sources of mechanical forces, viz., the cylinders. Each piston constitutes a "free end" of the transmission system. The distance from the center of cylinder to the center of main driver axle is not a hard and fast value, as a slight variation means only a change of crosshead overrun and of cylinder clearances. In an electric locomotive where there is a single motor, crank and rod connected to a countershaft, there are no "free ends" to the system. For this reason great accuracy of tram and parallelism of motor shaft and countershaft are essential, any error being accompanied by serious stresses in the transmission with associated low mechanical efficiency and high maintenance charge, especially for bearing brasses.

3. In the steam engine the stresses on the transmission system at any point in the cycle can be very closely approximated by means of indicator cards taken from the cylinder, together with centrifugal stresses. In other words, each side of the engine can be considered separately. With the electric locomotive on the other hand, there is but one source of mechanical force; viz., the motor which exerts a constant turning moment or torque throughout the entire revolution. This constant torque must be transmitted to the driving axle without modification except for the losses in bearings. At certain points in the cycle all the torque of the motors is transmitted through one crank; at certain other points it is transmitted through the opposite crank. At intermediate points it may or may not be transmitted through a single crank, as the interchange of work is different in different machines, being a composite function of journal and pin clearances together with bending and torsional deflections of all elements of the transmission and framing. It is therefore not possible to analyze the forces on one side of the locomotive independently of the other side.

4. In the steam locomotive the main rod connects the cross head to the drive wheels. In the electric, all the driving effort is transmitted through four running pins in series before any useful work is performed. This results in considerable loss of mechanical efficiency. It may be noted that the use of knuckle pins would avoid one or possibly two of the running pins mentioned but thus far no railway operator has been found in this country who

is willing to accept knuckle pins in an electric locomotive. Knuckle pins have caused so much trouble from breakage that they will have to be modified considerably before they will be acceptable. The trouble seems to lie in the twisting of the rods due to uneven track.

The side rod type of locomotive is at a disadvantage when compared with the high-speed geared type described, because of the fact that the mechanical parts of the locomotive and also the motor frames must necessarily be much heavier to withstand the reciprocating stresses imposed on them. They will also require much more careful work in assembling and will therefore be more expensive. On the other hand, it would seem that after the side-rod locomotive is once completed, the mechanical parts should be very cheap to maintain. The results of the operation of the Pennsylvania locomotives will be awaited with great interest.

Scotch Yoke Side Rod Type

The type of drive which has been used to the greatest extent with the three-phase locomotives in Italy is that illustrated in Fig. 9, utilizing the so-called " Scotch Yoke " for connecting the motors with the driving wheels. This has been in use for several years and has apparently given excellent results. In these machines much of the criticism attendant upon connecting rod applications has been obviated. The motors, being flexibly attached to the spring-borne parts, are not subject to severe cranking strains and can therefore be made light mechanically. The motor shafts, it is true, should line and tram accurately but they are so located that this can be done with minimum difficulty. The mechanical parts also can be made considerably lighter because of the fact that there is no jack-shaft required, and the cranking strains are taken directly on the armature shafts which are supported in bearings in the side frames. The design, however, sacrifices high center of gravity, and some alternate plan for securing easy riding qualities must be adopted. One which has been suggested utilizes a plan somewhat in line with that suggested for the gearless concentric motors; namely having springs between the motor and side frames for cushioning lateral shocks. The mechanical efficiency of this type should be higher than that of the rod-connected design, because of the fact that the power is not transmitted through so many running pins. It has the objectionable feature of a sliding connection between the driving yoke and the pin on the middle driving wheel, but this apparently causes no trouble whatever. In fact, the locomotives as observed on the Valtellina Railway operate smoothly, and apparently with small friction loss. This may be ascribed in part to the fact that all bearings are kept flooded with oil. The use of knuckle pins for transmitting power from the "Scotch Yoke" to the outer driving wheels is made perfectly safe by the use of spherical pins or spherical bearings.

This type of drive will give probably a lighter locomotive than is possible with any other drive having motors operating at the same speed as the driving axles. It has thus far not met with favor in this country, but its merits will undoubtedly bring it into use for moderate speed work where gearless motors are desired.

COMBINATION GEAR AND CONNECTING ROD DRIVE.

Where slower speeds are desired than can be secured by the use of motors operating at the same speed as the axles it is sometimes more economical to use two motors geared to jackshafts and connected to the drivers by means of the "Scotch Yoke" in the same way as just described. Fig. 10. This scheme has some advantageous features which are not at first apparent. It permits the use of large motors and gives much greater space for them than can be secured between the drive wheels where the motors are geared either to the axles or to quills surrounding the axles. The motor is mounted so that its center of gravity is high, and as it extends through the floor into the cab, the bearings and brushes are easily accessible. In this respect the motor has all of the advantages possessed by the rod-connected motor. Gears can be located outside of the driving wheel so that they can be replaced without dismantling the locomotive any further than required by the removal of the side rods. Locomotives involving this priciple have been built in Europe, and a large one is now under construction for the Midi Railway in France. As stated before, it is especially fitted for work where it is desirable to reduce the number of motors to a minimum and at the same time operate at slow speeds with heavy tractive efforts.

This locomotive, however, is subject to such criticism as is involved in synchronous revolution of many parts with a consequent loss in efficiency and with possible inertia complications. In this respect it is practically on a par with all rod-connected locomotives.

ROD-CONNECTED LOCOMOTIVE WITH RADIAL AXLE

A description of the principal types of transmission would scarcely be complete without mention of the three-phase locomotives now in use in the Simplon Tunnel. These locomotives have been described in the technical press. The chief point of interest lies in the location of the motors, the connection to the drivers, and in the radial driving wheels at the ends of the locomotive. The motors are located as close together at the middle of the locomotive as possible, and their crank pins are connected together by a frame. From pins on this frame on a line with the center of the axles, rods are carried to the nearest driving wheels, and thence other rods connected to the axles of the outer drivers, there being four pairs of driving wheels. It is, of course, essential where side rods are used that all axles should remain substantially parallel, and in order to secure the radial motion of the wheels at the ends of the locomotives, it is necessary to mount the wheels on quills which surround the axles and connect them together only at the middle point by a kind of universal joint. By these means the wheels are able to move in a radial direction, while the axles which drive them are kept parallel to the inside driving axles. This seems to be operating very satisfactorily, and with some modifications will probably meet other conditions where all the weight is carried on the drivers, and a rigid frame locomotive with flexible wheel base is required.

CONCLUSION

The foregoing survey is incomplete, as the possible combinations of locomotive framing, motors, and transmission between motors and drivers are almost limitless, and it would be impossible in a paper of reasonable length to discuss even those that are well-known. The aim has been to present the problem as viewed by the authors, and to discuss a few of the fundamental principles on which the design of the locomotive should be based.

The problem is in a word: To design a locomotive incorporating all essential features, and as many non-essential but desirable features as possible, and for a price that will make electrification attractive to railway officials.

DISCUSSION ON "THE DESIGN OF THE ELECTRIC LOCOMOTIVE". JEFFERSON, N. H., JULY 1, 1910.

Wm. McClellan: I should like to emphasize the absolute necessity of designing electric locomotives with reference to track conditions.

As speeds increase and loads get heavier, maintenance of track is difficult in any case. It is especially so, however, when trains of a great variety of speeds pass over the same track. Roadway men know how difficult it is to fix proper elevation of rail, surface and align the rail, and bed the ties so that the result will be equally good for low-speed freight trains and for high-speed passenger trains.

In regard to the question of interchangeability, there is another feature which is of great importance. In freight service, we cannot dispatch trains and adhere closely to the schedule with the same degree of accuracy that we can in passenger service. We can design a locomotive for handling a certain kind of passenger service and it is quite likely that the locomotive will not often be used under very different conditions. On the other hand we may design a locomotive for a certain kind of freight service, and instead, for example, of going over the road with few stops at a good speed, traffic conditions may compel it to start and stop with great frequency, or run at an extremely low speed for the bulk of the time. To put it differently, the freight locomotive may be designed for through service, but may be compelled through the exigencies of conditions to do the equivalent of switching service. This does not apply to the electrification done so far which has been chiefly on tunnels and grades.

A. F. Batchelder: There are a few points to which I would call special attention and about which I cannot fully agree with the paper.

As to the order of importance of the different points of design, I cannot agree that the dead weight per axle is necessarily second. A great many differently designed locomotives have been built and operated. So far as my experience goes, I have not seen as yet, neither have I been able to find anybody that has seen, any design where the dead weight has had any detrimental effect on the track as long as it is limited to the weight of the motors, the journal boxes, spring saddles, and with the rotating parts balanced and the trucks properly equalized.

There are electric locomotives in regular operation that have dead weight per axle as high as 17,000 lb., and so far as I can learn, there is no indication that this dead weight has any bad effect on the road bed or track.

Of course it is well understood that on steam locomotives where the wheels are not well balanced and the locomotive running at high speeds, the unbalanced weight has a bad effect on the rails and road bed.

Relative to the height of the center of gravity being important, I believe a high center of gravity will assist in making an easy guiding locomotive, providing the spring supported portion is carried on journals placed between the wheels, making the spring centers approximately 42 in. apart, as is the general practice on steam locomotives; but with electric locomotives with outside journal boxes where the spring centers are placed approximately 80 in. apart, a high center of gravity say from 60 to 75 in. is but very little assistance to making the locomotive guide easily.

The feature desirable to obtain is the rolling effect in entering curves, and it will be seen that the rolling effect will be much less with a high center of gravity locomotive where the spring centers are 80 in. apart than it would be if the spring centers were only 42 in. apart. It will be seen that in order to obtain the same effect where the spring centers are 80 in. apart it is necessary to have the height of center of gravity above the point of thrust nearly twice as great as with spring centers 42 in. apart.

The paper also speaks of the different opinions of engineers and their choice as to the weight per axle. It has been my experience that it is not the opinion of the engineers, but the physical conditions such as the weight of rail, and strength of bridges and road bed, that determine the weight per axle allowed, and the railway engineer is in position to know these, and insist upon designing the locomotives to suit the conditions.

Another point that the paper brings out very nicely is the necessity of concentrating the mass of the locomotive as near the center as possible. I might add that it is also desirable to make the guiding wheels as far forward of this weight as possible, as it is well understood that if we have something to guide, the longer the handle the easier it is to manage.

I might also mention that it is the spring-borne portion of the locomotive that is the most difficult to manage. It is this portion that can set up oscillations and build up a movement that is difficult to stop without doing damage to the track by the guiding wheels. If the greater portion of the weight of the spring-borne part is concentrated near the center or well back from the guiding wheels and with a damper to prevent its building up oscillation, it is perfectly practicable to guide a very heavy locomotive without damage to the track.

Every locomotive truck that runs on rails is bound to oscillate from one side to the other, on some portion of the railroad, and it is practically impossible to make a locomotive run without doing this. Therefore, it is necessary for us to accept this oscillation as being inherent, and for high-speed locomotives, we must design so that this oscillation will do no damage.

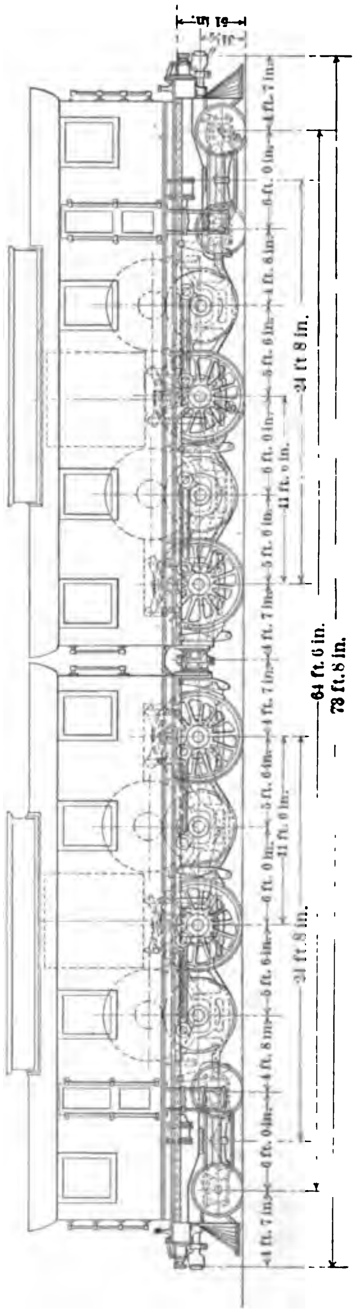
It may be interesting to examine the design of the locomotive shown in the accompanying illustration which I believe embodies most of the desirable features discussed and which we have worked out to meet the requirements of heavy trunk line service; it has a tractive effort of nearly 30,000 lb., continuously, and a maximum tractive effort for short intervals of time of 80,000 lb.

It will be noted that it has a reasonably high center of gravity, narrow distances between springs, the weight of the spring-borne portion well back from the guiding wheels, motor flexibly supported, and each driving axle is driven through quartering cranks and side rods from a jack shaft which is driven by the motor through spur gearing.

We have looked into this design very carefully and find it possible to build it with motors of sufficient capacity for the heavy trunk line service on mountain divisions and keep the total weight within reasonable limits.

In general the locomotive is made up of two American type engines coupled back to back having two driving axles and a two axle leading truck on each section.

It has been well proven that the American type engines operate very satisfactorily at all speeds on our American railroads and for this reason, I believe that this type of electric locomotive will operate the same under the same conditions.



Frank J. Sprague: I cannot express my belief as to the best type of electric locomotives, for I am a member of the Electrical Commission of a prominent railroad company which will soon be engaged in the task of dissecting proposals which have been accumulating for the past eight or nine months, from manufacturing companies, involving quite a variety of locomotive designs as well as methods of motor operation: It would, therefore, be improper for me at the present to express any preference for a particular design, even if I had any. As a matter of fact, I am of an open mind.

We can all agree with the authors in the general statement of the requirements of an electric locomotive, which might more tersely be stated to the effect that we want to get all that we can in capacity and good tracking characteristics for the least money. That I think is the argument which will appeal in behalf of electric traction to railroad officers and engineers. Not only must we seek all that is possible in the matter of capacity and good riding qualities, but also incorporate in the locomotive all that is practicable which has been found to be good in the steam locomotive, but which is not necessarily individual to, or especially characteristic of steam operation, and also all that is good so far as possible in electric operation. Now, how? I suppose there are few engineers of maintenance who do not at times think the superintendent of motive power ought to scrap most of his engines, and likewise it is a good natured and patient superintendent of motive power who does not occasionally condemn the track engineer for the condition of his track. Perhaps that is stating the facts a bit strongly, but it illustrates the feeling which exists oftentimes between two great operating departments of our railroads which should coöperate, because after all the locomotive and the track are married, and you cannot divorce them. Each affects the other, and neither has the right of way over the other; both are vital to the operation of the railroad.

The authors describe various methods of motor mounting and their effect upon the construction of the locomotives. I find it more convenient to consider locomotives, at first, irrespective of their motor mountings, and as divided broadly into three classes: locomotives with fixed wheel bases, either with or without a leading truck, the truck having either one or two axles; locomotives with bogie trucks, symmetrical or otherwise, and either linked together or independent; and articulated locomotives, that is, made up of two sections each having drivers forming a fixed wheel base, and with a bogie truck, the two parts being hitched back to back. There are many modifications of these types. Each of these forms can have a variety of motor mountings. A typical example of the first are the locomotives of the New York Central & Hudson River Railroad; of the second, the locomotives running on the New York, New Haven & Hartford Railroad, on the Great Northern, and in the Detroit Tunnel; and of the third, the locomotives which are being installed on the Pennsylvania railroad. Motors can be geared, according to my original practice, and there are some scores of thousands running that way, many of them at almost the maximum speeds that are attained by any steam locomotive in this country; that is, there are plenty of interurban roads on which bogie truck cars, with motors geared to the axles, are running up to sixty miles an hour without materially bad effects on the track. That method of construction has certain advantages which have been well expressed by the authors. Then there is the gearless type of motor, one which has appealed in many respects to every engineer who looks alone to the question of the simplicity of electric operation, because of the removal of every detail of side rod, extra bearings and gears as a necessary connection between the motor and the wheels. The gearless locomotive has some very distinct advantages, but also some distinct disadvantages. Space limitations, necessarily are somewhat exact, and part of the dead weight is carried on the axles; it may, however, be almost entirely spring-borne. The wheels are of moderate diameter, and the capacity of the machines, if built for low speeds, somewhat limited.

Then there is the side rod locomotive, which now seems to be coming into vogue, having been appropriated from steam railroad practice. There is also the combination of the geared and side rod locomotive, as illustrated in the drawing shown by Mr. Batchelder. One thing we must bear in mind, and that is the further we get away from direct gearing, or from gearless motors, the further we get away from simplicity. Every locomotive design must be a compromise; it cannot be one which is limited primarily by the kind of current one is going to use, nor on the other hand by the desire for simplicity; it certainly must not be limited by the demands of the steam engineer.

The latter has handed to us a morsel which we are rolling under our tongues with a good deal of avidity, and which is expressed several times in the paper presented this morning by the phrase " high center of gravity." I agree with Mr. Batchelder that the question of high center of gravity is less important than many other things in the construction of an electric locomotive, and I consider it perfectly possible to build a locomotive with a large disregard to the center of gravity, which will operate satisfactorily at either low or high speed. What is vital is that every wheel on a locomotive shall be independently shackled, if I may use that expression, so that it can have reasonable vertical and lateral movements to meet track irregularities without disturbing any more than necessary the balance of the locomotive, or the position of the superstructure. Of course, if wheels are rigidly mounted in bearings so that they cannot traverse in any direction without moving the whole mass of the locomotive we have a condition which is intolerable, no matter whether it is in a steam or an electric locomotive.

I will refer to the developments on one or two locomotives which will illustrate some practical points. Let us first consider the conditions which take place when a locomotive is running, both at slow and high speed. Every road is made up of tangents and curves. If we had a dead true surface and alignment, continuous rails and close gauge, it would not make much difference on a tangent whether high or low center of gravity was used, or what the springs were. With like conditions on a true curve, it would, after entering the curve, make little difference where the position of center of gravity is, because, after all, the flange of the wheel and the head of the rail are in intimate contact, and must remain so. Of course, we do not have these conditions, and therein lies the necessary for building locomotives to meet the actual conditions. However, with all the variations of surface and alignment, the track does not come up and hit the locomotive in the face, or give it a slap on one side. We have a pair of wheels slightly coned, and a certain lateral movement, traveling on two uneven rails, and as Mr. Batchelder has explained, it is impossible for two cones to so travel and maintain a central position, even on a true track. There is a tendency for these wheels to travel first one way and then another. The more slowly the locomotive moves the more difficult it is to traverse the rail, the faster it moves the more easily will the wheel traverse to one side or the other, the more severe will be the blow of the wheel when it does so traverse, and the heavier the blow which the flange will give to the rail when it recoils. You are all familiar with the early practice in regard to dynamos, putting a spring on the end of the armature to make the armature traverse back and forth to bring about an even wear of the commutator and brushes. The faster the armature traveled the easier it was to get it to move laterally. If you gave it too much play, a sharp push would drive it with a violent hammer blow against one bearing, and it would then rebound and strike the other. That happens on the locomotives at high speed on the rails as well as on the fast turning armature of a dynamo.

It has been said that with a high center of gravity, when you strike a curve the mass of the locomotive rolls over, the center of gravity goes towards the outer wheels, and the pressure on the outer rails is increased, thus increasing the rail resistance. I wonder if anyone who has made this statement has really investigated the problem to find out how far the center of gravity does travel, and what is the actual increase of pressure on the outer rail. If the rail is not properly banked and properly spiked to the ties, it would be better not to attempt to run a high speed locomotive on curves, because the increase of side pressure on the rail would be such that the ties would never hold it in place no matter what the increase of top pressure. The essential thing which takes place is the introduction of a time element before the flange has to take the entire pressure, as, of course, it eventually must.

On the New York Central, and also on the New York, New Haven & Hartford locomotives, certain characteristics early developed in practice which made it advisable to make some changes. The original Central locomotive had a fixed wheel base with four driving axles, and a pony truck at each end.

in this country; that is, there are plenty of interurban roads on which bogie truck cars, with motors geared to the axles, are running up to sixty miles an hour without materially bad effects on the track. That method of construction has certain advantages which have been well expressed by the authors. Then there is the gearless type of motor, one which has appealed in many respects to every engineer who looks alone to the question of the simplicity of electric operation, because of the removal of every detail of side rod, extra bearings and gears as a necessary connection between the motor and the wheels. The gearless locomotive has some very distinct advantages, but also some distinct disadvantages. Space limitations, necessarily are somewhat exact, and part of the dead weight is carried on the axles; it may, however, be almost entirely spring-borne. The wheels are of moderate diameter, and the capacity of the machines, if built for low speeds, somewhat limited.

Then there is the side rod locomotive, which now seems to be coming into vogue, having been appropriated from steam railroad practice. There is also the combination of the geared and side rod locomotive, as illustrated in the drawing shown by Mr. Batchelder. One thing we must bear in mind, and that is the further we get away from direct gearing, or from gearless motors, the further we get away from simplicity. Every locomotive design must be a compromise; it cannot be one which is limited primarily by the kind of current one is going to use, nor on the other hand by the desire for simplicity; it certainly must not be limited by the demands of the steam engineer.

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This truck may be described as a triangle, pivoted at the apex, and driving a single pair of wheels at its base. It was spring centered to normally maintain a central position. On the trial runs, at high speed on a tangent, some oscillation developed, with resultant side pressure on the rails. This was corrected by damping the motion of the truck, in other words, steadying it.

Shortly after the equipment was put into regular operation, there was a grave accident to a double header light train running at high speed, which some people have taken as a basis for a criticism of that type of locomotive, and various comments about the position of the center of gravity have appeared. A writer in an engineering magazine some time ago referred to this accident in a critical sort of way, not by name but by plain inference, and said that the responsibility for the accident was probably due to the low center of gravity. As voicing the admitted findings of every investigation committee, that statement is unwarranted. Referring to this accident, it is a curious fact that the locomotives never got away from the track; some of the wheels jumped the rails, but the coupled locomotives did not topple over, nor get away, notwithstanding their mass and the high speed at which they were traveling.

The same machines, without any change, were in operation for a long time subsequently, and are in operation to-day. Sometime since, however, a change was made which for some reasons I think was advisable. This did away with the single wheel truck, and substituted therefore a four-wheeled pivoted truck, an experience through which the steam locomotive has also gone.

On a curve such a truck yields easily, as it first turns on a pivot, instead of attempting to at once turn the mass of the locomotive. Then the forward wheel acting as a guide, with the rear as a fulcrum, helps the head of the locomotive around; in other words, the truck is the handle for turning. That is one improvement, but another was also introduced, and it was so good that our steam friends applied it to certain types of their steam locomotives; this was to give a greater lateral, but spring-resisted traverse to the wheels. I make it a practice, in going to and from my summer home, to ride on these locomotives to watch their operation. They run on old and new track, up to a speed of sixty miles an hour, and I find them very satisfactory.

It is a curious coincidence that on the New Haven road a train came within the closest shave of a disaster of even greater seriousness, when, running at high speed, two of the locomotives left the rails at the bridge at Greenwich, with the result, most fortunately, that but one person was killed. The wreck, however, was a pretty bad one. An immediate inspection of the track, following back a considerable distance, is reported to have disclosed some lateral displacement of rails. These locomotives, it will be remembered, have bogie trucks, spring suspended motors, and a somewhat higher center of gravity than the Central's. The difficulty developed has been largely corrected by extending the wheel base, and putting a pair of leading wheels on each truck. I think in this respect they are now running satisfactorily.

It has been stated that a non-symmetrical locomotive is essential to prevent oscillation in a horizontal plane on the track. I think the term is more or less misunderstood, but if we take the locomotive on a whole, I cannot agree with that conclusion. I believe that a symmetrical locomotive, whether it be of the articulated, or fixed wheel base, or any other type, is the electric locomotive of the future; the halves, of course, o an articulated or bogie truck locomotive can, and probably should be unsymmetrical.

The authors have made one statement to which I must take exception, and that is that from an operating standpoint the railway man would like to have one locomotive which will handle at the desired speeds the heaviest freight and the fastest limited passenger trains. That statement can hardly be intended to be accepted in the fullness of its meaning. While it may be true as to its desirability, if it were possible, in the matter of a steam locomotive, it is distinctly not true with an electric locomotive, because the multiple-unit system which I introduced some twelve years ago has made possible any desired combination of locomotive units under a single crew. But what I would call to your attention is the fact that under some conditions it is highly desirable to consider the possibility of a locomotive which will be interchangeable for freight and passenger service for certain *fixed units of trailing load*. For example, it may be desirable, with certain limiting mountain grade conditions, to have a locomotive which can operate, say, 400- to 450-ton passenger trains at one speed, and a 500-ton freight unit at half that speed, and then to consolidate these locomotives as desired according to the train make-up. It can be admitted that theoretically this is not the most economical plan on which to build locomotives per se, but the alternative, of course, is to build electric locomotives for passenger and freight service of distinct characteristics and sizes, and without interchangeability of parts. Now on most of our mountain grade divisions we have stretches of single track operation, with frequent sidings, to take care of opposing slow and fast freight and passenger traffic. Every single-track railroad, no matter how frequently it is equipped with sidings, is a difficult road to operate, especially if the traffic is heavy. On account of varying grades it is the practice when using steam locomotives, and it will be so with electric equipment, to add to and drop off locomotives as may be demanded by the varying duty, but in any case idle movements of locomotives is a thing to be avoided, as far as possible, because locomotive movements cannot oppose traffic without affecting materially the whole movement of through freight or passenger service on the line for a considerable period. Therefore if a locomotive can, without too great cost, be made available for interchangeable service, that is a desideratum to be seriously considered. It may result, of course, in a somewhat larger powered machine than is strictly required in the freight service, and a little heavier one than required for passenger service, but there will be a less total number because, instead of having two kinds of locomotives for each of which there must be reserve equipment, there will be only one kind, with a less total reserve equipment.

Another thing, it is cheaper to build a locomotive of a certain capacity than to build two of half power. The cost does not increase in proportion to the capacity. Another fact to be remembered is the importance of being able at any portion of the line to pick up or drop off a locomotive which shall be equally available for passenger or freight service.

I do not intend to take further time, but I want to emphasize two points. I am opposed to the idea that a very high center of gravity is vital to a successful electric locomotive. The idea has been handed down to us by our steam friends, and it has certain advantages. They cannot for many reasons get along without it on steam machines built for high speed. I also wish to emphasize the practical importance of sometimes having locomotives interchangeable for unit freight and passenger loads, as conditions may dictate the absolute necessity for such interchangeability.

A. H. Armstrong: In my opinion Mr. Sprague has not put the case too strongly in insisting upon the necessity of having freight and passenger locomotives interchangeable on mountain divisions where the maximum speeds are necessarily low. The weight of passenger trains may reach 600 tons trailing load and freight trains from 1800 to 2500 tons trailing load. It is desirable to move a train with a single locomotive unit if possible, but where grades approach two per cent on the better class of mountain divisions and even higher than this on some lines located before the requirements of modern freight traffic were thoroughly appreciated, it becomes necessary to consider two or more units per train in order to provide the draw bar pull required.

It is entirely feasible to consider an interchangeable type of locomotive running full speed with 600 ton passenger train units and half speed with a somewhat greater freight train load. A passenger train could be handled by a single unit while two or three units may be required with freight trains weighing two or three times as much.

The ratio of speeds, passenger and freight, may be taken at about 2 to 1 on mountain divisions, so that interchangeable locomotives of a uniform type offer a great advantage to the operating department on such grade sections as demand the use of helpers. Should such a uniform design of locomotive be adopted for passenger and freight service, a difficulty is removed with electric locomotives which is not experienced with steam helpers. The electric locomotive operates to best advantage at one or two speeds only while the steam locomotive can give its full horse-power output at nearly any speed, and hence is adopted to act as helper to either a passenger or freight train, working efficiently at the operating speeds of both.

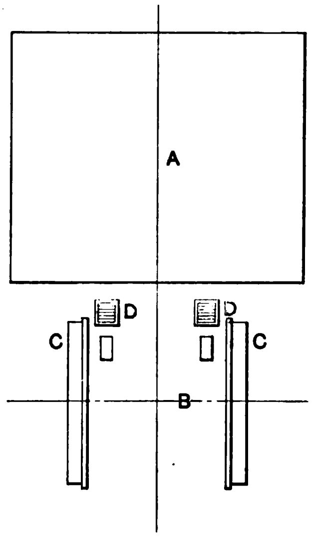
I think therefore that the matter of interchangeability is one of very vital importance and one that will be thoroughly appreciated by the operating department.

G. M. Eaton: Mr. Batchelder, in discussing this paper, was pleased to call it a mechanical paper. I wish to give you the reason why it seemed best to make the paper mechanical. In discussing Mr. Gasche's paper on Wednesday night, Dr. Steinmetz stated that in mill work the service, while far more severe than railway work, was a definite service. Now, in railway work, we find that the service of the motor from an electrical stand-point is very definite, and can be calculated to quite a degree of nicety, but we are confronted with an entirely different problem in calculating the mechanical stresses resulting from the negotiation of rails at high speed. This service produces maxima on the structure of the locomotive which are very hard to determine accurately. We can take a single rail defect, and assume all the conditions necessary, such as a known dead weight on the rail, spring-borne weight on the journal, speed of locomotives, etc., and under these conditions, we can work out a close solution of the stresses resulting on the framing. Unfortunately, however, when the locomotive strikes the first soft spot in the track, the conditions which are met are sure to be different from the conditions which were assumed in the calculations. We have then a nice set of figures, but the only real gain consists of the clearer conception, in the mind of the calculator, of what takes place in negotiating track of the particular characteristics assumed. This again is only the first step, as we must then consider the phase in which the various track irregularities occur, and the possible combinations with which we are confronted are legion. The application of exact mathematics is therefore impracticable in determining the precise dimensions of any given locomotive frame. Designers of electric locomotives must devote much study, however, to the means for minimizing the mechanical stresses on locomotive framing, and on track construction, and for this reason the paper under discussion is largely mechanical.

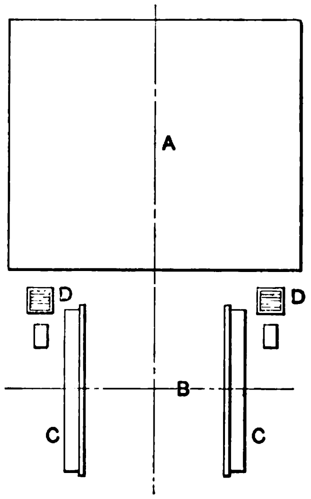
Mr. Batchelder stated that the dead weight on the axle was not productive of track destruction, so long as this weight was not in rotative unbalance. An examination of track maintenance on high speed interurban lines where dense traffic exists, shows room for improvement, and considerable experimentation is being carried out by some large operators' with a view to reducing the dead weight on rolling stock of this class.

Mr. Batchelder stated that the transverse distance between the semielleptic springs is of more importance than the height of the center of gravity. If this theorem could be substantiated it would constitute a severe arraignment against a low center of gravity locomotive with outside frames and a broad spring base. I wish to take exception to this theorem, however, for two reasons. Sketch No. 1 shows a locomotive with inside frames, and sketch No. 2 a locomotive with outside frames.

In each case, *A* represents the spring-borne parts of the locomotive, *B* the axle, *C C* the wheels and *D D* the springs. We agree at once that the arm with which the springs resist the swinging of the spring-borne parts is longer with the springs outside of the wheels; but, referring to Mr. Batchelder's illustration, you will note that as the locomotive has been laid out the advantage of the inside frames, namely, the short transverse spring base, has been very largely sacrificed by the short stiff spring. This is not inherent in the design, but attention is called to it to show that we must go further than the spring location, and must examine the spring characteristics. If the springs are designed with greater flexibility, then with outside frames, the desired angular displacement of the mass of spring-borne parts can be secured. This greater flexibility will mean somewhat heavier springs, and to that extent a heavier locomotive; but in the locomotive shown by Mr. Batchelder far too many sacrifices are made in order to gain the lighter spring. When countershafts and connecting rods are added, introducing reciprocating stresses, I am convinced that too much has been spent in payment for a narrow spring base.



Sketch No. 1



Sketch No. 2

The locomotive as shown has the great advantage of having the minimum amount of rotative masses tied together, that is, each driving axle has its own motor, and if the wheels on one axle wear a little faster than those on the other, it is not necessary to machine all the wheels. This seems to be the chief advantage of the design as shown.

The second reason for taking exception to Mr. Batchelder's statement, though this reason is of first importance, is that the swinging of the spring-borne parts is resisted first by their own inertia, and second by the springs. The springs cannot act until after motion has actually started, and when the center of gravity is close to the point of side restraint, the blow on the rails will have been delivered, and whatever mischief is going to occur will have taken place before the springs have a chance to get in their work. It is, therefore, of paramount importance to secure the maximum operative vertical distance between the center of gravity of the spring-borne parts, and the point at which the transverse blow is delivered to the spring-borne parts, and any other considerations, such as narrow or broad spring base, are entirely secondary.

Mr. Batchelder also remarked that the dead weight in steam locomotives designed for switching service did not produce harmful effects on the track. In studying electric switching service, if we set up as our ideal the track maintenance that is involved under steam operation we are looking at the problem from an erroneous standpoint. The maintenance in steam operated yards is heavy, but it is something to which operating men have become accustomed. They expect it, and they certainly get it. In considering the electric locomotive, we must remember that there is no incentive to electrification if we cannot beat the steam locomotive. We must beat them at their own game, or we cannot make good.

Referring to Mr. Sprague's remarks, I like the phrase that the locomotive and the track are in a state of matrimony and cannot be divorced. We can in fact carry the comparison a little further. We are led to believe that the compromise in many matrimonial relations is entirely one-sided, and in our American locomotive designs, we make the locomotive so rigid that all the compromising in the horizontal plane must be done by the track. This is not a fair proposition. In this connection I want to make a plea for plate frames on electric locomotives. We have not come to it in this country, but it is being done very successfully in Europe. They have frames which will yield, and which will take their share in the horizontal plane, and this results in a reduction of track maintenance. In this country the track maintenance, that is, the maintenance of rails, ties, culverts, and bridges—runs from about the same as rolling stock maintenance to as much as twice rolling stock maintenance. It is quite generally conceded that much more than half of the track destruction resulting from the passage of a train can be charged up to the locomotive. We can, therefore, imagine a locomotive in which maintenance is increased a little, while the maintenance of the entire system is very materially decreased and this with greater safety of operation. What seems to be necessary then is for the railway organization to be under one supreme head who will say to the heads of the various departments: " Now, gentlemen, get together ". In this ideal organization, the various departments are not working each for themselves, but all are working for the railroad as a whole. This is the ideal to which large railroad organizations just the same as any other large organizations should bend.

Referring further to Mr. Sprague's remarks on center of gravity, he said, that it was entirely possible in his opinion to build a low center of gravity machine for successful high speed operation. I agree with Mr. Sprague that it may be possible. I do not believe, however, that it has ever been done.

Mr. Sprague referred to the Greenwich wreck on the New Haven Road, and I should like to add a little to his remarks. Mr. Storer and I left the Grand Central Station on the train immediately following the one which was wrecked, and arrived at the scene of the wreck within about 20 minutes of the time it occurred. The most impressive feature of this wreck to me was the way in which the locomotives held the train in tension after the derailment occurred. Instead of going through the bridge as a steam locomotive would probably have done, they carried every car safely over the bridge, although nothing but the steel bridge girders was left after the last car passed. The motors slid on the rails, so that the wheels could not cut deeply into the ties, and it was not until a Pullman truck had skewed around, causing its car to turn on the side, that any buckling of the train occurred. After this coach overturned, there was sufficient inertia in the locomotives to pull out a car drawhead and the locomotives and several cars ran 300 ft. further before stopping. The locomotives were then put on the rails and proceeded to the power house by their own power.

The number of deaths that have been caused by steam locomotive derailments, would have been materially decreased if the locomotives had been fitted with skid bars which would perform the duty so well fulfilled by the motors at Greenwich. A locomotive with high center of gravity and equipped with skid bars, would combine the desirable features of minimum derailing tendency, together with a minimum of destruction due to a derailment caused by a track defect.

N. W. Storer: Mr. Sprague took exception to our statement in the early part of the paper, to the effect that the superintendent of motive power and the superintendent of the operating department, would like, if possible, to have an absolutely interchangeable locomotive. He denied that statement, and then proceeded to prove it was absolutely necessary to have an interchangeable locomotive. I believe that the statement in the paper is correct; I believe fully it would be desirable to have an interchangeable locomotive if it is commercially possible. That is the whole point in the matter, and it is not necessary to try to prove at all that such a thing is desirable. If the operating man can afford to spend, or if the company can afford to spend, a large percentage more for locomotives for operating the trains over the road under a system which will make it necessary to have only one type of locomotive on the road, then it is commercially possible and quite practicable.

Elmer A. Sperry: The Institute is to be congratulated upon so timely a paper as that of Messrs. Storer and Eaton dwelling as it does upon the detailed construction of the heavier class of locomotives, especially with reference to the more general mechanical arrangement, distribution of weights, methods of power transmission, etc. In connection with mechanical design it might be well to point out one other phase, namely, its bearing upon the development of draw bar pull, upon the apparent adhesion and also upon tractive effort.

Many observations have been made in connection with slipping of drivers of locomotives, and of trucks, especially those employed in heavy service. There has also been considerable discussion with regard to the internal stresses and especially the redistribution of weights upon drivers under conditions of developing maximum draw bar pull.

In 1888, the writer drew attention to the very large apparent difference between the total coefficient of adhesion as between separately driven and coupled axles. There were cases where the latter showed repeated and continuous evidence of developing some 40 per cent more draw bar pull than the former. An investigation was started to ascertain the nature and extent of the difference between these two types. As the work progressed, it was at once seen that perfectly concordant results were being obtained and that a law governed the case which could be expressed by formula which was afterwards found to be a correct expression of the facts. This formula may be stated as follows:

Maximum draw-bar pull with independent axles.

$$P = \frac{W\phi}{20\frac{h}{b} + 1}$$

in which

P = the draw bar pull (maximum).
W = the weight (total) of locomotive in pounds.
ϕ = the coefficient of adhesion.
h = the height of bolster or drawhead.
b = the wheel base.

With coupled axles, either by rods or gears, the maximum pull is simply $W\phi$.

It will be observed from the foregoing that in any truck where the bolster height is *equal* to the wheel base, we are obtaining about 66 per cent of what we are really entitled to, and the coupling of the drivers will give us an increase of tractive effort of *one-half more*; in trucks where the wheel base is 1½ times the bolster height we are obtaining 75 per cent of what we are entitled to and the coupling would yield one-third more; and in trucks where the wheel base is twice the bolster height we are obtaining 80 per cent and the coupling would yield 25 per cent more. We thus see that this is not at all an insignificant matter but one of large magnitude.

FIG. 1

In 1890 the writer was engaged in manufacturing locomotives in which this principle of coupling the drivers to obtain maximum draw-bar pull was carried out to an extent quite unique at that time, and even since, namely, the class of locomotives having four axles or eight drivers connected with a single motor. See Figs. No. 1 and 2.

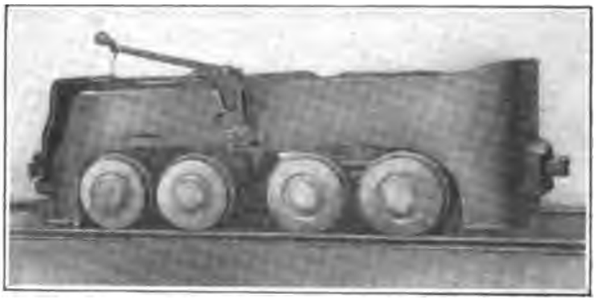


FIG. 2

In June 1892 the writer presented a paper before this body at its annual meeting in Chicago referring to experience and results obtained with this class of locomotive under service conditions. See TRANSACTIONS for 1892, Vol. IX, page 397.

The drivers of the locomotives referred to were in groups of four upon each of the two trucks and were arranged so they could swivel in taking the short radius curves present in mines. The heavier type of these locomotives often work on curves as small as a 10-ft. radius. In this connection it is interesting to note that these locomotives were not only designed for heavy service but they were successful in a marked degree in accomplishing this purpose.

Fig. 1 is a photograph of a locomotive which was installed 1890 or 1891 and Fig. 2 is a photograph of the same locomotive after it had been continually in service for some eighteen years or more. This locomotive seems to be unique in that it has been in continuous service for a longer period than any equipment of which I am aware. In any event it is a noteworthy instance of an apparatus standing up under service which is acknowledged to be severe in the extreme.

More recently some interesting tests have been undertaken with a view to determining by experiment to what extent the redistribution of weights occurring upon two axle trucks affect the apparent adhesion. To this end, two locomotives were tested with a draw-bar pull at two heights above the rail, each locomotive, being 12 tons and motored to the point of easily slipping its drivers. The log of the test is as follows:

SLIPPING TESTS

14.5 in. height drawbar above rail

Amperes	Drawbar pull at slipping	Drawbar pull in per cent of weight
415	7000	29.15
412	7200	30
435	7500	32.3
	Average. . .7316	30.48
Drawbar height 9½ in. wheel base 48 in.—33 in. wheels, steel tire.		
375	7100	29.15
410	7300	30.4
450	7500	31.3
418	7300	30.4
445	7700	32.15
445	7700	32.15
449	7500	31.3
405	7100	29.6
	Average. . .7388	30.71

Tests were also made on a 12-ton locomotive equalized with the first as to total weight and having independently driven axles. Slipping took place at a drawbar pull of about 5250 lb.

with the 9.6-in. height of drawhead and 4850 lb. with 15.5-in. height of drawhead, averages of all the tests being as follows:

Height of drawbar above rail	Amperes	Drawbar pull at slipping	Drawbar pull in per cent of weight
15.5 in.	312	4950	20.6
9.6 "	334	5250	21.85

The average percentage of adhesion at point of slipping in the case of coupled drivers is about 45 per cent in excess of that in the two-motor equipment; same standard steel tires and identical rails were used in each case.

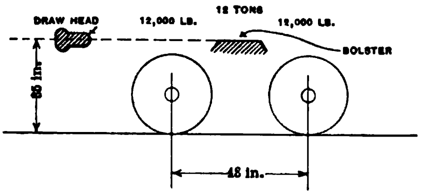


FIG. 3

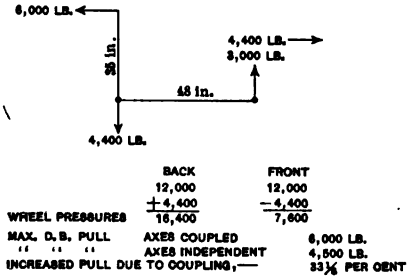


FIG. 3a

This indicates that the coupling of drivers effects favorably and to quite an unexpected extent the apparent coefficient of adhesion.

The nature of the shifting or redistribution of the weights as between the two axles upon an ordinary car truck or two-axle locomotive is very much greater than has been usually understood by builders of independently driven axle equipments, and the loss of capacity incurred has been generally underestimated. Ordinary practice with double motor street car or interurban trucks by the simple act of coupling would be entitled to between ⅓ and ¼ more total tractive effort than is obtainable with independent driving.

When a locomotive or truck is pulling a load, there are only two forces acting, which are external to the locomotive and independent of any internal forces. These two are the pull at the draw head or the bolster and the opposing pull of the wheel rims against the track. If these two forces are not in the line of travel, a tilting action will be produced, tending to elevate one pair of wheels, reducing the weight on them, and transferring additional weight to the other pair. As the draw head is always at some distance above the rail surface, there will always be shifting of loads on the drivers, due to the tilting effect of the draw bar pull.

Tests were undertaken to determine just the extent of this redistribution by apparatus shown in Fig. 4, namely, the front axle of a four-wheel locomotive weighing 12 tons, 48-in. wheel base, was placed upon rails *B* secured to a platform scale *A* the rear axle being placed upon the rails *C* and as between the pairs of rails the link *E* was supplied to take up the reaction without interfering with the action of the scale. The draw head *H* was rendered adjustable as will be seen in the table and was coupled with a rigid point *R* also adjustable as to height by a dynamometer *G*. The log of this test is as follows:

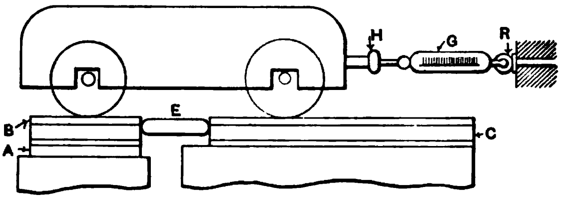


FIG. 1

Draw bar		Decrease in load upon front axle		
Height	Pull	Observed		Computed
			Probable limit of error in readings	
12 in.	6060	1520	160	1515
14 "	6100	1800	170	1780
16 "	6080	2000	210	2030
18 "	6010	2300	140	2280
20 "	6045	2700	180	2520
24 "	6030	3150	160	3015
35 "	6020	4500	190	4460

To give the foregoing analysis some definiteness, consider an example of a 12-ton locomotive with a 48-in. wheel base, the draw-bar being 35 in. above the track, adhesion taken at 25 per cent, we find that when the draw-bar pull is 6,000 lb. the weight upon the rear axle is 116 per cent in excess of the weight upon the forward axle. This is illustrated graphically in Fig. 3. Fig. 3*a* shows the force diagram, followed by deductions therefrom.

Summing up then, an electric truck or locomotive having two axles which are driven by independent motors has the weight on the forward axle reduced by an amount proportional to the drawbar pull; the pull it can exert is limited by the tractive effort of the least adhesive pair of wheels; because if one pair of drivers slips the other pair slips also.

If the two pairs of wheels be coupled together it is clear in case slipping occurs all the wheels must slip together. Therefore, the shifting of the weight due to the tilting effect of drawbar pull, does not decrease the maximum drawbar pull for although one pair of wheels gives a less pull than the other pair, the sum of the two is always constant, and since they must act together, the maximum draw-bar pull remains constant regardless of the tilting effect. The connecting of the wheels serves to automatically distribute the power of the driving motor between the two pairs of wheels in direct proportion to their respective adhesion to the rails.

All that has been said about tractive effort is equally true and quantitatively so as regards increased capacity for breaking or de-energizing the masses; here the shifting of weight loads the front axle and lifts the rear axle, allowing it to slip at much lower brake pressures than are easily permissible with coupled drivers.

Frank J. Sprague: Replying to Messrs. Eaton's and Storer's closing remarks, I am glad to note that it is acknowledged that it is " theoretically possible " to build a low center of gravity locomotive to run at high speed, and the possibilities of a flexible frame are suggested. That suggestion is quite in line with a thought of my own, and it is possible that in connection with some form of a linked truck construction, properly restrained or damped, there may be found one acceptable of solution of satisfactory locomotive construction.

Mr. Eaton in his reference to the New Haven wreck somewhat unwittingly and naively introduces a new element of discussion in locomotive design which gives emphasis to the statement that all such must necessarily be a compromise. He states that had the derailment occurred with steam locomotives the results would have been appalling, but that, as constructed, the axle-mounted motors helped to hold the locomotives in line with the track after the wheels had left the rails; in other words, motors with their axes coincident with axle axes prevented a disaster which would have been certain with motive power carried with a high center of gravity. The query naturally arises: What would have been the result had electric locomotives of the more recent vogue been used, that is, those with motors well up in the cab, driving by side and connecting rods through intermediary jack-shafts?

I will have to correct Mr. Storer's statement. He said that

I took exception to the author's statement to the effect " that the superintendent of motive power and the operative department would like, if possible, to have an absolutely interchangeable locomotive," and that then, while denying this statement, I proceeded to prove that it was necessary. The quotation is in error. I took exception to the statement as actually given in the author's paper, that " from an operator's standpoint it would be very desirable to have one locomotive which would be capable of handling at the desired speed any train from the heaviest freight to the fastest limited." I stated that this was not desirable, but that on certain roads, like some mountain divisions, it might easily be desirable within the ranges of speed which were required to have an ***interchangeable locomotive for a " given unit weight,"*** which would impose the same maximum drawbar pull, and to then combine these unit locomotives as required under multiple unit control. This is quite another thing, and its application becomes apparent when the makeup of passenger and freight trains in such service is considered.

A paper presented at the 27th Annual Convention of the American Institute of Electrical Engineers, Jefferson, N. H., July 1, 1910.

POWER ECONOMY IN ELECTRIC RAILWAY OPERATION--COASTING TESTS ON THE MANHATTAN RAILWAY, NEW YORK

BY H. ST. CLAIR PUTNAM

The power required for the operation of electric railways can be predetermined with great accuracy providing the cars or trains are operated in the manner assumed in the calculation of the speed-time and power curves employed for this purpose. Unfortunately, the cars are seldom operated as they should be, and although allowance for this variation is made engineers have long recognized that a material reduction in power could be realized in electric railway operation if the motormen could be induced or trained to operate the trains in a manner approximating the speed-time curve used in the preliminary calculations. It is proposed in this paper to describe some tests made on the Manhattan Elevated Division of the Interborough Rapid Transit Co., New York, in which a clock was used to record the amount of coasting employed in the operation of trains, the object of this device being to obtain from the motormen a better manipulation of the trains with the resulting economy in the use of power.

The clock as used in the tests consists of a clock mechanism manufactured for factory and office use for recording the time of employes. To the balance wheel escapement a braking device has been added, as shown in Fig. 1, which is lifted free from the balance wheel by an electromagnet which is energized only during the coasting of the train. This permits the clock to record the coasting time only. Each motorman is provided with an individual key which he inserts on taking charge of the train and again on leaving. The turning of this key records the motorman's number or initials and the time as shown by the clock mechanism; the difference in the time between the two records made by the key representing the total time of coasting during his run. The slip record is torn off by the motorman and turned in to the proper official. This is checked up with his running time, and the motorman is rated according to the percentage that the coasting time is of the total time of his run, due allowance being made for variation from the schedule. His individual rating is based upon the average results of a week or month as may be selected.

The electric circuits controlling the clock are interlocked with the master controller and the brake mechanism and arranged so that the coasting clock will start only after the two actions of turning the power on and then off. The connections used are shown in Fig. 2. The operation of the clock is stopped as soon as the air brakes are operated and the brake cylinder has started to move to the braking position. If, for any reason, after the brakes are applied, the air is released and additional coasting obtained before the train stops, this additional coasting is lost from the amount of coasting recorded unless power is again applied. This is not an important factor in normal operation as the actual amount of coasting of this character is small.

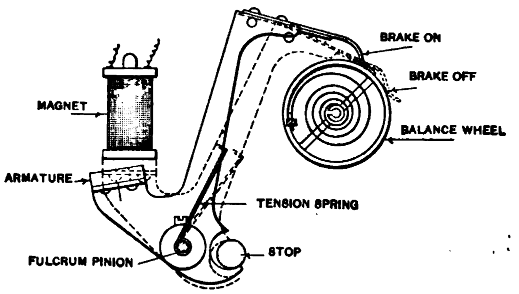


FIG. 1.—Details of clock mechanism

SPEED TIME CURVE CHARACTERISTICS.

While the principles involved in the use of speed time curve calculations in electric operation are well understood, for the purpose of making clear the economies in power consumption that can be realized from the better operation of trains, which it is the object of this clock to encourage, the following brief discussion of the various factors entering into electric operation is given.

Acceleration. The rapid acceleration of trains, providing the schedule speed is unchanged, results in an important saving of power for two reasons, first, the maximum speed reached is less with a high acceleration, and consequently the train resistance is somewhat less; second, and of much greater importance, is the fact that with a high rate of acceleration the speed at the start of breaking is less than with a lower rate and, consequently, the energy absorbed and lost in braking is less. The energy absorbed in braking is the essence of the whole subject, as in such train operation as that on the Manhattan system, and to a lesser extent in single car operation the increased train resistance resulting from the higher maximum speed due to a slow acceleration is unimportant and may be neglected. The only energy not utilized in useful work is

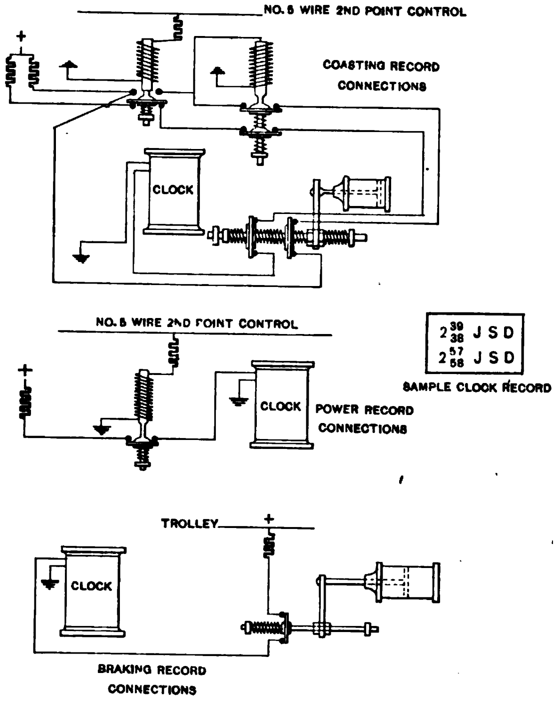


Fig. 2—Clock connections

that absorbed in the rheostats in direct current acceleration, the motor and control losses and the energy absorbed in the brake shoes.

The equipment provided naturally limits the permissible rate of acceleration, but within such limitations, a quick acceleration is one of the most feasible methods of reducing the power required in such service as exists on the Manhattan Railway.

Fig 3 shows the typical average run on the Second Avenue line, using the same rates of acceleration and braking and length of stop as used in the original calculations for the electrification of the Manhattan system but using the train resistance as derived from tests made in 1905. This run as shown is representative of the average run on the Second Avenue line where the coasting clock tests have been made, and is also representative of the average run of the entire Manhattan system. The distance between stations on the portion of the Second Avenue line tested, between Canal Street and 127th Street, is 1768 ft. as compared with 1763 ft. for the entire Manhattan system. In this typical curve the acceleration used is 1.33 miles per hour per sec. and the schedule speed is based upon the printed schedule of the road.

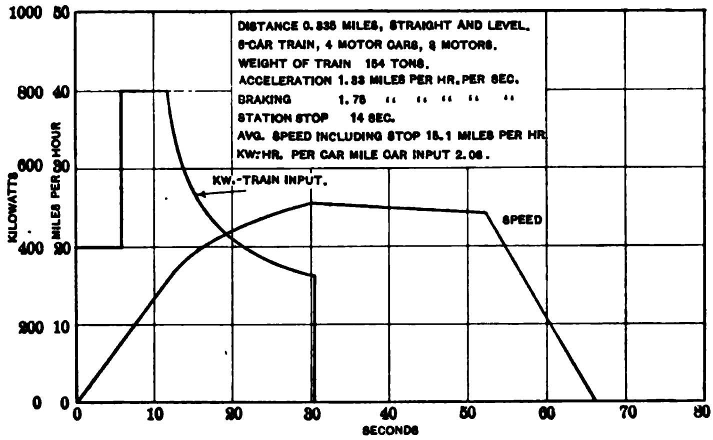


FIG. 3—Typical run

Fig. 4 shows the original speed-time curve used in the electrification of the Manhattan Division, and it will be noted is in close agreement with the curve shown in Fig. 3.

In Fig. 5 is shown the precentage increase in coasting time resulting from the increase in the rate of acceleration from 0.9 miles per hr. per sec. to two miles per hr. per sec., and the resulting decrease in power consumption, based upon an average run on the Second Avenue line. In the tests on the entire Manhattan system conducted on March 22, 1910, the acceleration of different motormen was found to vary from 0.9 miles per hr. per sec. to 1.47 miles per hr. per sec. Providing other factors of train operation remain the same (that is, the braking, running time and time of stop) the increase in the rate of acceleration from 0.9 to 1.47 miles per hr. per sec. will result in an increase in the percentage of coasting time from 0 to 40.5 per cent of the total time, and a saving of 36 per cent in energy consumption. A motorman on the Manhattan system on full runs will average about 600 car miles per day, and the energy used at the car with 0.9 acceleration will approximate 2.82 kw. hr. per car mile. As between these two motormen, therefore, providing the scheduled speed is maintained, the motorman who accelerated his train at an average rate of 0.9 miles per hr. per sec. will waste during the day 610 kw-hr. at the car. With 80 per cent efficiency to the power house, this becomes 762

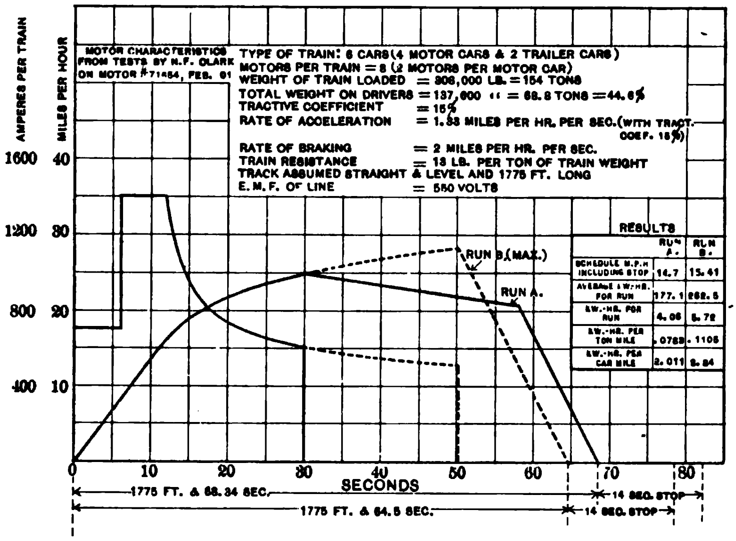


Fig. 4—Speed and power curves for train with eight motors
Gear ratio 71:18 = 3.94—Wheel diam. = 33 in.

kw-hr. This energy of course must be supplied from the power house where additional apparatus must be installed to meet the demand. In practice the full saving of power resulting from better acceleration is not realized, owing usually to the better running time made by the good operator. This results frequently in his having to wait for the train ahead and by so doing, a large part of the saving in power which should follow his good operation is lost. The use of this clock should result, however, in a material increase in coasting time under such circumstances, with a resulting reduction in power. The men will learn to gauge their trains, and instead of stopping for the man ahead, will utilize the surplus time in coasting. In order that schedules shall be maintained, however, some sort of penalty must be imposed to prevent the motorman from over-doing the coasting at the expense of the running time.

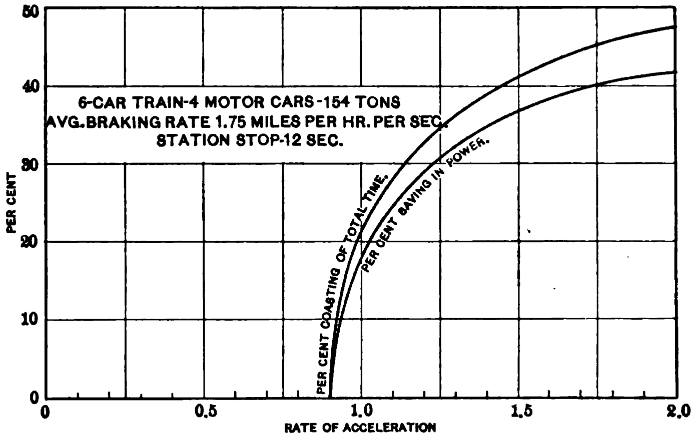


Fig. 5—Influence of acceleration

Series Running. In Fig 6, the effect of series running upon the percentage of coasting obtained and the resulting energy consumption is shown. It will be noticed that an increase in the percentage of coasting obtained by reducing the amount of series running does not effect a corresponding saving in energy. This is due to the fact that while the total time during which power is applied is increased and the time of coasting reduced by holding the controller in the full series position, say for four or five seconds, the actual energy used remains practically the same because the additional power required on account of the longer time of power application is offset in large measure, if not entirely, by the saving in rheostat losses owing to the reduced time that the rheostat is in circuit in passing to full multiple. This is shown in Fig. 7, which has been used in calculating the results plotted in Fig. 6. A limited amount of series running, therefore, is not objectionable, and under certain

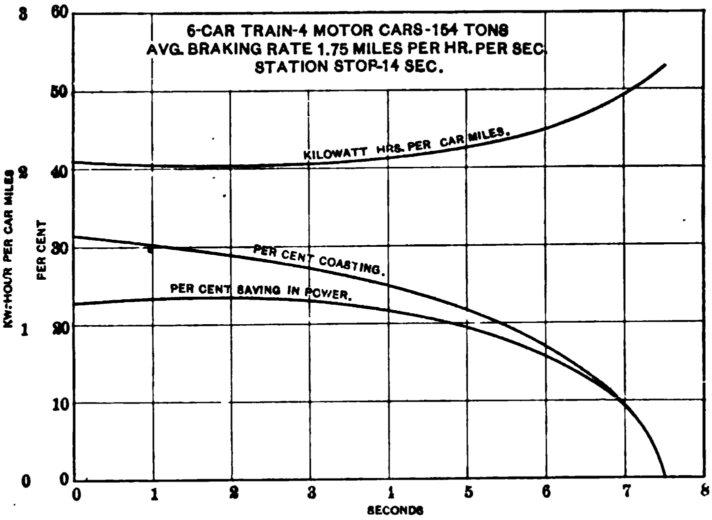


FIG. 6—Influence of series running

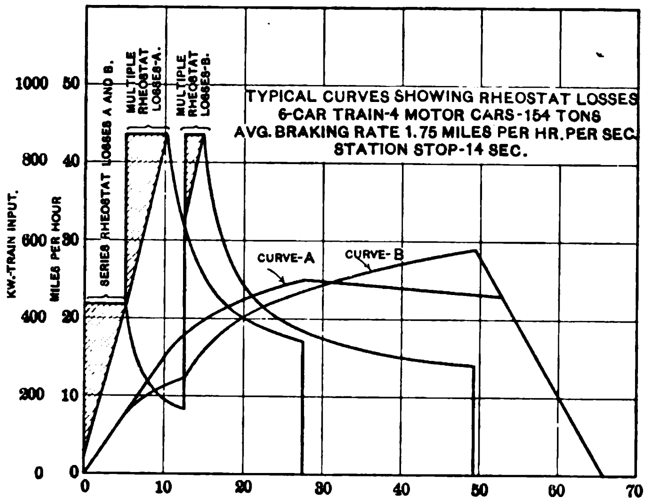


FIG. 7—Influence of series running

conditions it is better to run in series for a short time than to pass to the multiple position, especially where power is cut off almost immediately after the multiple position is reached as under certain conditions in approaching a station. The decrease in coasting time resulting from a moderate amount of series running does not therefore necessarily represent an increase in power consumption, unless the series running has been excessive. In this respect the coasting clock will give misleading results; but as under normal conditions there is little occasion for running in series, excepting around curves, the error thus introduced into the record is not important.

Braking. A high rate of braking results in a reduction in power consumption for reasons similar to those existing as to the rate of acceleration. It permits the power to be cut off at an earlier point, a longer time of coasting introduced, energy otherwise wasted in the brakes to be recovered and the train brought to a quick stop. Perfection in braking is much more difficult of attainment than acceleration, as the train must be stopped at the station within a space limited to a few feet. The motorman, therefore, in approaching a station must judge his distance, speed, grades, if any, as well as the weight of his train, and over-running the station causes serious delay. Many motormen therefore, operate on the side of safety and feel their way into stations, with a resulting material increase in the power used if schedules are maintained.

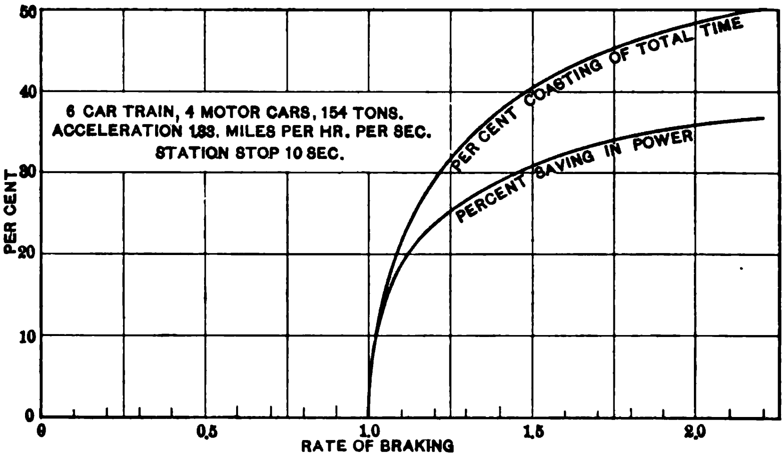


Fig. 8—Influence of braking

In Fig. 8, is shown the percentage of decrease in power on account of the increased percentage of coasting introduced by increasing the rate of braking from one mile per hr. per sec. to 2.25 miles per hr. per sec. These limits are frequently found in the operation of Manhattan trains. Two miles per hour per second is entirely practical as has been determined by carefully conducted tests. An increase in the rate of braking between the limits of one mile per hr. per second and two miles per hr. per sec. results in increasing the coasting to 48.5 per cent. of the total time with a saving of 35.5 per cent in the power as well as the energy used.

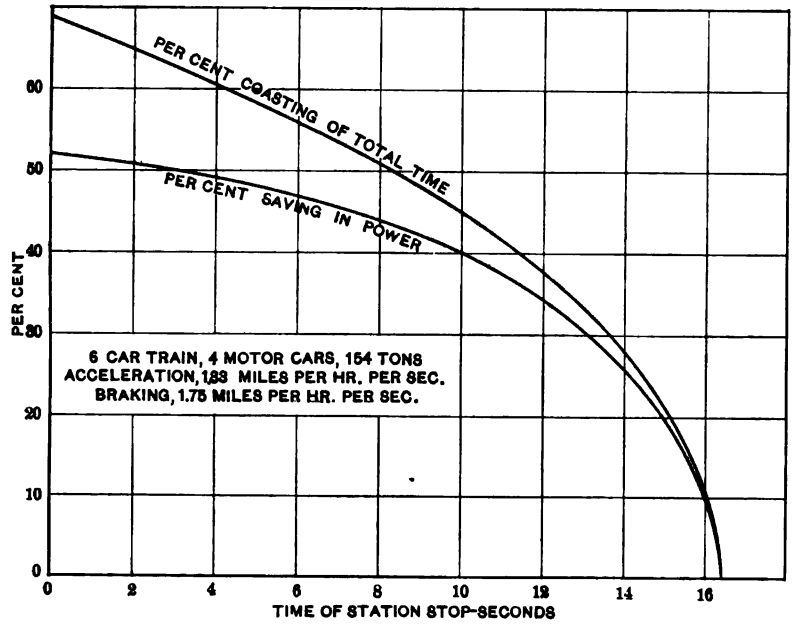
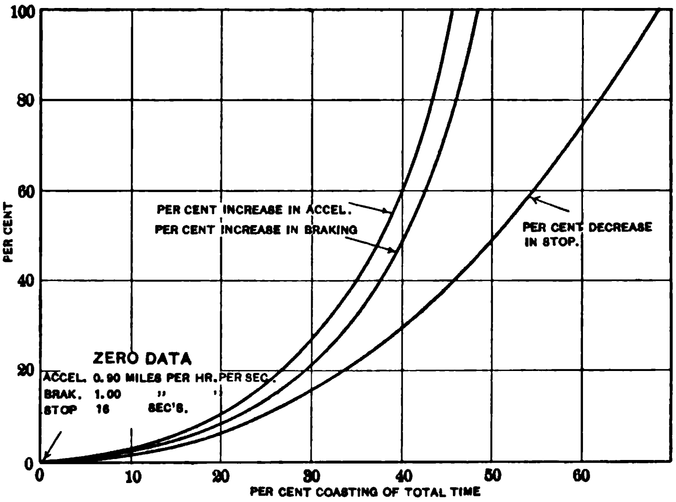


Fig 9—Influence of station stop

In the tests made over the Manhattan system on March 22nd, the trains were not equipped for getting the braking rate. The average time required by the motorman in bringing the train to a stop varied from 10.2 sec. to 20.2 sec. This would indicate approximate braking rates of 1.15 and 1.90 miles per hour per sec. The higher rate would increase the coasting time from 26 per cent for the lower rate, to 47.5 per cent, and result in the saving of approximately 280 kw-hr. per day by the better operator.

Station Stops. In Fig. 9 is shown the influence of the station stop. On the Second Avenue line, the average run is 0.335 miles and the maximum possible stop with the maintenance of the schedule, and with no coasting, is 16.2 sec., assuming an average run as typical, which is substantially correct for the purposes of the present discussion. A reduction in the time of stop to 10 sec. results in an increase in coasting time to 45 per cent of the total time and a reduction of 40 per cent in the power used.



Percentage change in operating conditions and resulting percentage of coasting

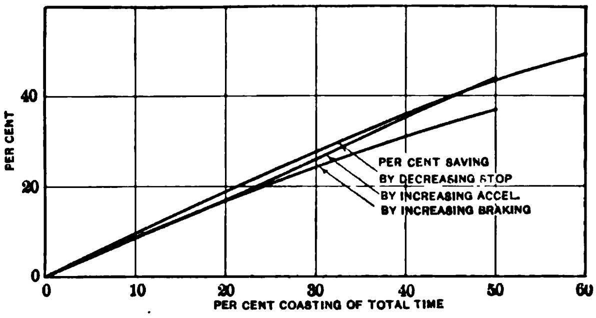


FIG. 10—Percentage reduction in power corresponding to percentage of coasting

Coasting. The amount of coasting which a motorman can obtain and still maintain his schedule, is obviously the result of the factors of operation above discussed. The ideal amount of coasting will result from the observance of all these factors. The theoretical coasting as shown on the typical curve is 27.5 per cent of the total time including stops. It has been shown in the above dicsussion that it is possible to obtain this amount of coasting and even to exceed it by changes in operation which are entirely within the range of practicability.

In Fig. 10, is shown the percentage of change made in these operating factors and the resulting percentage of coasting obtained and the corresponding percentage decrease in power. It will be noted that it makes but little difference which factor is altered. The percentage of energy and power saved is substantially the same however the increased coasting is obtained. This of course is to be expected. It is well to point out the very large saving in power consumption which results in reducing the stop from say 15 sec. to 10 sec. assuming that the schedule speed remains the same. This results in the saving of 25 per cent in power through the increased coasting thus made possible.

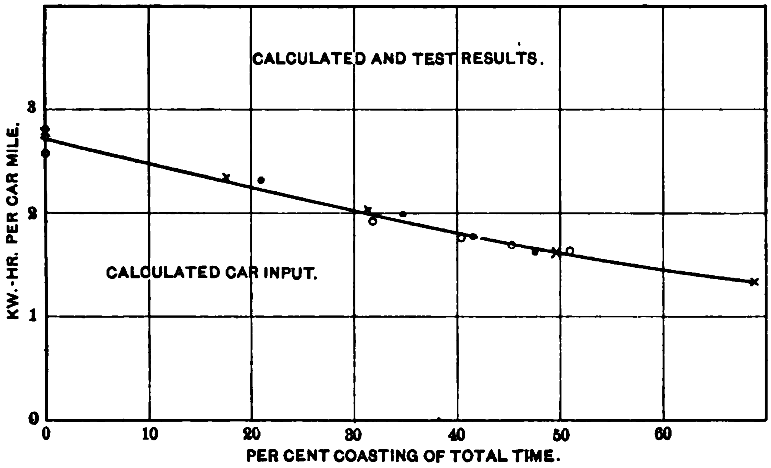


FIG. 11—Kw-hr. required per car-mile

Energy Consumption. In Fig. 11, the calculated energy required at the car, per car mile, is plotted under different conditions as to acceleration, braking and station stops as above discussed, these factors being plotted in terms of the resulting percentage of coasting obtained. This curve illustrates graphically the very material saving effected by any change in the methods of operation which results in an increase in the coasting time.

SECOND AVENUE TEST RESULTS.

The results of the tests of the coasting clock which have been conducted on the Second Avenue line are plotted in Fig. 12. All trains on the Second Avenue line were equipped with coasting clocks, and the energy supplied to the section between 127th Street and Canal Street was metered by direct-current integrating wattmeters on the substation feeders. Corrections have been made for heaters and light, and the wattmeter readings corrected in accordance with frequent calibrations.

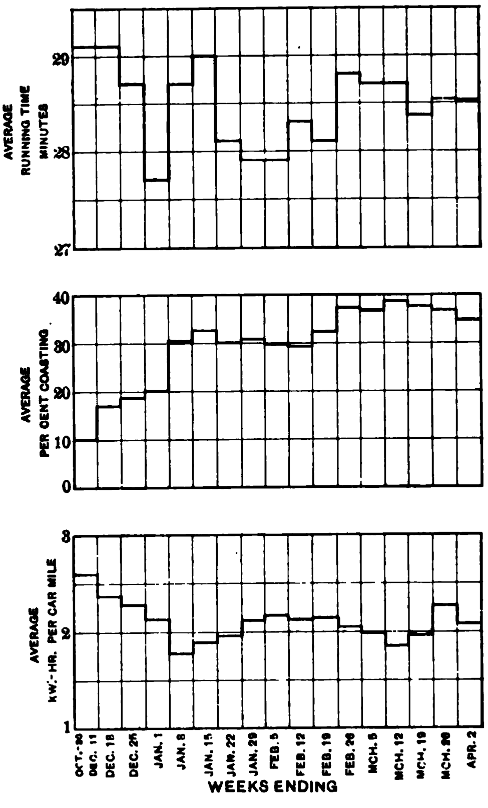


FIG. 12—Coasting clock tests on Second Ave line 127th St., to Canal St.—Oct. 30 to Dec. 11 before clock installation—Dec. 18 to Apr. 2 after clock installation

On account of the corrections that have to be made for heaters light, control and auxiliaries, the results obtained are necessarily approximate. Under these circumstances, therefore, the records are remarkably consistent and show graphically the material improvement in coasting which has resulted from the use of the coasting clock, and also the reduction in the energy required for the operation of the cars.

In Fig. 13, the kw-hr. required per car-mile as shown by these tests is plotted in terms of the percentage of coasting.

In Fig. 14, the average curve obtained from the Second Avenue tests and the average curve as obtained from our calculations, both expressed in terms of kw-hr. per car-mile, and the percentage of coasting obtained, are plotted on the same sheet. The agreement of these curves is remarkably close, the curves expressing the percentage of energy saved from the increased coasting practically coincide. Of course this is as it should be if the calculations and tests have been correct. Quantitatively, the kw-hr. per car mile obtained from the tests is about seven per cent higher than the calculations. The test results are measured at the substation while the calculations are at the car. The difference would represent the third rail losses, but it is believed that they are somewhat greater than this would indicate. The important feature contained in this curve is that on the Second Avenue line the increase in the time of coasting from 10 per cent as it was prior to the installation of the clocks to 38 per cent following such installation, resulted in a saving of 25 per cent in the energy required for traction. This result is in agreement with what should be expected from the theoretical calculations.

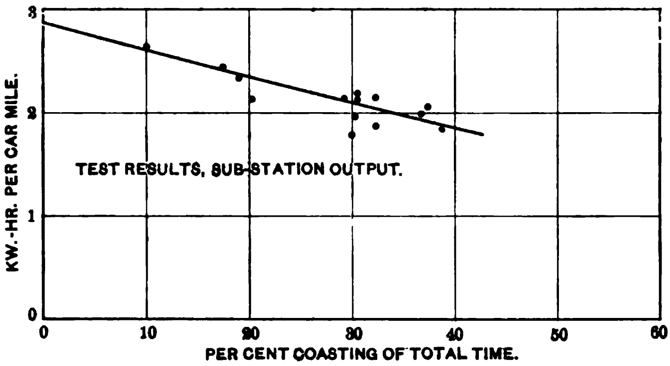


FIG. 13—Kw-hr. required per car-mile

MANHATTAN TESTS—MARCH 22, 1910.

On Second, Third, Sixth and Ninth Avenue Lines.

In order to compare the operating conditions existing on the Second Avenue line with the conditions on the other lines of the Manhattan system, on March 22nd a test train was run in actual sevice over all divisions of the Manhattan system. A seven-car train composed of four motor and three trail cars was used. Each trail car was equipped with one of the record-

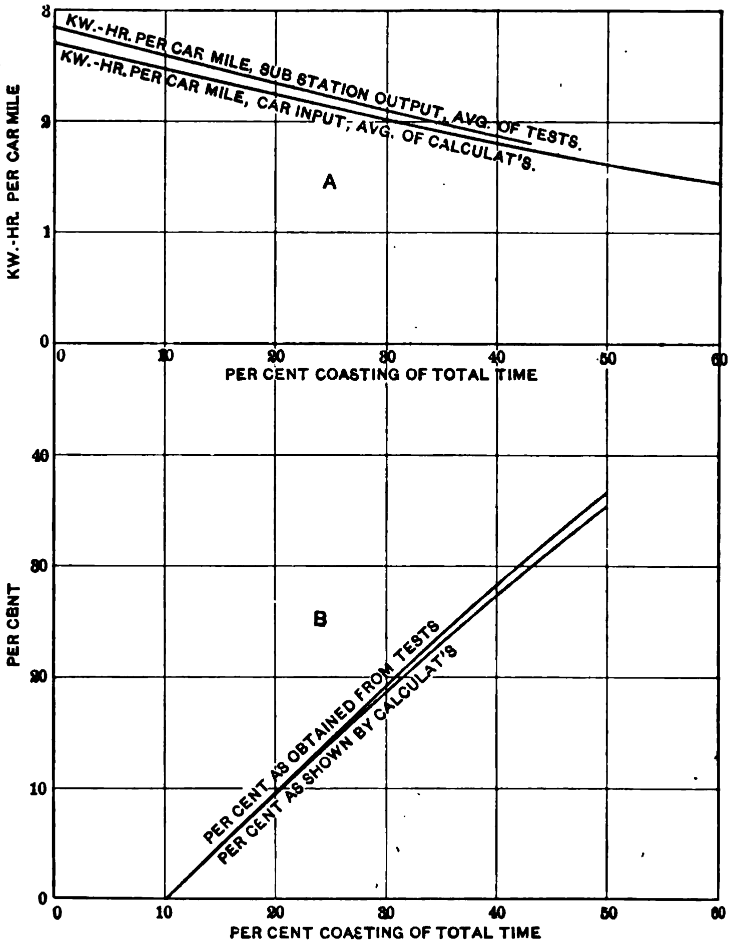


FIG. 14

A-Kilowatt-hours per car-mile

B-Percentage reduction in power resulting from coasting

RECORDING CLOCK TESTS—MARCH 22, 1910. MANHATTAN DIVISION. INTERBOROUGH RAPID TRANSIT COMPANY

	Power applied min.	Coasting min.	Braking min.	Stops min.	Total time by watch minutes
Second Ave. 129 *to S. Ferry*					
Test No. 1— Stop watches.........	11.7	18.8	5.3	7.0	42.3
8:01 a.m. S.— Recording clocks......	11.9	19.6	6.3		
Test No. 2— Stop watches.........	11.1	19.8	4.4	3.7	39.1
8:45 a.m. N.—Recording clocks (To 127th St. only)...................	10.5	20.9	4.9	—	—
Test No. 5— Stop watches.........	12.0	15.8	5.0	4.8	37.5
1:23 p.m. S.—Recording clocks......	11.0	17.0	5.7	—	—
Third Ave. Bronx Pk. City Hall					
Test No. 3— Stop watches.........	27.1	7.5	11.3	10.4	56.7
9:45 a.m. S.—Recording clocks......	26.0	6.3	12.5	—	—
Test No. 4— Stop watches.........	21.1	15.4	9.8	8.9	55.1
10:53 a.m. N.—Recording clocks....	19.8	17.8	10.0	—	—
Sixth Ave. 155*th St. to S. Ferry*					
Test No. 6— Stop watches...	19.2	10.7	8.6	8.1	46.8
2:6 p. m. N.—Recording clocks (Start Battery Place)...................	18.0	11.0	9.0	—	—
Test No. 9— Stop watches.........	19.9	10.3	10.4	6.6	47.9
4:23 p.m. S.—Recording clocks......	18.5	11.5	12.5	—	—
Ninth Ave. 155*th St. to S. Ferry*					
Test No. 7— Stop watches.........	19.9	8.1	8.6	6.0	42.9
2:55 p.m. S.—Recording clocks......	18.2	8.2	8.7	—	—
Test No. 8— Stop watches.........	19.4	9.1	9.3	4.5	43.2
3:39 p.m. N.—Recording clocks.....	17.8	10.0	9.3	—	—

AVERAGE OPERATING CONDITIONS. RECORDING CLOCK TESTS—MARCH 22, 1910. MANHATTAN DIVISION

	Average Length of run feet	Average acceleration seconds	Average Power applied seconds	Average coasting seconds	Average braking seconds	Average stop seconds		Average total time seconds
						Station	Signal	
Second Ave.								
Test No. 1-S...	1723	11.4	26.0	41.7	11.9	13.2	2.4	95.2
Test No. 2-N...	1752	11.5	25.7	45.6	10.2	8.8	—	90.3
Test No. 5-S...	1723	10.3	26.7	35.0	11.2	9.9	1.3	84.1
Third Ave.								
Test No. 3-S...	1767	14.6	42.7	11.8	17.9	16.8	—	89.2
Test No. 4-N...	1767	12.8	33.2	24.2	15.6	13.2	1.3	87.5
Sixth Ave.								
Test No. 6-N...	1841	14.5	38.5	21.4	17.1	14.3	2.5	93.8
Test No. 9-S...	1833	11.4	38.4	19.9	20.2	11.2	2.0	91.7
Ninth Ave.								
Test No. 7-S...	1833	17.2	41.1	16.7	17.8	11.3	1.6	88.5
Test No. 8-N...	1833	19.1	40.2	18.7	19.3	9.3	0.6	88.1

ing clocks. These clocks were connected as shown in Fig. 2. One clock was used to record the coasting time, the second the time of power application, and the third the time of braking. Stop watch records were also made of the time of series running and total power application, time of coasting, time of braking and time of station and signal stops.

The result of these tests are tabulated on the preceding page.

SECOND AVENUE TESTS

The results of the tests over the Second Avenue line reduced to an average run are plotted in Fig. 15 in what we have called " Running Charts " for each of the three tests on this division. These curves approximate speed-time curves in form, but naturally as the different factors which enter into the characteristics of the curve are averages, the resulting curve does not pretend to give the correct area and distance. The curve is but a picture of the average operating conditions of the run.

It will be noted that motorman *S* in test No. 2 obtained 50.5 per cent coasting, the largest amount recorded during the day. Of the three tests on Second Avenue, motorman *O* in test No. 5, obtained the smallest amount of coasting, 41.4 per cent and carried power for the longest time, 31.6 per cent, yet he was the best operator of the two. If he had used the same time in making the run as motorman *S* in test No. 2, it would have been possible for him to obtain as high as 58.5 per cent coasting as shown by the broken line on test No. 5, and he could have cut his power application down to 22.2 per cent with a saving of 8 per cent in energy and as compared with motorman *S* in test No. 2. The good results in test No. 5 were obtained with an acceleration of 1.47 and braking of 1.85 (approximate) as compared with an acceleration of 1.35 and braking of 1.75 (approximate) in test No. 2. The rate of braking indicated on these curves is approximate only, as the average braking includes the signal braking between stations and at curves in addition to the braking at station stops. The slope of the braking curve, however, indicates quite accurately the relative rate of braking used by the motorman.

The motormen who operated the trains in the tests on the Second Avenue line were selected men and the runs were made to illustrate what could be accomplished after a thorough training of several months. The average coasting obtained in the three runs is 45.2 per cent. This indicates a reduction in

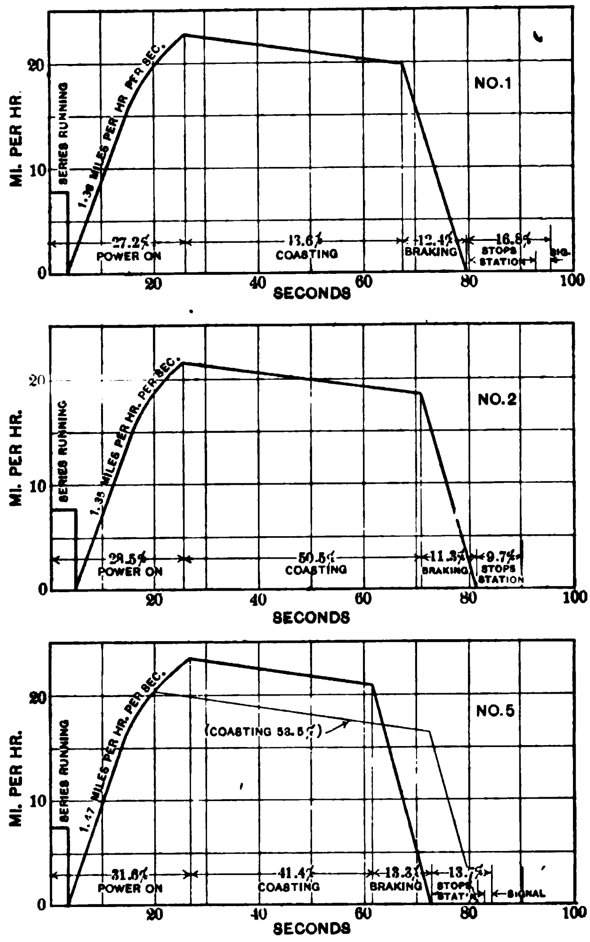


FIG. 15—No.1. Typical running chart, 129th St. to South Ferry—
8:01:20 a.m. to 8:40:43 a.m.—Motorman S—
Schedule time 35 min—27 runs—Average run 1723 ft.—
Average speed 12:3 miles per-hr.
No. 2. Typical-running-chart, South Ferry to 127th St.—
8:45:20 a.m. to 9:24:23 a.m.—Motorman S—
Schedule time 34:5 min. 26 runs—Average run 1,752-ft.—
Average speed 13:2 miles per hr.
No. 5. Typical-running-chart 129th St. to South Ferry—
1:23:15 p.m. to 2:0:45 p.m.—Motorman 0—
Schedule time 35 min.—27 runs—Average run 1,723 ft.—
Average speed 13.9 miles-per hr.

power consumption amounting to 34 per cent as compared with the conditions existing on this line prior to the installation of the clocks. This, of course, is in excess of the average saving of all the men as these men were specially selected.

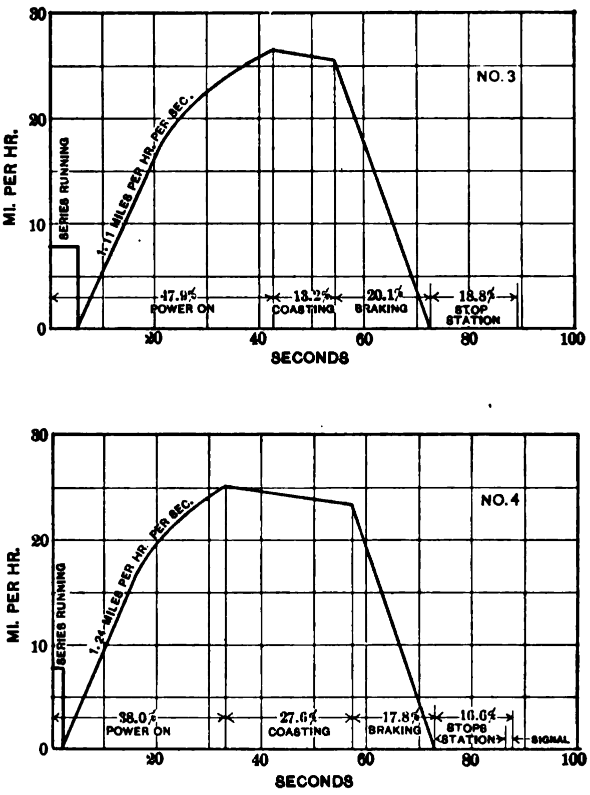


Fig. 16—No. 3. Typical running chart, Bronx Park to City Hall—
9:54:04 a.m. to 10:50:46 a.m.—Motorman C—
Schedule time 51 min.—38 runs —Average run 1,767 ft.—
Average speed 13:5 miles per hr.
No. 4. Typical running chart, City Hall to Bronx Park—
10:53:45 a.m. to 11:48:50 a.m.—Motorman G—
Schedule-time 51 min.—38 runs—Average run 1,767 ft.—
Average speed 13.8 miles per hr.

These tests also bring out strongly that any system of rewards or ranking of the men based upon coasting time should include a penalty for overrunning the scheduled time.

The tests on the Second Avenue line, as observed, show an average of 45.2 per cent coasting which corresponds to 1.70 kw-hr. per car-mile at the car.

THIRD AVENUE TESTS

Fig. 16, shows the average Running Charts obtained from the tests on the Third Avenue line. In the Third Avenue tests, the run south was made with the motorman whose turn it happened to be. This run shows 13.2 per cent coasting. The run north was made with an experienced man and shows 27.6

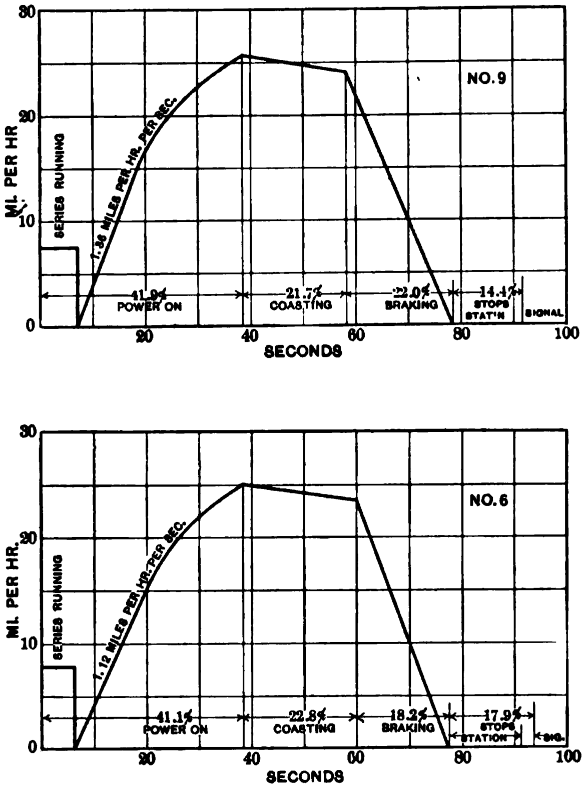


FIG. 17—No. 9. Typical runing chart. 155th St. to South Ferry—
4:25:07 p.m. to 5:13:00 p.m.—Motorman C—
Schedule-time 43 min.—31 runs—Average run 1,833 ft.—
Average speed 13.7 miles per hr.
No. 6. Typical running chart, Battery Pl. to 155th St.—
2:06:37 p.m. to 2:53:25 p.m.—Motorman W—
Schedule time 4:15 min.—30 runs—Average run 1,841 ft.—
Average speed 13.4 miles per hr.

per cent coasting. The difference is due mostly to the difference in the rate of acceleration, but partly to the braking rate and partly to an excessive amount of series running in test No. 3.

These two runs show an average of 20.4 per cent braking which indicates 2.22 kw-hr. per car-mile at the car. These men, therefore, used 30.6 per cent more energy than was used by the men on the Second Avenue test.

SIXTH AVENUE TESTS

Fig. 17 gives the Running Charts of the two tests made on the Sixth Avenue line. The motormen were taken as they came, and it will be noted that their handling of the train is in fairly close agreement.

On account of the number of turns on this line, the amount of necessary series running is considerably in excess of that obtaining on the other lines. The average coasting obtained was 22.3 per cent. This corresponds to an energy consumption of 2.17 kw-hr. per car-mile. As compared with the average obtained in the Second Avenue tests, this represents an excess consumption of 27.7 per cent.

NINTH AVENUE TESTS

Fig. 18 gives the Running Charts of the tests made on the Ninth Avenue line. The motormen were taken as they came, and it will be noted that the two men operated their trains very much alike. In both cases the acceleration was poor and the braking somewhat below the standard. Both used a large amount of series running.

The Ninth Avenue line is an ideal one on which to obtain a large amount of coasting on account of the longer runs, easy schedule and long grades, yet the coasting obtained by these two men was but 18.9 per cent and 21.2 per cent respectively. and averages 20.1 per cent. As compared to the average obtained in the Second Avenue tests, this represents an excess consumption of 31.8 per cent.

CLOCK RECORDS ON THIRD, SIXTH AND NINTH AVENUE LINES

In the tests conducted on March 22nd, the motormen were conscious of being under observation by the test crew as well as by their own road officials, and under such circumstances they naturally tried to do their best. The results obtained therefore, cannot be regarded as representative of actual conditions, but can be taken as fairly representing the best that these men could do, and therefore, as illustrating the knowledge of the motormen in general. The tests were too few in number, however, and the conditions under which they were made were such that they are not regarded as representative.

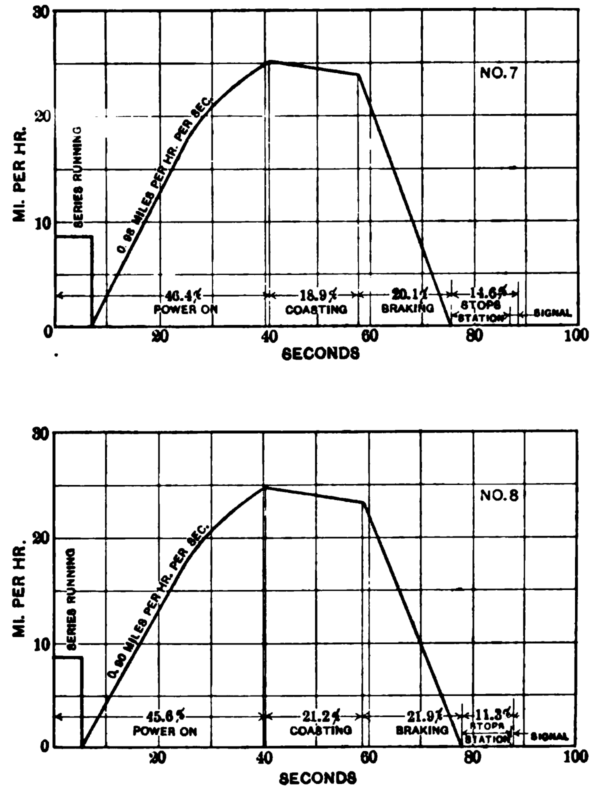


Fig. 18—No. 7. Typical running chart, 155th St. to South Ferry—
2:55:07 p.m. to 3:38:00 p.m.—Motorman M—
Schedule time 40 min.—29 runs—Average run 1,833 ft.—
Average speed 14.1 miles per hr.
No. 8. Typical running chart, South Ferry to 155th St.—
3:39:20 p.m. to 4:22:35 p.m.—Motorman C—
Schedule time 40 min.—29 runs —Average run 1,833 ft.—
Average speed 14.2 miles per- hr.

In order to determine the fair average conditions as to coasting existing on all divisions of the system, tests were made on the Second and Third Avenue lines last fall and two trains equipped with clocks were put in regular service this spring on the Sixth and Ninth Avenue lines.

The average of these results should be fairly representative of the coasting conditions at present, as well as prior to the installation of the coasting clock on the Second Avenue line. The men soon become aware of the trains equipped with clocks, however, and consequently are more careful in the operation than usual. It is probable, therefore, that the coasting data obtained from these tests are above rather than under the average conditions.

The results obtained on the Second Avenue line will be found plotted in Fig. 12, and show that prior to the installation of the clock, the coasting averaged 10 per cent of the running time. These tests were started in October and continued daily to December 11th.

Tests were made on the Third Avenue line last summer and the results agree very closely with those obtained at a later date on the Second Avenue line. The data collected on a test of ten days duration is given below:

THIRD AVENUE—SCHEDULE TIME—51 MINUTES

	Runs	Average running time minutes	Average coasting time minutes	Per cent coasting
July 16	7	52.9	6.3	11.8
July 22	6	51.3	8.4	16.4
July 27	3	52.2	3.7	7.1
July 28	7	52.9	3.3	6.2
July 29	7	52.3	3.2	6.1
July 30	7	52.8	5.1	9.7
July 31	4	53.6	6.2	11.5
Aug. 2	5	52.7	6.3	11.9
Aug. 3	7	52.6	5.9	11.2
Aug. 4	7	53.3	5.9	11.1
Average	60	52.7	5.4	10.2

Below is given the coasting tests recently made on the Sixth Avenue line. It will be noted that the amount of coasting agrees very closely to that existing on the Third and Second Avenue lines prior to the installation of the coasting clock.

SIXTH AVENUE—SCHEDULE TIME—43 MINUTES

	Runs	Average running time minutes	Average coasting time minutes	Per cent coasting
March 28	16	45.9	6.1	13.2
March 29	10	46.8	5.7	12.2
March 30	10	46.7	5.2	11.1
March 31	8	45.9	5.3	11.5
April 1	2	44.0	3.6	8.2
April 2	10	46.2	5.2	11.3
Average	56	46.2	5.5	11.9

The Ninth Avenue line as already mentioned, furnishes an ideal one upon which to obtain a large amount of coasting, on account of its undulating grades, longer distance between stations, and easy schedule. In addition to this, the average train on this line is made up of four motor cars and two trailers instead of four motor cars and three trailers, as on the other lines. The effect of these factors is seen in the results obtained from the coasting tests which are given below.

NINTH AVENUE—SCHEDULE TIME—40 MINUTES

	Runs	Average running time minutes	Average coasting time minutes	Per cent coasting
March 28	5	37.7	4.9	12.9
March 29	12	38.0	6.9	18.0
March 30	13	36.5	7.8	21.4
March 31	12	38.0	7.6	19.9
April 1	15	37.3	7.0	18.7
April 2	12	37.0	7.9	21.3
April 3	8	41.7	8.3	19.9
Average	77	37.8	7.4	19.1

SUMMARY—COASTING DATA

	Car miles per day	Per cent coasting
Second Avenue	28,863	10.0
Third "	79,403	10.2
Sixth "	46,571	11.9
Ninth "	33,826	19.1
Average	188,663 (total)	12.2

From the above tests it is probable that the average coasting obtained on the Manhattan system approximates 12 per cent of the running time. On account of the fact that the motormen are very alert to discover that they are under observation, it is probable that the actual amount of coasting is below, rather than above, this amount.

Result of Equipment with Coasting Clocks

In the table below is given the average coasting obtained during five weeks on the Second Avenue line, where the coasting clock has been in service for slightly over three months. The average run on this part of the Second Avenue line, as already pointed out, closely approximates the average run for the entire Manhattan system.

SECOND AVENUE LINE—COASTING DATA. COASTING CLOCK INSTALLED FOR THREE (3) MONTHS

	Average running time minutes	Average coasting time minutes	Per cent coasting
Week ending March 5	28.7	10.5	36.8
" " " 12	28.7	11.1	38.8
" " " 19	28.5	10.8	37.7
" " " 26	28.5	10.6	37.0
" " April 2	28.4	10.1	35.4
Average	28.6	10.6	37.1

VALUE OF POWER REDUCTION THROUGH COASTING

The result of these calculations and tests shows that an increase in the percentage of coasting from 12 per cent to 37.5 per cent as shown above, will effect a saving of 24 per cent in the power required for traction.

COASTING VS. POWER MEASUREMENTS

The various factors that enter into the operation of the train have been analyzed with a view to determine which is the preferable element to measure. The choice practically narrows down to the measurement of either the power input by wattmeter or time of application by means of a clock arrangement, or the measurement of the time of coasting. It is believed that it has been made clear that whatever good results are obtained from the better operation of the train by the motormen can only result in the saving in power through the increase in the coasting time. Coasting results in the recovery of energy already used, and hence is the key to the problem. The coasting clock, therefore, gives a direct measure of the energy recovered by the motormen and as this recovery can also only be made by cutting off the power application sooner, it is believed that it is the most effective element in train operation to measure. At the same time it concentrates the motorman's attention on that element of operation which is the direct reason for the reduction in power which results from changes in the methods employed as to the other factors of operation.

This subject has been discussed at some length, as it brings up some interesting features of electric train operation. Preliminary schedules for electric operation in service similar to that on the Manhattan system, usually included from 25 to 30 per cent coasting, partly for reasons of power economy and partly to provide a factor of safety, as it has been realized that motormen do not operate their trains in compliance with the calculated speed-time curve. It is believed that the use of the device here described will not only insure the better operation of trains but will result in a material reduction in the power used.

The writer is indebted to Mr. L. B. Stillwell and officials of the Interborough Rapid Transit Company for the use of material embodied in this paper.

DISCUSSION ON "POWER ECONOMY IN ELECTRIC RAILWAY OPERATION COASTING TESTS ON THE MANHATTAN RAILWAY, NEW YORK". JEFFERSON, N. H., JULY 1, 1910.

John B. Taylor: I wish to ask Mr. Putnam if the motormen have found any way to beat this clock. I have not studied the diagram very carefully, and wonder if by turning on the power and turning it off again immediately at a station, it would be possible for the motorman to make the clock record during the time of the stop.

A. H. Armstrong: The problem of reducing energy consumption of a train is now pretty well understood, and I am very glad to see that active steps are being taken to keep a record of the performance of the motorman. It is well known that rapid acceleration decreases the amount of power consumed in frequent stop service, but in connection with that I would ask Mr. Putnam if he has noticed any increase in the ragged appearance of the substation load curve, and whether the more rapid acceleration used has called for any appreciable increase in substation and distribution system capacity.

Rapid acceleration may be carried too far where the service is infrequent, and it is possible to approximate its benefits without unduly increasing the maximum demand per train by resorting to a very high rate of acceleration in series and a lower rate with the motors connected in parallel. The advantages in so doing are two fold. It affords a quicker get away from the station with a corresponding abrupt angle of the speed-time curve, and reduces the maximum demand of the train and the motors in multiple running where it will most effect the distribution system and the operation of the motors themselves.

N. W. Storer: This paper has been of great interest to me. It is certainly a great satisfaction to feel that railway operators are at last beginning to realize the necessity for careful instruction of their motormen, and the saving that can be effected by proper operation. I believe that ignorance of the correct theory of operation is at the bottom of a large part of inefficient operation of electric railways. I have great faith in the motormen of interurban railways, and believe that if they are properly instructed, they can usually be relied upon. The great trouble is not so much with the motormen as with the managers of the road.

The installation of the "coasting time clock" described by Mr. Putnam will automatically instruct the motormen as to the best method of operation, and will be a good check on them as well. This method seems to me to get at the root of the matter much more quickly than the use of the wattmeter. It has the great merit of giving the men practically one point to look out for, and if this one is kept constantly in mind, the efficiency of operation will undoubtedly be high.

L. B. Stillwell: The facts set forth in the paper which Mr. Putnam has presented are an excellent illustration of what may be called effective team work between the consulting engineers and intelligent, alert operative men. I quite agree with Mr. Putnam's suggestion that at times we are hard on the manufacturers, in asking them to do almost the impossible. Of course, it is right to obtain the best that is reasonably practicable, but in doing that we may be overlooking many opportunities for economy in our own particular province in the field of construction and operation. The value of the economies effected by the introduction of this coasting clock on the Manhattan Elevated Railway system in New York is extremely striking. The power bill of that division of the Interborough Rapid Transit Company approximates $4,000 a day. A reduction of twenty-five per cent is about $1,000 a day, and you can see what that means. That has been accomplished by the joint work of the consulting engineers and operating men. The particular device used is due to the operating men, who have very intelligently developed something which is effective with their motormen. They propose to establish a system of premiums, which will further stimulate the attention and effort of the motormen.

Referring to Mr. Armstrong's question, the effect has not been to increase the average acceleration, but to bring it up to what it was intended to be, not beyond what the substation was designed for, but to the standard of economy which the engineers originally intended in laying out the plant. The desirable coasting period, as determined theoretically is thirty-five to forty seconds, the actual performance without the clocks being only twelve. This condition of affairs required the introduction of a clock. The clock has brought the performance up to the economic standard set by the engineers.

Wm. McClellan: There is a point to which he refers, that I would emphasize in connection with Mr. Putnam's paper, and that is the question of lengthening out the coasting time at the end. My own experience is that it is difficult to get a motorman to brake a train in what you might call the theoretically efficient manner; in other words, the habit which the motorman has of putting on the brakes long before they need be put on, then letting them go, then applying them again, and letting them go again, etc.; and I think that this is a loss which the measuring of the coasting time would eliminate more effectively than any other power consumption on the train which is measured. The saving can hardly be estimated, but is very great, which could be secured from the elimination of this habit of the motormen of applying their breaks and releasing them without occasion. That point is referred to in the paper, but not emphasized.

Frank J. Sprague: The striking facts set forth by Messrs. Putnam and Stillwell are a somewhat tardy contribution to the efficiency of coasting and quick acceleration which have been advocated since the South Side Elevated road in Chicago was first operated electrically. No reference has been made to automatic acceleration. When developing electric elevators and establishing the secondary control of controllers, I quickly realized that the personal element of a man was a small thing to rely upon for perfect service; that to get even torque on motors, reasonable strains on apparatus and a proper consumption of the supply of electricity, whether from a battery or a dynamo, the movement of the controller should be automatically accelerated and controlled. In the case of the South Side road, where the first multiple trains were installed, every main controller was fitted with a throttle which permitted the controller, under control of the master switch, to automatically accelerate to either series or multiple position, at a rate determined by the amount of current passing through the motors.

Economy of operation between stations depends primarily on two things; first, the quickest, safest and most comfortable acceleration, and second, the maximum safe and comfortable braking. The necessary amount of coasting is determined by the relation of these two. Automatic acceleration, now used on most recent equipments, performs the first function. That, however, is not enough, for while it removes from the motorman the personal element in starting his train, he is still privileged to continue to accelerate, coast for a short distance, and meddle with the brakes in any way he sees fit. The introduction on the Manhattan Elevated Railway of the coasting clock, to check the operating engineers on that road by determining the coasting time, is an excellent method of insuring a fuller measure of the value of coasting on a railroad. Mr. Stillwell has pointed out that it means saving $1,000 a day in power supply in the case of that one road. It also means something else, for referring to the figures given in Mr. Putnam's paper, I estimate that it would have effected on the Manhattan Elevated Railroad a saving of about 5,000 kilowatts in initial equipment, which represents a capital cost of anywhere from $500,000 to $750,000.

L. B. Stillwell: The figure I mentioned, viz., $1,000 a day, was meant to include interest on the capital cost as well as the car operating cost.

N. W. Storer: There was one point I neglected to mention in my previous remarks, and that was to speak of the series operation which Mr. Armstrong brought out so well. I agree with him heartily, and want to mention that it is perfectly possible to arrange the control, as has been done in some cases, to accelerate at a high rate in series, and any other fixed rate in parallel, so as to get the automatic acceleration which certainly is most desirable.

G. H. Hill: The acceleration portion of the speed-time curve is undoubtedly the most important with relation to the comfort of passengers and the economy of power. As Mr. Sprague pointed out, the adoption of automatic control removes this element from the influence of the motorman. As Mr. Storer mentioned, and as in operation in different places, this can be accomplished either at a constant current per motor, or at different predetermined rates in series and in parallel. That leaves only two elements of the curve which may be varied according to the judgment of the motorman.

If there were developed a practicable system of automatic braking (that is, a system wherein the braking effort is applied automatically as some function of the speed), the proper amount of coasting would, for a given schedule, take care of itself. Such a system of braking is somewhat complicated, and has not to my knowledge been used. With heavy trains, operated at speeds higher than now usual in a service requiring frequent station stops at a high rate of braking, it may possibly become a desirable or necessary feature.

Mr. Putnam's apparatus aims at the desired result by checking the coasting period, so as to induce the motorman to reproduce as nearly as possible the proper predetermined run cycle. The results seem to fully justify the complication and expense incident to its use. The arrangement of circuits and apparatus illustrated can I think be somewhat simplified and perhaps improved so as to be self contained and quickly applied to any car. The scheme certainly seems more practicable than the use of recording wattmeters, which are sometimes advocated for a similar purpose.

H. St. Clair Putnam: Several questions have been raised in the discussion of this paper which I will take up as briefly as possible. Mr. Taylor has inquired what precautions have been taken to prevent the beating of the clock by the motormen. This subject has been carefully considered by the designers. The diagram of the connections used for measuring the time of coasting is given in the paper. All electric contacts and magnets used in the operation of the clock are placed inside the case excepting the contacts which are made and broken by the operation of the brake cylinder. The latter are placed beneath the car. It is impossible to cause the clock to register coasting time without manipulating these contacts and at the same time having the controller handle in the second position or beyond, so that the motors as well as the clock will receive current. This is practically impossible for the motorman to accomplish. In addition to these precautions, in the case of the Manhattan Elevated system, the clocks are placed on the trailers, entirely out of reach of the motorman.

Mr. Taylor suggests that it might be possible for the motorman to beat the clock by turning power on and then off again immediately during the time of stop. While this, of course, is physically possible, yet it is impracticable because the actuating current is taken from the second point of control, which the motorman cannot reach without moving the train, and if he attempts to hold the train with the brakes, the clock is immediately stopped. If he can coast into the stop the clock will continue to register, but as such a stop results in the largest possible return for the energy used, owing to the energy otherwise lost in braking being used to move the train, the motorman is entitled to all the credit he can obtain in this manner. Practically it will be impossible for the motorman to make such stops and maintain the schedule, and in most cases it is practically impossible for him to make a stop without using his brakes, or stand still with his brakes off, because of grades.

Mr. Sprague, Mr. Armstrong and Mr. Storer have commented upon the subject of the reduction made in the amount of energy required by increasing the rate of acceleration. This has long been recognized. The possibility of its accomplishment in electric operation, and especially in multiple unit operation, is one of the most important advantages obtained in electric traction. The amount that this acceleration can be increased is limited, in any particular case, by the capacity of the equipment provided. As Mr. Stillwell has pointed out, however, it is not the function of this clock to increase the acceleration over the amount for which the equipment has been designed, but to obtain in practice the acceleration that was contemplated by the engineers in selecting the electrical equipment for the system, including motor cars, substations, feeders and power house. As all operating men know, and as our tests of the Manhattan Elevated show, the motormen do not attain in practice the acceleration that they are instructed to use. This clock has demonstrated that under the guise of increasing the coasting time, the advantages of rapid acceleration are forced upon the motormen, and the desired result attained.

Mr. Sprague and Mr. Hill have called attention to the benefits to be derived from automatic acceleration and that this would take one of the elements of the speed-time curve out of the control of the motorman, and assist in accomplishing the results desired. This is true, but one of the most important factors in the operation of the Manhattan Elevated system which resulted in increasing the amount of the coasting obtained in our tests was not so much an increase in the rate of acceleration, as improvement in the manipulation and handling of the trains.

This is illustrated by the fact that since the clock has been installed the motorman coasts up slowly behind a preceding train, when delayed by the train in front, instead of coming up full speed and then applying the brakes and coming to a stop as is usually done. This results in a material reduction in the energy used. Furthermore, the motorman soon finds that he can increase the amount of coasting and still maintain his schedule if the stops can be cut down, so he gets after the rest of the train crew to cut the stops as short as possible. As most of the crew are candidates for promotion, they are forced to respond.

Mr. Hill has also called attention to the possibility of automatic breaking, and Mr. McClellan has emphasized the importance of braking. If automatic braking were possible of accomplishment in a practical manner it would be most desirable. The proper braking of a train on such a system as the Manhattan Elevated is the most difficult part of the operation to obtain from the motormen, as judgment, skill and experience are required. Such an automatic device, if perfected, must of necessity permit the motorman to increase or decrease at will the rate of braking fixed by the automatic device, so that he can make his proper stop at the station platform. There are many practical difficulties in the way of the attainment of this result, though I will not say that it is impossible of accomplishment. Experience gained on the Manhattan system, however, has shown that the installation of the coasting clock has resulted in a radical improvement in braking as well as in acceleration, and that with this device, the theoretical speed time curve as used by the engineers in designing the equipment of the road can be closely approximated in the average results obtained, while some of the motormen by careful handling of their trains obtain even better results.

Mr. Armstrong and Mr. Storer have suggested that a rapid acceleration can be used in the series position, and a reduced rate in multiple, with the result that a fair average rate of acceleration can be obtained without compelling the substation to take care of such high peaks as would otherwise result if the same running time were made by using a uniform straight line acceleration for both control positions. There are many advantages in this method of operation, especially for interurban roads where the substation capacity is limited, and the trains infrequent. With the short headway used on the Manhattan system, however, the advantages of such a method of operation largely disappears. As already has been pointed out, the strength of gears, motor capacity, and the comfort of passengers, limit the practical rate of acceleration that can be used. In all cases, if this rate of acceleration can be employed in series, the average of both the power and energy required will be reduced by using the same rate of acceleration in multiple, for the simple reason that in a large system such as the Manhattan, all apparatus in the power house, substations and feeders can be operated at their heating and economical limitations, and any reduction in the energy used therefore results in a corresponding reduction in the apparatus required.

In the case of interurban roads and other roads of limited service, the improvement made in the operation and handling of equipment resulting from the installation of some such device as this coasting clock, might result in the ability to reduce the rate of acceleration used during the multiple period, with a resulting reduction in the average rate of acceleration, and a corresponding reduction in the peak load on the substation feeder system and power house, without reducing the scheduled speed. This again, however, would have to be balanced against the cost of the increased energy used. In most cases, especially where the service and stops are frequent, the higher rate of acceleration usually will be found most economical.

P. A. Bancel: Mr. Putnam points out clearly the key to economical operation of heavy city railways by saying that "the energy absorbed in braking is the essence of the whole subject." One means of reducing the amount of energy lost in braking is to retard the speed of the train by causing it to climb a grade. By running a train up a slight grade as it approaches a station, and down a similar and equal grade as it leaves the station, an interchange of kinetic and potential energy is secured and corresponding saving in power obtained. The principle involved is evidently similar to that employed with elevators, where counter weights retard or brake the speed descending, and assist the motion in ascending.

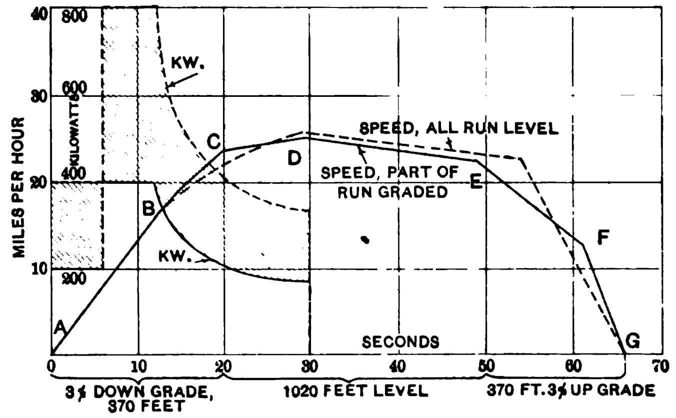


FIG. A.—*A-B*, acceleration due to gravity plus motors; *B-C*, acceleration due to gravity plus motors on motor curve; *C*, end of 3 per cent down grade; *C-O*, acceleration on level, due to motors on motor curve (resistance all cut out); *D-E*, coasting on level track, retardation due to train resistance; *E-F*, coasting on 3 per cent up grade, retardation due to gravity plus train resistance; *F-G*, braking, retardation due to brakes, gravity and train resistance.

The saving produced by applying such a principle to electric railway traffic can best be shown by an example. Taking the train of Fig. 3, assume that the train leaving the station at time zero, is on a 3 per cent down grade. Since the force of gravity acting on the train is 154 tons, the accelerating force in the direction of motion will be $3/100 \times 154 \times 2000 = 9240$ lb. Now the force necessary to produce an acceleration of 1.33 miles per hr. per second (the acceleration of Fig. 3) is 18620 lb., as found from the well known expression, force = mass × acceleration. Since the 3 per cent grade is providing 9240 lb. accelerating force, it is now necessary to obtain only 18620–9240 or 9380 lb. accelerating force from the motors of the train. This is approximately 50 per cent of the original force necessary.

If then a train of the same weight were equipped with motors of but half the capacity, and drew only half the current from the line, the same resistance acceleration would be obtained on a 3 per cent down grade. This line, *A B*, shown on Fig. *a* is therefore identical with that of Fig. 3 of the paper.

All the resistance being cut out, the motors accelerate on the motor curve. Assume now that the 3 per cent down grade lasts till the end of the 20th second. From the time that the resistance is all cut out at the 12th second, up to the 20th second, the train is also being accelerated by the component of its weight, 9240 lb., acting in the direction of motion. At any second the accelerating force along the motor curve is proportionate to the kilowatt input divided by the speed. Assuming that at any instant with the motor equipment reduced by half, the accelerating force due to the motors is also reduced by half, figures are obtained from which the accelerating curve from *B* to *C* and *B* to *D* was calculated. From *B* to *C* acceleration is due to both motor force and gravity, and the actual velocity at any instant was obtained from the acceleration, which in turn was derived from the total accelerating force at the same instant. This accelerating force has been seen to be the sum of the constant 9240 lb. and the variable motor accelerating force. The curve from *C* to *D* is the plain motor acceleration curve.

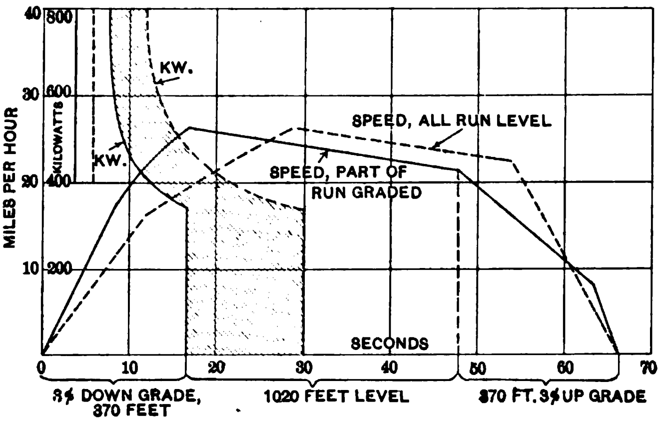


FIG. *b*

By assuming 3 per cent down grade for 20 seconds, followed by level track, it is seen that the speed time curve obtained coincides very closely with the original. The rest of the chart is constructed by following similar calculations. The line *E F* is the braking due to the upgrade alone, while *F G* is that due to both the up grade and the actual brakes. The point *E* was determined by trial to make the area under *E F G* equal to that under *A B C D*. Thus the distances of up-grade and down-grade are equal. From the areas the actual distances are calculated as 370 ft., 3 per cent down grade, 1020 ft. level track and 370 ft., 3 per cent up grade. By assuming these distances, and grades, the whole speed time curve is made to coincide very closely with the original, so that their areas and therefore the total distances traversed in either case are the same.

The saving to be obtained by such a see-saw arrangement of grades has already been indicated. For the same rate of acceleration about half the kilowatt-hour input would be required, and only half the motor capacity would be needed. The kilowatt-seconds input saved where grades are used is shown by the shaded area and this is roughly ½ that originally necessary. It is interesting to note that the time during which the brakes are applied and therefore the " energy absorbed in braking " is correspondingly reduced.

Fig. *b* is drawn to show the result when using the original motor accelerating force and motor equipment, with track profile similar to that for Fig. *a*. The total accelerating force is again increased by reason of the gravity component while the motor accelerating force is equal to that with the original train, so that the maximum speed is reached much sooner. The areas under the speed curves and therefore the distances traversed in both cases are approximately the same, and the saving in power is shown by the difference between areas under the kilowatt curves.

A paper presented at the 27th Annual Convention of the American Institute of Electrical Engineers, Jefferson, N. H., July 1, 1910.

A METHOD FOR DETERMINING THE ADEQUACY OF AN ELECTRIC RAILWAY SYSTEM

BY R. W. HARRIS

The adequacy of a railway system is often a point of contention between the public and the company. The many lawsuits and investigations carried on by various regulating bodies is evidence of this fact, and such cases are always a source of trouble and expense. In many instances they are unnecessarily brought about by " chronic kickers " who take advantage of every opportunity to gain political popularity through an attack on the railway company for lack of cars, unreliability of service, etc. The answers to such complaints are generally so indefinite and technical that the ordinary layman finds it difficult to obtain a satisfactory explanation and understanding. Consequently, there is a continual complaint and disturbance among the traveling public because, perhaps, of alleged insufficient accommodation and the lack of a fair knowledge of the railway business.

As a matter of fact, companies often do not know definitely whether or not their systems are really serving the public in the best possible way. A necessary requisite of successful operation is to satisfy as conveniently as possible the requirements of the public that are established by a natural development of the community. The petty whims and fancies of the few are not serious factors in determining the adequacy. There are, however, certain habitual movements (barring a certain amount of indiscriminate travel by pleasure seekers, shoppers, etc.) which the traveling public forms that are comparatively stable in character and magnitude. They are the natural resultant of the various routes automatically established by the passengers. These movements occur daily and, in general, do not fluctuate in direction, for when the habit of making a "usual" trip over a certain route is once formed, it is seldom broken.

Every city has its manufacturing, wholesale, retail, and residence districts definitely located and these are changed only very gradually through years of growth and development. Consequently, the origins and destinations, except in a few cases, will not change materially.

The extent to which these prevailing movements are met is an important index of the adequacy of a railway system. Adequacy involves many delicate and technical questions of a more or less intangible nature. The extreme fluctuations in the amount of travel caused by different weather conditions, etc., make it impossible, as well as impracticable, to endeavor to meet all peak conditions of travel with satisfaction to all.

It is the purpose of this paper to bring out certain conditions which were encountered while making an investigation into the adequacy of The Milwaukee Electric Railway & Light Company's railway system for the Railroad Commission of Wisconsin, under the direction of the author, and to show how they were considered.

If a system is adequate, it must be sufficient to care for the reasonable demand of the traveling public in its various forms as well as to be in line with a well directed plan to care for present and future business economically. The routing of the cars that serves the largest number of people by the most direct route, at times when the traffic requires it, free from delay and with a sufficient number of sanitary cars so the average amount of traffic will be comfortably cared for, is highly desirable. These are very material factors in establishing an adequate system. A failure to provide any one of these accommodations will result in an attack, sooner or later, on the company for giving poor service. In most cases the conditions become exaggerated in the minds of the public through the lack of sufficient understanding of the business and, as a result, the company may sacrifice a part of the public's good will.

A system that satisfies the above requisites, carried to such an extent that the amount of investment required and costs incurred will not exceed a reasonable proportion of the earnings as well as to be a convenient link in a systematic plan arranged to care for future growth of business, might be said to be an adequate system.

The particular layout of a city and the franchises that may be secured enters the case to such an extent that it is often impossible to establish a direct route for all classes of passengers. These, together with many other difficulties, may make it impossible to secure an adequate system in the strictest sense of the term. An adequate system, from a practical point of view, is one that will handle the demands of the public in the shortest time by the most direct route with as little distortion of headway as possible, and with the least inconvenience to the passengers. Reliability of service is necessary. If the regular headway is frequently distorted to such an extent that the public suffers from the lack of regularity in the service, the system is inadequate, since it does not supply the reliability characteristic. The nature of these various conditions are radically different, and are peculiar to each city. Each company must study its own characteristics of service and determine its own method of handling various conditions. There is very little reliable data to be had regarding the detailed features of service. However, considerable has been written regarding general conditions in various localities.

The data and curves shown in the following pages are not the result of a theoretical deduction but are compilations of data taken by a trained force of inspectors along a definite, pre-arranged outline so designed as to show the various conditions as they exist in the system's operation. All data were observed on the street and compiled so as to show clearly the features of operation. No dependence has been placed upon any records of the company that were obtained in the form of trip sheets, and general data collected by supervisors, etc. The effects of numerous personal elements of the uninterested trainmen, who so often fail to appreciate the importance and use of such information, do not enter.

A general study of the movement of people during the day revealed the fact that there were four distinct periods during which the majority of people travel. These periods were very easily determined, for during such times the amount of travel was much greater than that during other portions of the day. They were designated arbitrarily as Period No. 1, Period No. 2, Period No. 3 and Period No. 4, and were found to occur, respectively, from 6:00 a.m. to 9:00 a.m.; 11:00 a.m. to 2:00 p.m.; 5: p.m. to 8:00 p.m.; and 10:00 p.m. to 11:00 p.m.

The adequacy of the system will be measured by the conditions existing during these periods since all features of traffic will be encountered in their greatest degree of effectiveness. The rate of flow of passengers, so to speak, resulting in the largest demand for cars, is greatest during these periods as well as the amount of congestion in the down town districts, all of which are material factors in distorting headway. During these periods, certain classes of passengers are easily agitated and become abusive to the company on account of inconveniences experienced due to late cars, overcrowding, etc. This feeling becomes intensified with any neglect on the part of the company to rectify and improve such conditions.

A careful investigation of each line and a determination of the characteristics during the peak periods are the first requisites that lead to a definite measure of adequacy.

A definite plan was outlined for conducting a study of the system that would determine the practical working conditions as mentioned above and so arranged that all similar observations made by the inspectors would be on the same basis. Each inspector was assigned a line to observe and was directly responsible for securing accurate and reliable data. He made a preliminary study of the line with a view of locating the principal points where the most people boarded and left the cars. These were selected as points of observation. A sufficient number of points were chosen for each line that would give the main characteristics. As a rule, from 6 to 14 or 15 points were selected, depending upon the traffic of the line.

The following data were observed for all cars on each line going in each direction, at all points of observation, and throughout each period, with possibly a few exceptions. This method required the inspector to spend practically a day at each point. As a matter of fact, however, his time was distributed along the line so as to give characteristics that would embody the various conditions occurring during a long period of time:

Time car arrived at point of observation.
Direction car is going.
Number on car body.
Total number of passengers.
Total number of passengers in front vestibule.
Total number of passengers in car body.
Total number of passengers in rear vestibule.
Number of passengers leaving car.
Number of passengers boarding car.

Class of passengers.

Conditions of vehicular traffic.

Conditions of pedestrian traffic.

All data could be obtained by count or close estimates excepting the class of passengers and condition of vehicular and pedestrian traffic. These were recorded according to the following arbitrary scheme:

Passengers.

1st class—Professional and business people.

2nd class—Clerks and shoppers.

3rd class—Laborers.

Vehicles and Pedestrians.

1st condition—Few in number.

2nd condition—Considerable amount but not enough to cause delay.

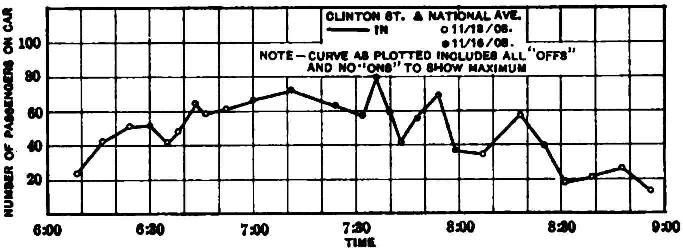


FIG. 1.—Fluctuations of traffic—Oakland-Delaware line (south end) Period 1

3rd condition—Sufficient amount to cause much delay to cars.

At first glance it might seem that the amount of data to be taken of each car going in each direction is more than could be expected without sacrificing accuracy, and especially when the time spacing of cars is often as short as ten seconds; this feature, however, is overcome by practice in making observations. As a matter of fact, the inspectors became so efficient that the data was found to be 95 per cent accurate by test, which is sufficiently close for this class of work. This data does not embody sufficient information to establish all characteristics of the lines and it was found necessary to obtain various miscellaneous data of a general character. This general investigation was made of each line by the inspector to supplement the detailed data which had been secured by the service inspection.

Considerable time was spent in observing the operation of the line and its surroundings in a casual way with a view of determining any special features of the line that were characteristic of all lines, as well as those that were more or less local. The following gives an outline of the data required of the inspector in making the general report of his line:

(a) Divide line into characteristic sections (bound each roughly) and discuss each as to class of passengers, time of travel and probable destination.

(b) Locate various origins of passengers along line, obtain as closely as possible their destination and probable route. (Refer to factories, etc).

(c) State transfer points and give an idea as to the number (in percentage of passengers leaving car from which transfer is made) transferring to other lines (name the lines) in various directions.

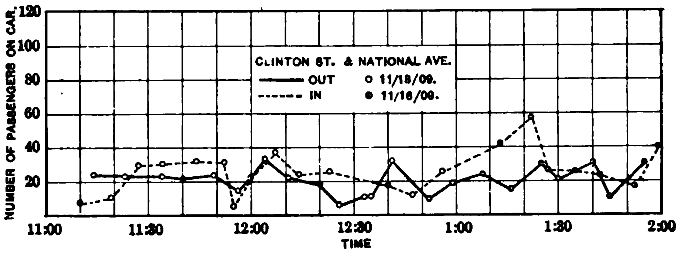


FIG. 2.—Fluctuations of traffic—Oakland-Delaware line (south end)—Period 2

(c) Determine the attitude of the public served by the particular line as regards the service given by the company. This can be done by several casual conversations with passengers.

(e) Make a few specific observations (record count) of the movement of the passengers (seated passengers to vestibule and vice versa) in the car as it approaches the stop in downtown and outlaying districts.

(A few continuous trips through the districts under investigation during the various periods will probably give the information desired.)

The above included a general reference to the transferring question but, on account of the impossibility of determining the number of people leaving or boarding the car who hold transfers, this data had to be supplemented by a study and classification of the transfers actually collected by the company

(Fig. 11). On account of the endless amount of work thus involved, it was considered advisable to classify the transfers taken on a representative day and qualify this information by that secured in the general report.

An investigation of the headway that existed in the various districts along the lines is embodied in the requirements of the detailed study. For the sake of comparison and assistance in determining what was the safe minimum time spacing of cars for any section of track, certain observations were made in various cities in the middle west where conditions were somewhat similar to those found in Milwaukee. The result of these observations are shown in the following pages.

The above gives a general idea of the method used to secure the field data. There are, however, many minor details omitted that perhaps would be of interest but, for the sake of brevity, they are left to be inferred from the various tables, curves, etc.

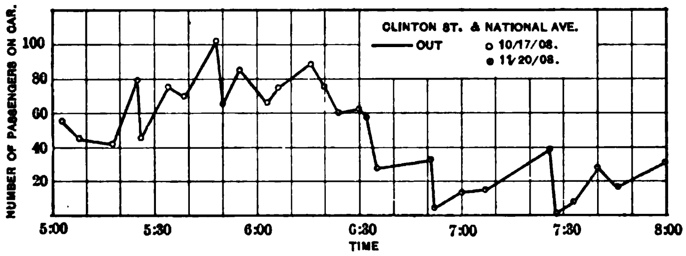


FIG. 3.—Fluctuations of traffic—Oakland-Delaware line (south end)—Period 3

While there was a marked difference in the amount of traffic during the various periods of maximum travel, as compared with other times of the day, yet the traffic was, by no means constant during any period. As a matter of fact, the traffic during one portion would be radically different from that of other portions of the same period. Fig. 3 gives an example of the curves showing the fluctuation of traffic during the periods of maximum travel with time as one axis and total number of passengers as the other. The most characteristic point of each line was selected and a similar traffic fluctuation curve plotted. These curves show a very pronounced difference in the amount of travel between practically two parts. A reference to Fig. 3 shows a maximum period from 5 p.m. to 6:30 p.m. and a minimum period from 6:30 p.m. to 8 p.m.;

TABLE I. SUBDIVISIONS OF PERIODS OF CONGESTION FOR VARIOUS LINES

Line	Place	Period I 6 a.m. to 9 a.m.		Period II 11 a.m. to 2 p.m.		Period III 5 p.m. to 8 p.m.		Remarks
		Maximum sub-period	Minimum sub-period	Maximum sub-period	Minimum sub-period	Maximum sub-period	Minimum sub-period	
1. Wells-Farwell	Jackson & Biddle	7:30-9	6-7:30	11:40-12:40 12:45-2	11-11:40 12:40-2 11-12:45	5-6:30	6:30-8	E. End-Out E. End In
Wells-Farwell	11th & Wells	6-8 7:30-8:30	8-9 6-7:30 8:30-9	12:45-2	11-12:45 11-11:45 12:45-2			W. End Out
				11:45-12:45		5-6:30	6:30-8	W. End In
2. Fond du Lac-National	Walnut & Third	6-8	8-9	11-2		5-7	7-8	North End
3. Walnut-National	Reed & National	6-7	7-9	11-2		5-6:30	6:30-8	So. End Out
		7-9	6-7	11-2		5-6:30	6:30-8	So. End In
4. 8th Ave.-3rd St.	Reed & Greenfield	6-8	8-9	11-2		5-6:30	6:30-8	South End
4. 8th Ave. 3rd 5. Burnham-3rd	North Ave. & 3rd St.	6-8	8-9	11-2		5-6:40	6:40-8	North End
5. Burnham-3rd St.	Reed & National	6-8	8-9	11-2		5-6:30	6:30-8	South End
6. Oakland-Delaware	Clinton & National	6-8	8-9	11-2		5-6:30	6:30-8	South End
Oakland-Delaware	Brady & Astor	6-9		11-2		5-6:30	6:30-8	North End
7. Holton-Mitchell	Clinton & National	6-8	8-9	11-2		5-6:30	6:30-8	South End
Holton-Mitchell	E. Water & Wisconsin	6-8	8-9	11-2		5-6:40	6:40-8	North End
8. Muskego-8th St.	3rd & State	6-8	8-9	11-2		5-6:45	6:45-8	North End
Muskego-8th St.	Reed & National	6:30-8	6-6:30 8-9	11-2		5-6:30	6:30-8	South End
9. Clybourn-Wisconsin	Grand & 6th	6-7	7-9	11-2		5-6:20	6:20-8	
10. Twelfth-Wisconsin	Wells & 11th	6-8	8-9	11-2		5-6:45	6:45-8	
11. State-Wisconsin	State & 3rd	7-9	6-7	11-2		5-6:30	6:30-8	
12. Vliet-First Ave.	Reed & Greenfield	6-8	8-9	11-2		5-6:30	6:30-8	South End
Vliet-First Ave.	Third & Chestnut	6-8	8-9	11-2		5-6:30	6:30-8	North End
13. Vliet-Howell	Reed & Greenfield	6-7:45	7:45-9	11-2		5-6:30	6:30-8	South End
Vliet-Howell	Third & Chestnut	6-8:20	8:20-9	11-2		5-7	7-8	North End
14. North Ave.	North & Twelfth	7:15-7:45	6-7:15 7:45-9	11-2		5-6:30	6:30-8	

these are termed " maximum sub-period " and " minimum sub-period ", respectively. This feature prevails throughout period No. 1 and Period No. 3, occurring practically at the same time for all lines (see table 1.) During Period No. 2 this characteristic is not so prominent and, on account of the comparatively small amount of travel, it was considered unnecessary to sub-divide it. Incidentally, these curves give a slight idea of the headway as it actually occurred.

TABLE II. SUMMARY OF PASSENGER DATA MUSKEGO EIGHTH STREET LINE

				Ave. No. people		Ave. No. of		Ave. No. pass. on		Ave. No. pass.	
Period	Sub-period	Place	Direction	on car	in car body	vacant seats	pass. stdg.	front vest.	rear vest.	on	off
3	5–6:45	8th & North	N(out)	55^{26}	44^{26}	—	2	5^{23}	9^{23}	2^{26}	4^{26}
3	6:45–8	"	"	32^{18}	25^{18}	17	—	3^{8}	6^{10}	2^{18}	4^{18}
3	Ave.	"	"	48^{39}	38^{39}	4	—	4^{30}	8^{33}	2^{39}	4^{39}
3	5–6:45	7th & Walnut	"	69^{26}	54^{26}	—	12	6^{27}	10^{26}	4^{26}	2^{26}
3	6:45–8	"	"	37^{9}	30^{9}	12	—	3^{7}	6^{8}	5^{9}	1^{9}
3	Ave.	"	"	61^{37}	48^{37}	—	6	5^{34}	9^{36}	5^{37}	2^{37}
3	5–6:45	7th&Chestnut	"	70^{26}	54^{26}	—	12	6^{26}	10^{26}	3^{26}	1^{26}
3	6:45–8	"	"	38^{9}	32^{9}	10	—	3^{6}	4^{9}	3^{9}	1^{9}
3	Ave.	"	"	61^{35}	48^{35}	—	6	6^{31}	9^{35}	3^{35}	1^{35}
3	5–6:45	3rd & State	"	63^{26}	52^{26}	—	10	5^{18}	7^{23}	5^{26}	0^{26}
3	6:45–8	"	"	27^{10}	24^{10}	18	—	3^{5}	4^{4}	2^{10}	1^{10}
3	Ave.	"	"	53^{36}	44^{36}	—	2	4^{31}	6^{30}	4^{36}	0^{36}
3	5–6:45	3rd & Grand	"	59^{26}	46^{26}	—	4	5^{23}	8^{25}	16^{26}	1^{26}
3	6:45–8	"	"	21^{9}	18^{9}	24	—	3^{4}	2^{8}	9^{9}	2^{9}
3	Ave.	"	"	49^{35}	39^{35}	3	—	5^{27}	7^{33}	14^{35}	1^{35}
3	5–6:30	Reed & Nat'l.	N(in)	16^{14}	15^{14}	27	—	2^{4}	2^{5}	4^{14}	1^{14}
3	6:30–8	"	"	19^{10}	15^{10}	27	—	2^{6}	4^{6}	1^{10}	1^{10}
3	Ave.	"	"	17^{24}	15^{24}	27	—	2^{10}	3^{11}	3^{24}	1^{24}
3	5–6:30	11th&Green'f	"	11^{13}	9^{13}	33	—	2^{5}	4^{3}	1^{13}	0^{13}
3	6:30–8	"	"	10^{16}	9^{16}	33	—	2^{6}	2^{5}	2^{16}	0^{16}
3	Ave.	"	"	11^{29}	9^{29}	33	—	2^{11}	2^{7}	1^{29}	0^{29}

The detailed observations were classified, compiled, and arranged according to these sub-periods as shown, for example, in Table 2. These results show an average of several observations during a sub-period at any point of observation. For the sake of a correct interpretation of the data, the number of observations upon which each average is based is shown by an exponent. These averages are plotted and form a basis for the " car demand curve ", Fig. 4, one axis of which is the number of people on the car while the other represents the line in question drawn to scale and shown as if the route were straight. Separate curves were plotted for each sub-period as well as for the entire period and arranged so the same vertical axis is common to all, but with the horizontal axis so placed that the curves could be easily compared. On account of period No. 4 being the theater period, during which the traffic is more or less local, investigation into its characteristics was confined to a general study. Practically all the characteristics of this period were found to be effective, to a general degree, in Periods No. 1, 2 and 3. For this reason it was considered that any scheme sufficient to meet the requirements of the other periods would satisfy those of Period No. 4. Hence, no further investigation was made.

The average number of people on the car for that particular period or sub-period was plotted and represents the average number of people arriving at that particular point of observation. Through this point, and parallel to the horizontal axis a line is drawn of such length as to represent the average number of people leaving the car. From the extreme left end of this another line is drawn, superimposed upon the former, of such a length as to represent the average number of people boarding the car at this point. The right end of this line then represents the average number of people on the car as it leaves the point of observation. This point was then joined by a straight line to the point representing the average number of people arriving at the next point of observation. The slope of the line joining any two points represents approximately the resultant of the various changes of load through the intervening territory.

The diagram at the left is drawn to scale and represents the class and extent of territory served by the line in question. The information upon which the classification of territory is based was obtained from the general report mentioned in previous pages and later outlined on the map, Fig. 5, after which that portion served by each line, either alone or in conjunction with other lines, was shown by the respective car-demand curve.

These car-demand curves show, at a glance, the principal characteristics of the line, the time, amount and duration of travel, origin of passengers, as well as their destination; and, by reference to the "district diagram," the class of people and very material bearing upon the adequacy. A little study the conditions, in connection with the general layout of the system, gives a definite idea as to whether or not the passenge are carried over a direct route to their destination.

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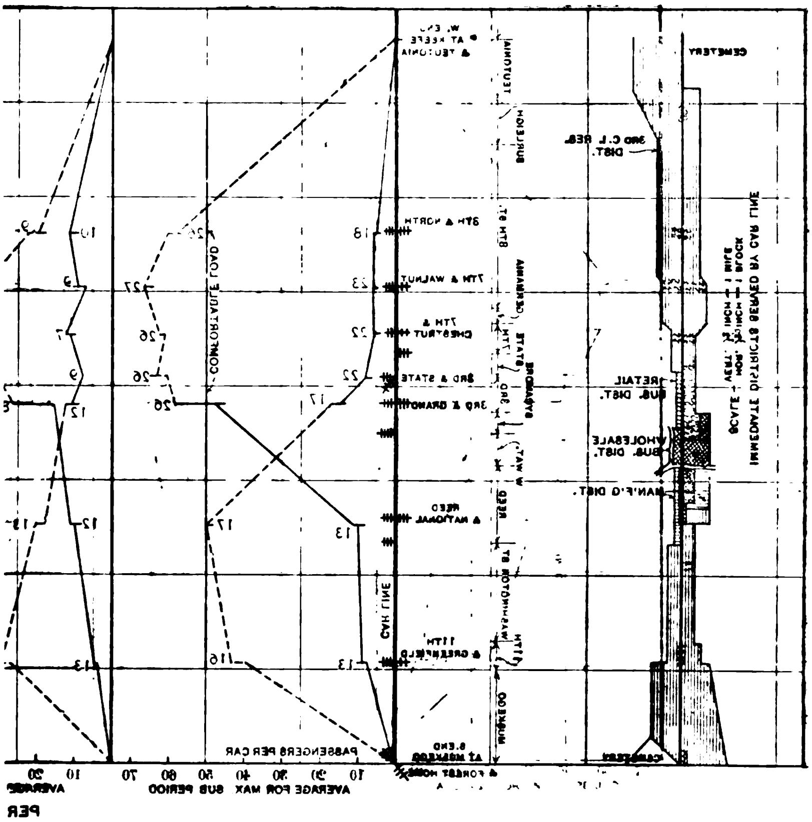

el, origin of passengers, as well as their destination; and, eference to the "district diagram," the class of people and extent of territory served, can be seen. The average number of people boarding and leaving the car at any point of observation as well as the general tendency of the load to increase or decrease in a certain territory, is also shown. All these facts have a very material bearing upon the adequacy. A little study of the conditions, in connection with the general layout of the system, gives a definite idea as to whether or not the passengers are carried over a direct route to their destination.

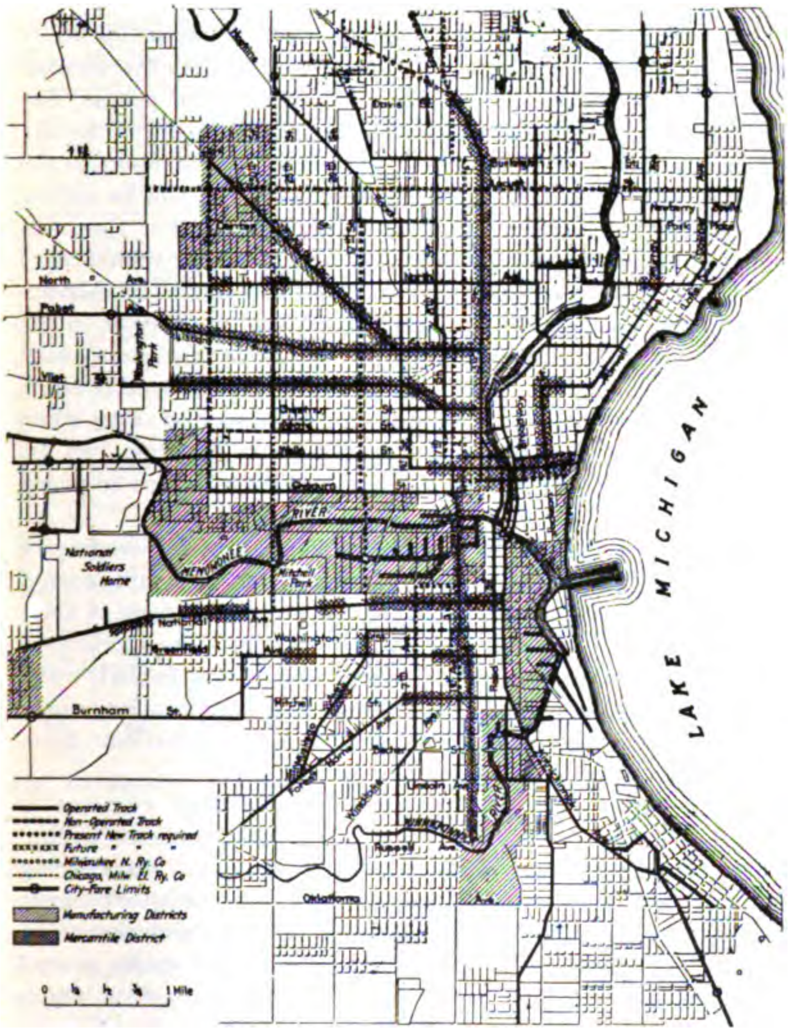

FIG. 5.—Routing of the Milwaukee Electric Railway & Light Company's lines

The adequacy, however, is not fully determined until the number of cars in service is compared with the demand for cars. By associating the curve with the number of observations upon which the car averages are based, an idea of the average number of people carried can be had.

The number of cars per hour required depends naturally upon the number of people to be carried as well as the number that can be carried by one car. The number of people that can be carried, under average conditions, with comfort to all, or the "comfortable load" as it may be called, is equal to the seating capacity of the car plus the number that will be willing to stand by preference. It is to be understood that the comfortable load is not the maximum allowable load a car should carry but is that which, under average conditions, will comfortably accommodate the passengers. The rate of flow, so to speak, of the traffic is entirely beyond the control of the company and very often is such that the cars become unexpectedly overcrowded. Such conditions are likely to occur at any time, and often when least expected. No practical arrangement or schedule can be devised that will provide comfort under all conditions to every one.

Fig. 6 shows the result of the classification and averaging of approximately 9000 observations, and gives accurate information regarding the number of people who are willing to stand of their own accord for various degrees of loading. The horizontal axis represents the degree to which the car is loaded while the vertical axis represents the average of all observations made for any particular load. The number of observations upon which each average is based is given.

The average seating capacity of a Milwaukee city car is 42. A reference to the curve shows that eight people are willing to stand when the car is loaded with 42 people. Considering the vast number of observations made and the consistent curve obtained by plotting the averages for the different degrees of loading, it is reasonable to believe that there exists a well grounded law regarding the average proportion of a load which will be willing to stand by preference. It is reasonable to believe that eight is a consistent number for this degree of loading. Hence, the comfortable load will be 50 people. A line drawn through 50 on the horizontal axis of the car-demand curve, parallel to the vertical axis, establishes a reference line. From this it is easily seen through what territories, at what times, the direction of travel, and the amount that the line is inadequate from a service point of view. A measure of this inadequacy, during any period of maximum travel, can be readily seen by observing the average number of people who are forced to stand through the territory, multiplied by the average number of cars used, and this divided by the comfortable load. This gives the number of additional cars required. The averages referred to, however, are not necessarily arithmetical averages of the numbers shown on the curve, but are such as represents a fair figure for the particular territory when the conditions, as shown by the curve, are modified by local features and good judgment.

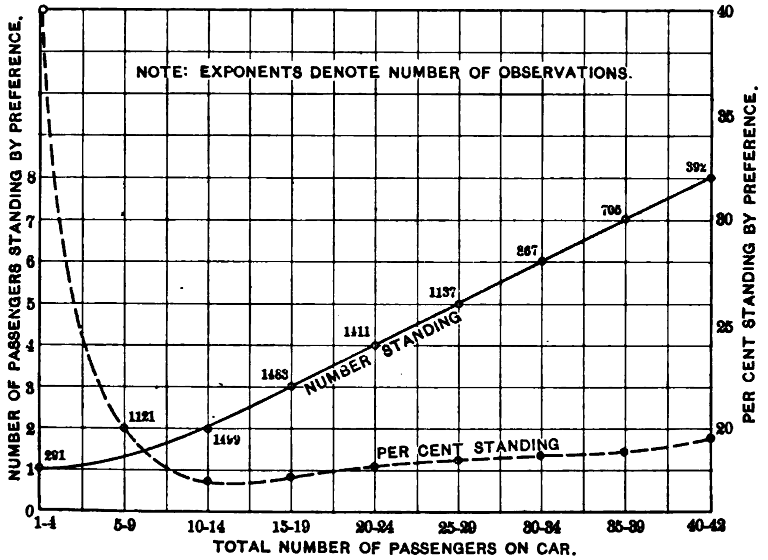

FIG. 6.—Number and percentage of passengers standing on cars by preference

The scheduled headway, or time spacing of cars, is scarcely, if ever, effective, to any degree of certainty during any great length of time, for many reasons, as for example, delay due to railroad crossings, opening of bridges, exceptionally heavy vehicular traffic, delay of other cars, slippery tracks, and other operating features that are continually fluctuating and uncertain in character. It must be considered, in the design of any schedule, that the headway should be such that with the amount of distortion which usually exists it would not be less (fewer seconds) than a certain safe minimum amount. This minimum time spacing of cars may vary for different places where a different combination of conditions is in existence. It is the determining factor that fixes the "full load" capacity of that section of track.

The following is the method used in determing the safe minimum headway at which cars can be operated on Grand Avenue near Third Street, where double tracks crossing double tracks are used in connection with one pair of opposite quadrants one more than the other. All figures are based upon accurately observed data taken in Milwaukee and compared with similar observations made in other cities. (Table 6).

In determining the safe minimum headway from data observed in the field, the basic elements were considered separately:

A. The minimum safe practicable time spacing of cars when in continual motion unaffected by any delay.

B. The average amount of delay of any given car due to causes arising from other cars operated over the same or intersecting tracks.

C. The average amount of delay due to causes having their origin within the car under consideration.

Specific observations were made of the above elements the results of which were shown on the various tables. The results of the basic elements embodied in group *A* are given in Table 3 by which it is shown that the average safe minimum time spacing between consecutive cars, under these conditions is 8.3 seconds for 49 observations, taken during the congested period. In calculating this table, allowance was made; first, for the space covered in one second at full speed to allow the train crew to act; second, for the distance required to stop the car at the observed speed with an assumed negative acceleration of 1½ miles per second; third, for a clear space of 15 feet between cars when stopped.

Group B and C Elements. Conditions which may cause delay to the movement of the cars in one direction under conditions found at Third St. and Grand Ave. are:

(*a*) Car ahead going in same direction upon approaching the intersection but taking the curve.

(*b*) A car taking curve in nearest quadrant but resulting in going in the opposite direction.

(*c*) One car crossing at right angles.

(*d*) Two cars crossing at right angles but going in opposite directions.

TABLE III. TABLE SHOWING TIME SPACING OF CARS AT THIRD STREET AND GRAND AVENUE AS AFFECTED BY GROUP A ELEMENTS
(Time of stops and intersections is not considered here)

Observations taken during	Length of car	Safe space between cars when stopped	Ob-served speed ft. per sec.	Miles per hour	Distance car travels after braking ft.	Safe minimum spacing ft.	No. of cars passing a given point per hr.	Headway (Time spacing of cars) seconds	Remarks
Congested period............	41′	15′	12.27	8.4	34.22	102.49	433	8.3	Average 49 observations
Non-congested period..	41	15	14.26	9.73	45.76	116.02	433	8.1	Average 36 observations
Congested period............	41	15	13.34	9.11	40.44	109.78	438	8.2	Av. frequency of cars for congested period
Congested period............	41	15	16.90	11.53	61.80	134.70	452	8.0	Frequency somewhat decreased
Congested period............	41	15	8.05	5.50	14.73	78.78	368	9.8	Much delay

(*e*) Regular service stops.

(*f*) Unusual vehicle and pedestrian traffic.

(*g*) Delay due to hesitancy of motorman and supervisor.

(*h*) Delay due to hesitancy of cars approaching switches before taking curves.

(*i*) Any other conditions.

OBSERVED DATA RELATING TO ABOVE CONDITIONS.

TABLE NO. IV

Date of observation	Period of traffic	Time of count	(1) Total No. of cars approaching curves	(1) Total No. of cars taking curve	Per cent $\frac{(2)}{(1)}$	Remarks
11/21/08	1	7:00–8:00 a.m.	55	17	30.9	Ordinary conditions of peak traffic
11/20/08	2	12:00–1:00 p.m.	54	16	33.8	Same as above
11/20/08	3	5:15–6:16 p.m.	91	31	34.1	Maximum conditions of peak traffic

(*a*) Since the problem resolves itself into safe operation for maximum conditions, it is advisable to use those as found in Period No. 3, or 34 per cent.

(*b*) Conditions same as (*a*), for as many cars take curve at Third St. and Grand Ave. going north as those that take curve from north going east, or 34 per cent.

(*c*) Data on cars crossing at right angles.

Date of observation	Period of traffic	Duration of count	(1) Total cars crossing going west	(2) Total cars crossing going north	(3) Total cars crossing going south	(2) + (3)	Per cent $\frac{(2)+(3)}{(1)}$
1/13/09	3	5:15 to 6:15p.m.	68	68	59	127	187*
(Congested cars taking curves not considered).							
1/11/09	Between 1&2	10:03 to 11:03a.m	39	36	35	71	182*
(Non-congested cars taking curves not considered).							

NOTE:* Relation (in per cent) of cars on two tracks to those on one intersecting track during the given interval. This percentage is here used as a measure of the tendency to interruptions.

(*d*) Two cars crossing at right angles but going in opposite directions. Approximately 10 per cent of total cars make a straight intersection.

(*e*) Regular service stop; may be made by any car (100 per cent).

(*f*) All cars are submitted to usual vehicle and pedestrian traffic (assume 10 per cent).

(*g*) Approximately 50 per cent of all cars are delayed, due to hesitancy.

(*h*) About 75 per cent of all cars taking curves are delayed on entering curves.

(*i*) Any car may be delayed approximately two seconds for other reasons.

NOTE: It should be remembered that each of the above elements (*a*) to (*i*), inclusive, relates to interruptions caused by a preceding or intersecting car.

TABLE 5. DETERMINATION OF THE COMPOSITE DELAY DUE TO GROUPS B AND C ELEMENTS
(By weighted averages)

Cause or condition	Per cent of cars affected as observed	Seconds delay	Seconds × per cent
a	34%	15.4	523.6
b	34	15.4	523.6
c	187	9.9	1851.3
d	10	13.0	130.0
e	100	15.2	1520.0
f	10	8.0	80.0
g	50	5.0	250.0
h	75	5.0	375.0
i	100	2.0	200.0
Total	600		5453.50

Weighted average delay for 1 per cent of cars observed is 9.09 seconds.

As shown in table 4 the number of cars actually observed was 91 and is represented by 100 per cent in the above table. From this the composite delay due to the causes listed under groups *B* and *C* is 9.99 seconds, or 10 seconds.

The minimum safe practicable headway is, therefore, 8.3 plus 10 seconds, or 18.3 seconds. By a comparison and interpretation of data obtained in various other similar cities (Table 6) it is considered that the operating speed in Milwaukee is somewhat faster than that of other cities. For this reason a minimum safe practicable headway of 20 seconds is more conservative. It will permit a maximum of 180 cars per hour to pass a given point in one direction with safety. A comparison of this minimum safe headway and the headway in operation on Grand Ave., near Third St.,(see Fig. 7) gives an idea as to the adequacy of this section of track. Forty-eight cars out of 197, or 25.4 per cent, were operated at a headway which, under favorable average conditions, is equal or less than the safe minimum time spacing. If there is no possible way of reducing the amount of distortion, and the same scheduled headway is required as shown by the car demand curves, then this section is inadequate for the lines. A re-routing scheme, therefore, becomes necessary. The adequacy of any section of track, from a safety point of view, can be determined in a similar way.

The average actual headway of the various lines in the down town district for periods No. 1 and 3 is approximately 6 minutes,

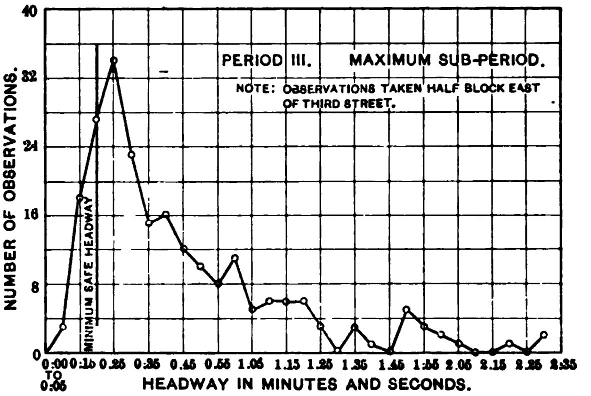

FIG. 7.—Actual conditions of headway of all cars on Grand Ave.

Fig. 8 shows the headway as observed in the down town district. Out of 6433 observations there are 4237, or 65.9 per cent less than the average headway; 890, or 13.8 per cent equal to the average headway; and 1306, or 20.3 per cent greater than the average headway.

In other words, then, 20.3 per cent of the cars, so to speak, are inconveniently spaced from a point of view of reliability. Since this amount is made up of spacings above 6 min., and range in length up to 20 min., some idea can be obtained as to the reliability characteristic of service.

As hinted before, this distortion may be due to causes which cannot be controlled but there are, however, certain environments that can be influenced with proper care on the part of the company and assistance on the part of the passengers. A very important condition effecting headway is the time required for service stops. The stop should be made at a definite point suitable for all conditions of travel thereby reducing the amount of confusion caused by passengers boarding and leaving the car. The rate at which the passengers board and leave cars, together with other minor conditions, practically determines the length of.service stops. Figs. 9 and 10 show the results of an investigation made in various cities by which the fact is brought out that Milwaukee traffic is much slower than that in other cities, especially when a large number of people desire to board or leave the car. In fact the Milwaukee traveling public is practically 25 per cent slower than that found in St. Paul, Minneapolis, Duluth, Indianapolis and St. Louis. It is to be noted that practically identical curves were obtained by plotting data observed in Milwaukee on different days.

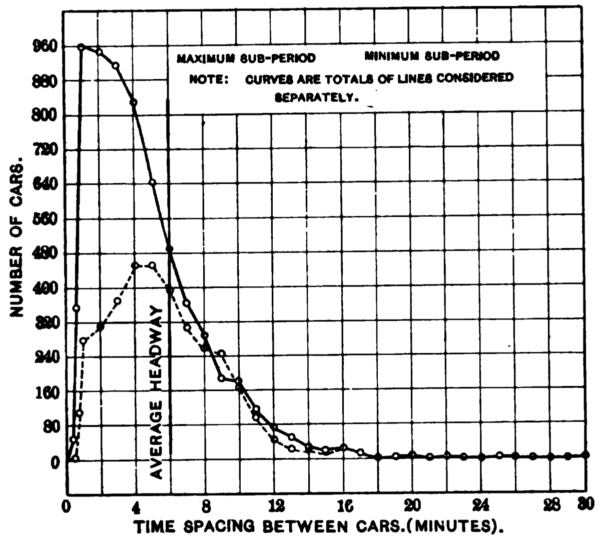

FIG. 8.—Time spacing of cars as observed at principal points—Period 1 and 3

The use of properly worded signs, etiquette on the part of the employees, as well as a little coöperation by the public, etc., are necessary to reduce the distortion of headway which results in an increase of the reliability of service.

The author has endeavored to bring out, in a very general way a method for determining the amount of service given by a railway system as well as to show an example of a method for showing the requirements of the public in a specific case. A correct knowledge of the various conditions mentioned above is an invaluable asset to the company's operating data both with a view to satisfying the demand of the public

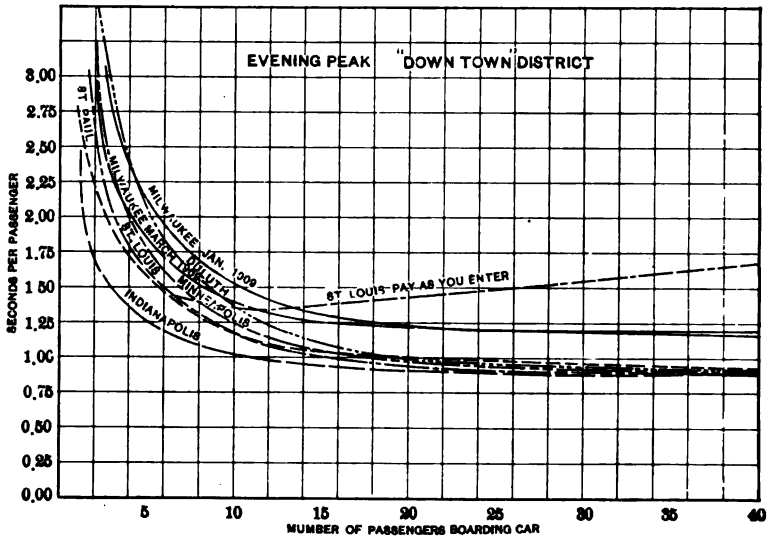

FIG. 9.—Movement of passengers boarding cars

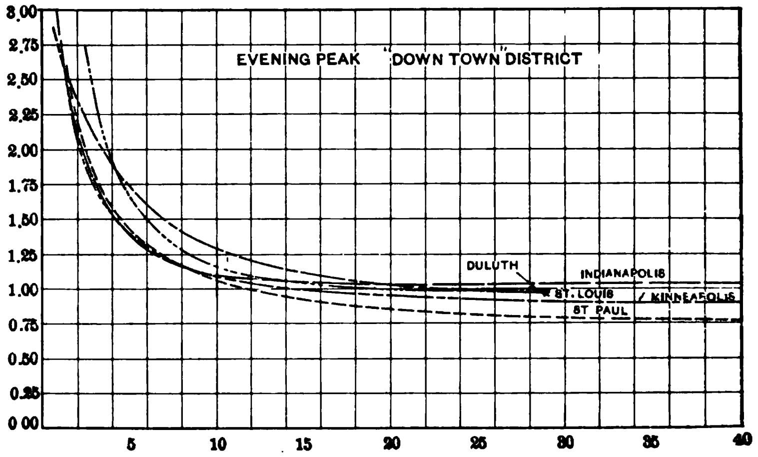

FIG. 10.—Movement of passengers leaving cars

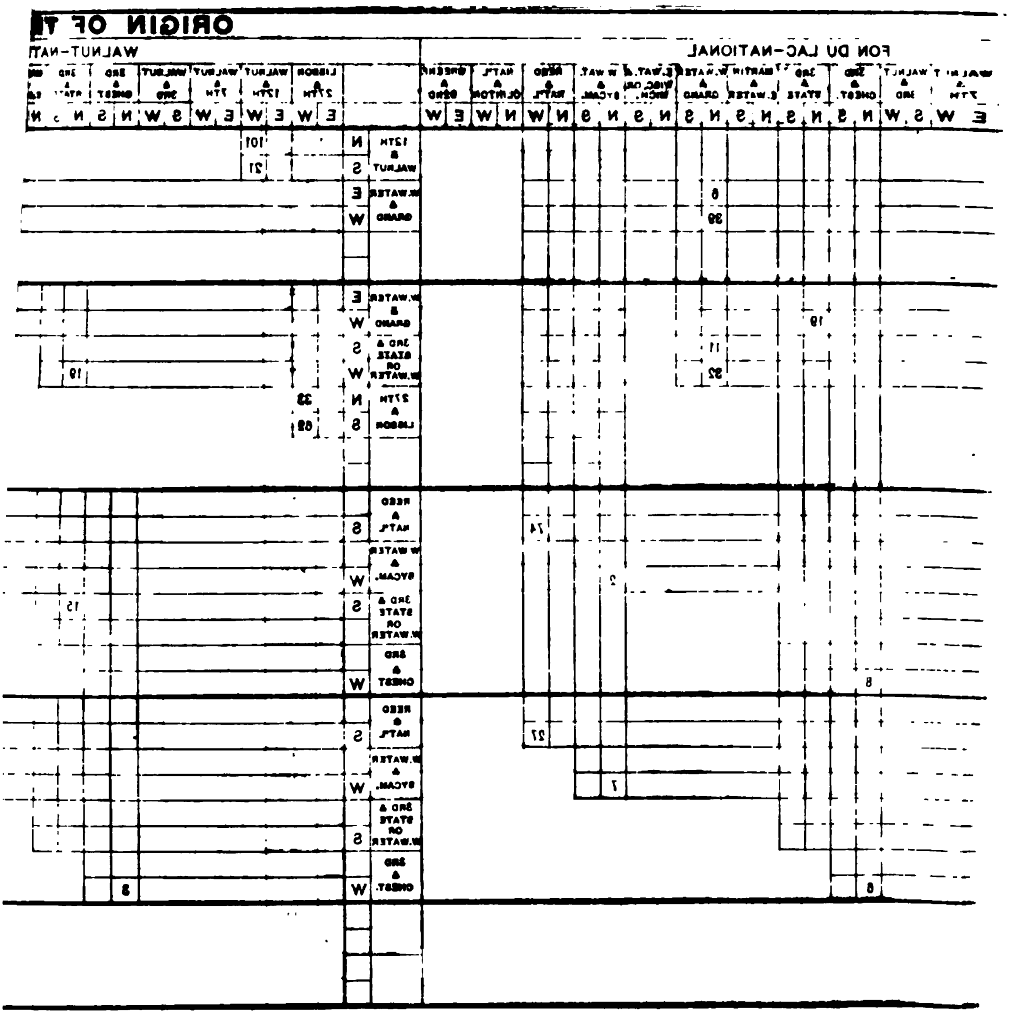

Fig. 11.—Diagram showing the clas

(Transferring is from the direction indicated at the top

as well as a check on the economical features of operation and investment.

No attempt has been made to show the method of arriving at a satisfactory schedule; however, the time, direction and amount of travel are shown on the car demand curves. It has not been the object to determine what is an economical "yearly load factor" for the cars or the relation this load factor bears to the investment required. The author has made a special study of these features but on account of their importance and length of discussion involved they are not embodied in this paper. The data and description contained in the foregoing pages represents observed conditions regarding a special case where only surface lines are operated and is given with a view of bringing out a discussion that will afford many suggestions which will aid in determining the amount of service necessary to care for any given demand.

TABLE 6. DATA SHOWING AVERAGE SPEED AND TIME FOR MAKING INTERSECTIONS AS OBSERVED IN ACTUAL OPERATION IN VARIOUS CITIES

I. Speed Observations.

(a) Congested period.

	No. of observations averaged	Feet per second	Miles per hour	Remarks
Milwaukee conditions........	49	12.27	8.4	
Indianapolis "	28	13.00	8.86	
St. Louis "	7	8.65	5.9	Av. peak conditions
	1	4.6	3.1	Blocked
	4	12.45	8.5	Cars moving freely
	12	9.58	6.54	Total average
Minneapolis "	30	9.08	6.2	
St. Paul "	26	14.14	9.65	
Duluth "	31	12.51	8.53	
(*b*) Non-congested Period				
Milwaukee conditions	36	14.26	9.73	
Indianapolis "	15	16.01	10.93	
Minneapolis "	31	14.91	10.16	
St. Paul "	30	19.27	13.13	
Duluth "	30	13.40	9.13	
(*c*) Miscellaneous speed observations to show effect of a few causes of delay.				
Milwaukee conditions...........	6	13.34	9.11	Average frequency and free movement of cars
	3	16.90	11.53	Frequency decreased. Free movement of cars.
	1	8.05	5.50	Much delay.

II. Intersection and Curve Observations.

(*a*) Congested Period.

One car making a straight intersection (from the time the front end of car passes over switch frog until rear end is clear of second crossing track).

		Number of observations averaged	Seconds	
Milwaukee	conditions	26	9.9	
St. Louis	"	14	9.2	
Indianapolis	"	10	10.3	
Minneapolis	"	28	10.6	
St. Paul	"	15	7.8	

Two cars making a straight intersection, but going in opposite directions (from time front end of first car blocks traffic until last car clears).

Milwaukee	conditions	15	13.0	

Two cars taking curves of same quadrant, but going in opposite direction (from time first car enters curve until curves are cleared).

Milwaukee	conditions	15	18.8	
Indianapolis	"	9	12.3	

One car taking a curve (time front end of car enters curve until rear end clears curve).

Milwaukee	conditions	22	15.4	
St. Louis	"	6	7.2	City cars
		3	16.8	Suburban cars
Indianapolis	"	13	11.4	
Minneapolis	"	7	14.3	
St. Paul	"	14	10.8	
Duluth	"	13	8.8	

One car taking a curve with one car making an intersection resulting in both cars going in same direction (from time front end of first car blocks traffic until last car clears).

Milwaukee	conditions	5	14.7	

(*b*) Non-congested period.

One car making a straight intersection (from the time the front end of car passes over switch frog until rear end is clear of second crossing track).

		Number of observations averaged	Seconds
Milwaukee	conditions	28	10.0
Minneapolis	"	21	8.4
St. Paul	"	18	7.9

One car taking a curve (time front end of car enters curve until rear end clears curve).

Milwaukee	conditions	14	14.2
Minneapolis	"	17	8.5
St. Paul	"	17	9.8
Duluth	"	11	8.9

III. Service Stops.

Congested period.

Period 1	58	16.1
Period 2	31	14.9
Period 3	20	13.1
Average	109	15.2

A paper presented at the 27th Annual Convention of the American Institute of Electrical Engineers, Jefferson, N. H., July 1, 1910.

SOME RECENT DEVELOPMENTS IN EXACT ALTERNATING-CURRENT MEASUREMENTS

BY CLAYTON H. SHARP AND WILLIAM W. CRAWFORD

In common with other laboratories, the Electrical Testing Laboratories have found that the more exacting demands of modern engineering work for precise alternating current measurements, have outstripped the capabilities of the older methods of measurements. It is the purpose of this paper to describe certain of the new methods and apparatus which have been developed in response to these demands.

The development of a method of measurement involves first, the establishment of certain theoretical relations between the quantity to be measured and known quantities, and second, the design of the apparatus for the application of the method. If the method together with the apparatus is such that it can be successfully applied to making accurate measurements under the conditions of ordinary engineering work, its field of usefulness is greatly extended, for it is often desirable to make tests outside the laboratory.

There are many important measurements which are outside the range of ordinary commercial instruments. Among these are the measurement of electrostatic capacities, self and mutual inductances, and of extremely large and extremely small values of voltage, current, and power. For the measurement of large quantities, the range of ordinary instruments is extended by means of voltage and current transformers, but the measurement of the ratios of the transformers presents a problem requiring special methods.

It is well recognized that zero methods furnish possibilities for precise measurements beyond the capabilities of deflecting instruments, inasmuch as the quantity to be measured is balanced against some other more easily measured quantity, and the inherent errors due to the mechanical moving parts,—springs, suspensions, divided scales, etc., of indicating instruments, are avoided. In precise direct-current work, zero methods are used to the exclusion of all others.

In alternating-current measurements, zero methods have not been used to so great an extent, largely because of the lack of proper facilities for applying them when using currents of commercial frequencies. The necessity for zero methods, is however greater in alternating-current measurements than in direct-current measurements; first, on account of the limitations of alternating-current indicating instruments, and second, because of the practical impossibility of obtaining alternating currents as steady as the direct currents furnished by the storage battery.

The difficulty of applying zero methods to alternating currents lies chiefly in the instrument used as a detector in obtaining a balance. If an electrodynamometer is used as a zero instrument, the deflection falling off as the square of the current results in low sensitiveness as the current approaches zero. By separately exciting one of the coils, the sensitiveness may be greatly increased but it is then necessary to provide means for bringing the excitation in phase with the current to be measured.

The telephone under proper conditions, is very sensitive as a zero detector. Its great advantage is its simplicity and cheapness, but when working on the commercial frequencies of 60 and 25 cycles per second, its sensitiveness is for physiological reasons, very low.

Various alternating-current galvanometers have been made, but none of them has come into wide commercial application. The vibration galvanometer when properly tuned, is very sensitive; but being a delicate suspension instrument, it is not suited to all locations, and with a change in frequency, a great decrease in sensibility occurs.

THE SYNCHRONOUS REVERSING KEY

The idea of rectifying the alternating current and passing the rectified current through a direct-current galvanometer, or detector, is not new. It underlies the secohmmeter, which has been used for many years. More recently, attempts have been made to use as a zero detector a direct current galvanometer with an ordinary brush-contact commutator on the generator shaft, or on the shaft of a synchronous motor driven by current from the same source as that to be measured. This plan has been tried and found to be capable of convenient application in many cases, but great difficulty has been found with it due to the fact that the apparent resistance of the sliding-brush contacts under working conditions tends to become very high as the current falls to a low value.

Platinum contact keys used in galvanometer circuits being known to be free from this difficulty, the next step was to construct a rectifier consisting of a reversing key with platinum contacts operated at synchronous speed by means of a synchronous motor and cam.

FIG. 1—Synchronous reversing key No. 1

FIG. 2—Synchronous reversing key No. 2

Means are provided for adjusting the angular position of the contacts with respect to the poles of the motor, so that the reversal occurs at any desired phase of the current. By properly locating the contact setting, the galvanometer may be made to respond to any given component of the current while it is insensitive to the component in quadrature with it.

Figs. 1 and 2 shows two rectifiers which have been constructed. The first is attached to a small four-pole synchronous motor of the type described by Mr. L. T. Robinson before the last year's Convention.* This rectifier, while fairly satisfactory, had certain defects in the design of the key, and was greatly handi-

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* PROCEEDINGS A. I. E. E., July 1909, p. 1000.

capped due to the impossibility of adequately insulating the key circuits from the motor circuits. Rectifier No. 2 is driven by a larger eight-pole motor which while having the disadvantage of requiring a direct-current field, has a larger torque, permitting the construction of the key with heavier moving parts and greater durability.

The insulation of the motor circuits from the galvanometer circuit is of the greatest importance. An extremely small electrostatic capacity or surface leakage between them may introduce serious errors in measurement. Accordingly, in rectifier No. 2, the key was mounted on a separate bed plate insulated entirely from the motor. By grounding the bed plate of the key to the proper point in the measuring circuit, whatever residual leakage occurs may be led away in such a manner as not to affect the galvanometer.

It has been found in practice that this apparatus gives very good results. The oscillating lever and contacts will operate satisfactorily on a frequency of 60 cycles or more. The wear on the contacts is practically nil, provided that the surfaces are broad enough. The sensitiveness of the galvanometer is practically the same on alternating currents as on direct currents. Theoretically the ratio of the deflections for the same effective value of current should be the form-factor of the alternating-current wave. Due to various minor imperfections in the apparatus so far constructed, however the method is not accurate as a means for the determination of form-factors.

The apparatus places alternating-current measurements on the same basis as direct-current measurements with respect to the sensibility of the galvanometer. Using the galvanometer as a deflection instrument, such quantities as the drop in a short length of iron rail or in a bond carrying alternating current, the measurement of the leakage and charging current of a few insulators, or of a short length of cable, etc., may be easily measured The mechanical imperfections of the rectifiers so far constructed. are such that the calibration as a deflection instrument is not accurate, due to the reversal not taking place exactly at the zero of the wave, but when the calibration is made under the conditions of use, it will be sufficiently accurate for the class of measurements involved. Since the deflection obtained represents the average value of the voltage, any uncertainty in the wave form introduces a corresponding uncertainty in the calculation of the effective value. The wave form may, however, be approximately determined by taking the deflections with a series of settings of the contacts, as is explained later.

In the greater part of the work a portable galvanometer, such as a Paul single pivot galvanometer, giving one division deflection for one microampere and having 50 ohms resistance, gives sufficient sensitiveness. With a galvanometer of this type, the use of a telescope and scale is avoided, and vibration does not effect the measurements. This makes it possible to set up the apparatus in practically any location; *e.g.* in a power house, and to make measurements which with more delicate apparatus would be impracticable. An ordinary portable millivoltmeter makes a very good galvanometer for measurements not requiring the maximum sensibility.

Current Transformer Ratios

The method of introducing low resistances in the primary and secondary circuits and balancing the drops against each other by means of a zero detector, has been tried by various experimenters. The ratio of transformation is the inverse ratio of the resistances. Due to the slight phase difference between the two currents, there will remain, when the drops are adjusted to equality, a slight voltage, practically 90 degrees in phase from the resistance drops. The effect of this voltage may be eliminated by properly setting the angular position of the contacts, but unless the phase angle of the transformer is very small, it is difficult to set the contacts with sufficient accuracy.

In order to obtain a more accurate value of the ratio and at the same time to measure the phase angle, some means of bringing the two drops in phase is needed. Several methods of doing this which have been developed at the Electrical Testing Laboratories were described before last year's Convention.* The one finally adopted as most desirable is shown in Fig. 3. The primary and secondary resistances are R′ and R″, respectively. A mutual inductance, *M* is introduced which adds to the drop in R″ a small voltage, *a*, in quadrature with it, thus balancing the phase displacement. The double adjustment is made as follows:

By trial, the angular position of the contacts is found in which the galvanometer is sensitive only to changes in the secondary resistance *R″* and not to changes in the inductance. The resistance balance is made with this setting. The contacts are then shifted through 90 electrical degrees, and the inductance

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* Proceedings A. I. E. E., Oct. 1909, p. 1356.

is adjusted until the inductive drop has been annulled. The contacts are then returned to the original position for a check on the resistance setting.

The ratio and phase angle are computed from the following formulæ:

$$\frac{I'}{I''} = \frac{R''}{R'}\sqrt{1+\left\{\frac{2\pi f M}{R''}\right\}^2}$$

$$\tan\gamma = \frac{2\pi f M}{R''}$$

When the phase angle is less than two deg. the correction term in the ratio formula may be neglected. In practice, the calculations are simplified by the use of curves which give the results directly from the readings.

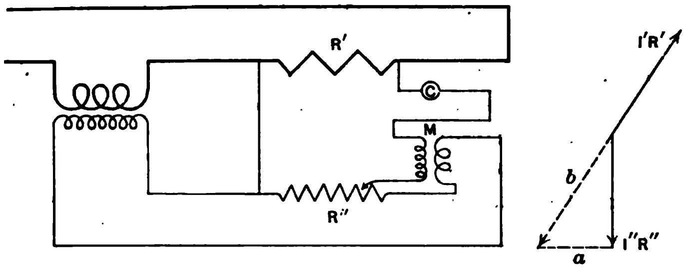


FIG. 3—Connections for ratio and phase angle test of current transformers

Sensitiveness. The minimum value of secondary resistance used is 0.025 ohm. The drop is then 0.125 volts at full load. With a portable galvanometer of the type above described the balance may theoretically be obtained within 5 microvolts in 125,000, or to one part in 25,000, by setting to 0.1 division. At 10 per cent load, a balance may be obtained within one part in 2500. The accuracy of measurement is therefore limited not by the sensitiveness of the galvanometer, but by the accuracy of calibration of the resistances, leakage and stray fields, etc. It is found that in measuring the same transformer at different times, the results will, barring mistakes, invariably agree within 0.1 per cent in ratio, and a few minutes in phase angle, at full load.

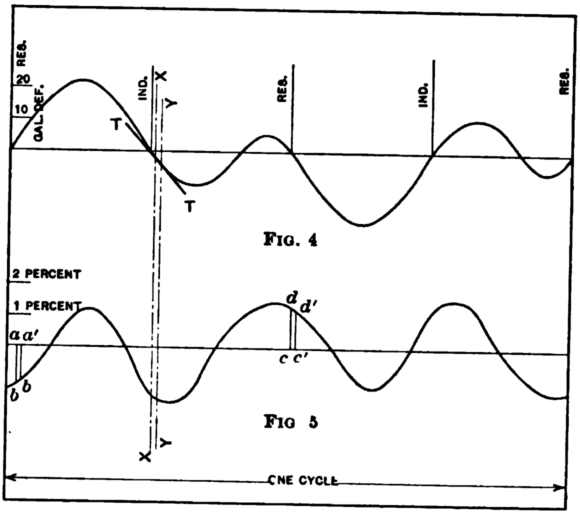
Leakage. Due to the necessity of connecting the secondary and primary circuits together, trouble is experienced from leakage and electrostatic effects. If the apparatus is at a moderate voltage above the ground, leakage may occur from the primary through the cross connection into the secondary and thence to earth. Referring to Fig. 3, it will be seen that very little of this current will pass through the galvanometer, the direct connection between R' and R'' furnishing a path of much lower resistance. The leakage current will, however, add to the current in R'' and may if large introduce an error. The amount of the leakage current is determined by removing one connection so that the total leakage must pass through the galvanometer.

Measurement of Distortion of Wave Form. An interesting property of the method is that, when used in connection with the rectifier, a determination of the relative wave form of the primary and secondary currents may be made without additional apparatus.

If the primary current has a sine wave form, and no distortion is introduced by the transformer, balancing in the " resistance " and " inductance " positions, as previously described, will insure that when the contacts are shifted to intermediate positions, the deflection will remain at zero, since the secondary wave will balance the primary wave at all points in the cycle. If, however, the primary and secondary wave forms are different, the two waves will not balance at all points in the cycle, and with intermediate settings of the contacts, a deflection will be obtained on the galvanometer. From the curve of these deflections, the difference in wave form between the primary and the secondary currents may be derived.

Fig. 4 shows a curve of deflections obtained on a transformer which on account of certain features of design showed an unusually large distortion. The test was made under severe conditions of load in order to magnify the effect. Fig. 5 shows the wave form, as derived from the above curve, of the distortion introduced into the secondary current. Evidently, the triple frequency component is predominant. The maximum ordinate is about 1.5 per cent of the secondary current. The method of derivation is as follows:

Since the rectifier closes the galvanometer circuit in one direction during a half cycle and in the reverse direction during the next half-cycle, the deflection represents the average current during a half cycle. In Fig. 5, with the contacts set to reverse at a and c, the galvanometer would be sensitive to a sine current whose maximum is at $X X$. On a distorted wave form, its deflection represents the area of the curve between *a b* and *c d*. When the contacts are shifted to reverse at *a′* and *c′*, the change in deflection represents twice the area *a b b′ a′*, and gives a measure of the ordinate of the curve at this point. This change in deflection is equal to the difference in the ordinates at *X X* and *Y Y*, in Fig. 4. The wave form of the distortion introduced in the secondary is therefore derived by taking the differences of successive ordinates of the observed curve of deflections, or more accurately, by taking the slopes of the observed curve at various points. Corresponding points on the observed and derived curves are 90 degrees apart.



FIGS. 4 and 5—Distortion curves of current transformer

The actual values of the ordinates of the distortion curve may be computed from the following formula:

$$x = \frac{d}{4\,d'}$$

where x = ordinate of distortion curve expressed as a percentage of the total secondary current.

d = slope of deflection curve expressed in divisions per cycle.

d' = deflection produced with the resistance setting of the contacts, by one per cent change in the secondary resistance.

Design of Apparatus. In designing apparatus for measuring current transformer ratios, an important point to be considered is the impedance introduced in the secondary circuit. Any appreciable impedance raises the voltage which must be supplied by the transformer, and thus has an influence on the ratio of transformation. In practice, transformers are often used with a single instrument of very low impedance and with very short leads, precluding the use of measuring apparatus of considerable impedance.

In the apparatus designed, the secondary resistance and primary of the mutual inductance combined amount to 0.1 ohm, and the leads introduce 0.05 ohm more, making the total 0.15 ohm. Where results are required with less resistance the small correction necessary may be easily determined by extrapolation from tests with higher values of resistance.

FIG. 6—Slide wire and mutual inductance

In order to save trouble in making connections, the secondary resistance and mutual inductance were constructed as a unit. The apparatus is shown in Fig. 6. A fixed resistance is used from which taps are brought out every 0.05 ohm to a dial switch. The fine adjustment is obtained by means of slide wire which shunts a part of the main resistance. The advantage of this arrangement is that sliding contacts are not introduced in the current circuit and that the amount of impedance in the secondary is always the same. The slide wire has a total resistance of 0.06 ohm, so that it overlaps the fixed steps by 0.005 ohm in either direction. This facilitates making settings near an even value. Where a number of taps are to be brought out, and where a slide wire is involved, it is difficult to make the resistance perfectly non-inductive. Loops are avoided in the leads by binding them close to the doubled manganin strip. To make the slide wire non-inductive, it is made double the required length and the unused half is brought back under the used half. The sliding contact bridges from the slide wire to a second wire lying close to it. These refinements, while they may not always be necessary, are advisable to insure accurate results in phase angle measurements.

Astatic Mutual Inductance. The mutual inductance requires careful design, the following qualities being desirable:

Long scale.

Freedom from stray field effects.

Low impedance of primary circuit.

Freedom from eddy current effects.

Permanence and reliability of calibration.

Easy adjustment.

The arrangement of coils adopted is shown in Fig. 7-a and 7-b. In Fig. 7-a, the coils are in the position of maximum mutual inductance. Rotating the hard rubber disk on which the secondary coils are mounted, through 180 degrees brings the coils to the position shown in Fig. 7-b. The lines of force from the primary coils then thread the secondary coils in a reverse direction, resulting in a negative value of mutual inductance. Between the two positions a zero is found. The positive maximum is larger than the negative maximum, which is not undesirable in the measurement of transformer ratios. Four coils being used, the inductance may be made astatic so that the effect of stray fields is small. A strong and non-uniform field may induce an error, but by keeping all instruments and heavy current conductors at a distance from the mutual inductance, or by taking direct and reversed readings, the effect may be eliminated. The primary may be constructed with a very small number of turns; the desired value of induced e.m.f. is obtained by constructing the secondary with a much larger number of turns. In order to obviate eddy currents in the primary, the coils are wound with small wire, a number of windings being placed in parallel.

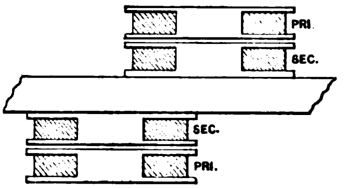


FIG. 7a—Position of maximum positive mutual inductance

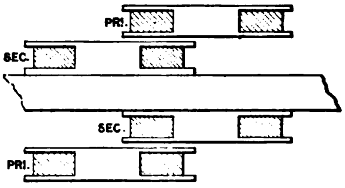
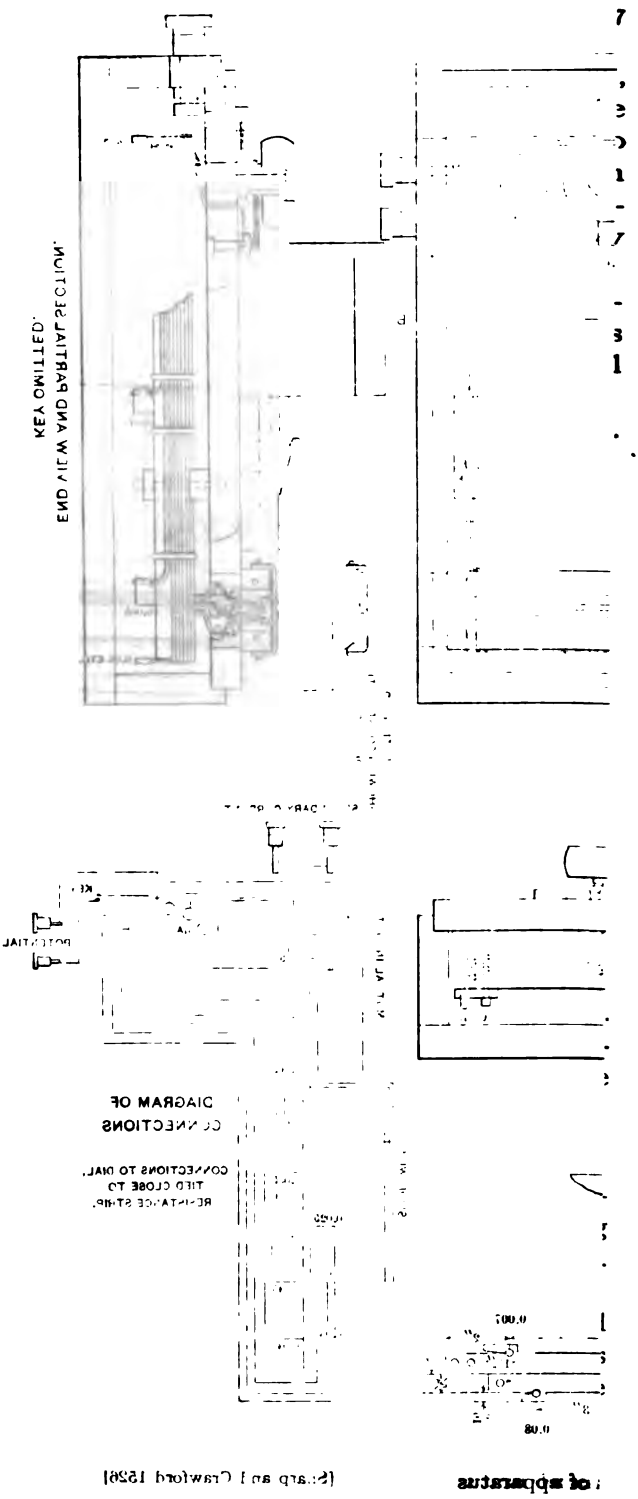


FIG. 7b—Position of maximum negative mutual inductance

The mechanical details are shown in Fig. 8. Due to the loca-



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tion of the coils, it is impossible to mount the disk on a pivot, and a special three-point peripheral grooved bearing is therefore employed. The construction is satisfactory with respect to rigidity and permanency, no measurable difference having been found in calibration since the apparatus was finished. Although the bearing works stiffly, there is no great difficulty in making an exact setting.

Test Table. A set of resistance and inductance coils is provided for introduction into the secondary to duplicate the effects of various combinations of instruments. The steps are so small as to furnish practically a continuous variation.

Fig. 9 is an illustration of the entire apparatus set up for use.

FIG. 9—Complete apparatus for testing current transformers

The complete connections of the testing table are shown in Fig. 10. This table is designed with a view to the maximum convenience in laboratory use, but all measuring apparatus can be removed from it and used in any desired location.

METHOD USING MUTUAL INDUCTANCES

The following additional method of measuring current transformer ratios has been considered, but has not been tried owing to the fact that the present apparatus suits the requirements. It offers, however, certain important advantages.

In the suggested method, mutual inductances are substituted for the resistances previously used. The electromotive forces induced in the secondaries are balanced against each other, one of the mutual inductances being variable. The connections are shown in Fig. 11. The phase difference is compensated by a resistance drop introduced by a slide wire, *S*, carrying the secondary current. The ratio and phase angle are given by the following formulas.

$$\text{Ratio} = \frac{M''}{M'} \sqrt{1+\tan^2 \gamma}$$

$$\tan \gamma = \frac{R_s}{2\ \pi\ f\ M''}$$

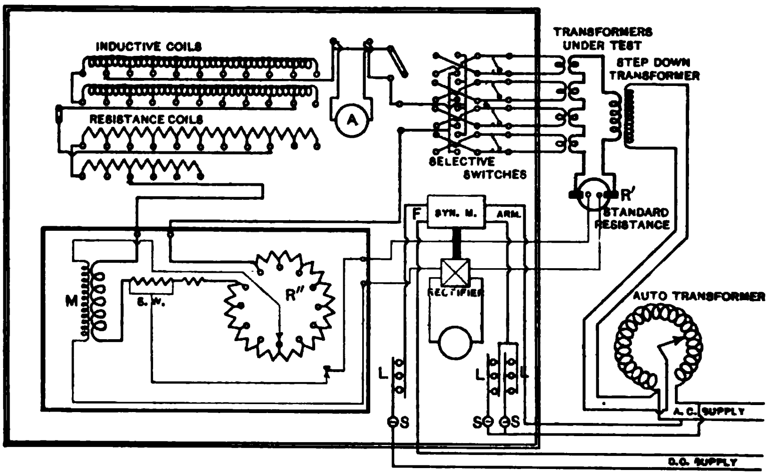


FIG. 10—Connections of current transformer testing table

The advantages of this method over the method using resistances are:

(*a*) The energy expended in the apparatus may be made exceedingly small.

(*b*) By properly proportioning the numbers of primary and secondary turns on the mutual inductances, it is possible to obtain electromotive forces in the galvanometer circuit which are much greater than the drops in the primary coils hence greater sensitiveness can be obtained without the introduction of an undue impedance in the secondary of the transformer under test.

(*c*) It is not necessary to connect the primary and the secondary circuits together, and leakage effects are therefore reduced.

The disadvantages of the proposed method are:

(*a*) Mutual inductances are not so easily calibrated as resistances.

(*b*) It is difficult to construct accurate mutual inductances for large currents, although probably not more so than in the case of resistances.

(*c*) Stray field effects will influence the ratio directly, requiring astatic construction of the mutual inductances and great pains with the location of the leads carrying heavy currents.

MEASUREMENT OF MAGNETIZING CURRENTS

As a means of determining the ratio and phase angle of current transformers, where apparatus for their direct measurement is not available, or as a check on direct measurements, the value of computations from magnetizing current determinations is well recognized. Assuming a certain value of secondary current, the electromotive force which must be furnished by the transformer, and the phase relation of this electromotive force to the current, can be computed from the resistance and reactance of the secondary circuit. At the given voltage, the value of the magnetizing current and its phase relation to the voltage is determined. The primary current then includes, first, a current sufficient to make the primary ampere turns equal to the secondary ampere turns, and second, the magnetizing current which is combined with the load component in a certain phase relation which is the resultant of the phase angle between the load current and the voltage, and the phase angle between the voltage and the magnetizing current.

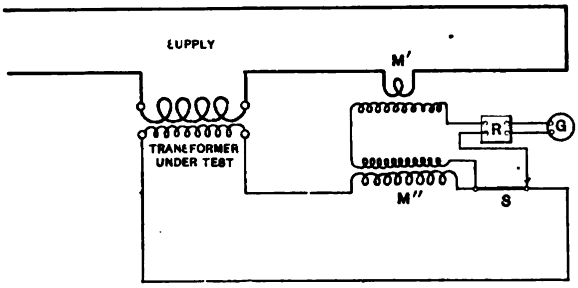


FIG 11—Measurement of current transformer ratio by means of mutual inductances

The magnetizing current is measured on open circuit the voltage being adjusted to the value corresponding to a given load of the transformer. It is best measured by supplying the current to the secondary or low current winding and computing the results in terms of the primary.

For the determination of the magnetizing current, a sensitive electrodynamometer may be used. To obtain both the magnitude and phase relation, the most obvious method is to use the electrodynamometer as an ammeter to measure the total current, and as a wattmeter to measure the power component. A preferable method is to determine the power and wattless components by separately exciting the electro-dynamometer alternately from the phases of the two-phase circuit (Fig. 12). The electrodynamometer is calibrated by substituting for the transformer a known non-inductive resistance. For very low voltages, a step-down transformer of known ratio may be introduced. The voltage is then measured on the high side and the current on the low side.

These measurements may also be made by means of the rectifier by inserting the transformer in an inductance bridge and ascertaining the equivalent alternating-current resistance and the reactance under the working conditions of voltage and frequency. The distortion of the wave form will have the same effect as in a ratio measurement and may be determined in the same way.

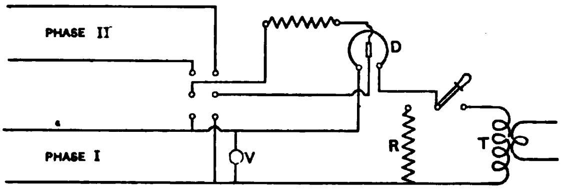


FIG. 12—Measurement of core loss by means of electrodynamometer

VOLTAGE TRANSFORMERS

A number of methods for measuring the ratios and phase angles of voltage transformers have been used. The simplest method is to use a rectifier; as shown in Fig. 13, R and r are high resistances connected in series to the primary circuit. A balance being obtained by varying r, the ratio of primary to secondary voltage is

$$\frac{R+r}{r}$$

As in the case of current transformer measurements, it is necessary either to pay strict attention to the setting of the contacts or to use some means of bringing the primary and secondary voltages in phase. The latter procedure is preferable. Various methods of balancing the phase displacement by introducing capacities or self or mutual inductances, may be used.

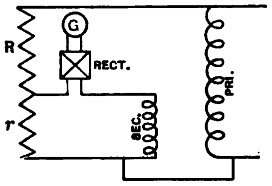


FIG. 13—Measurement of voltage transformer ratio by means of rectifier

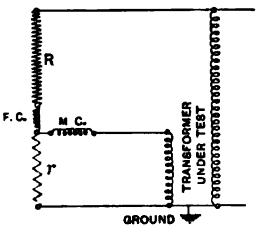
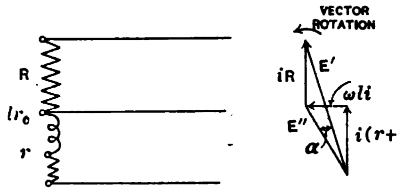
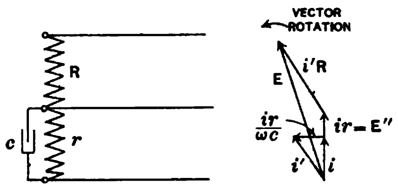


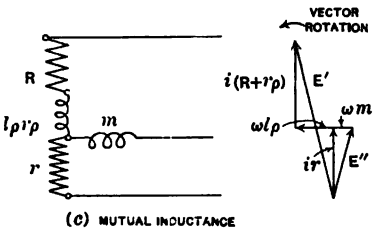
FIG. 15—Measurement of voltage transformer ratio using electro-dynamometer



(*a*) SELF INDUCTANCE



(*b*) CAPACITY



(*c*) MUTUAL INDUCTANCE

FIG. 14—Means of balancing phase displacement

A few of these are illustrated in Fig. 14. The method using a mutual inductance is probably the most satisfactory.

Methods employing a sensitive electrodynamometer similar to those used in other laboratories* have been tried. It has

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* L. T. Robinson, PROCEEDINGS A. I. E. E., July 1909.
Agnew & Fitch, Bulletin Bur. of Stds., Vol. 6 No. 2.

been found possible to simplify these methods by the employment of one electrodynamometer only in phase angle tests whereas previously two electrodynamometers have been employed. The connections are shown in Figs. 15 and 16. In Fig. 15, the fine wire fixed coil of the electrodynamometer is excited by inserting it in series with the bridge resistances. The excitation being in phase with the voltage, the phase angle of the transformer (if small) does not affect the measurement.

In Fig. 16, by using a two-phase circuit, the electrodynamometer is first excited in phase with the voltage of the transformer under test and the adjustment of resistances to obtain the ratio is made. The excitation is then shifted to the other phase and a deflection is obtained which is a measurement of the phase difference between the primary and secondary voltages. For the evaluation of the phase angle, the electrodynamometer is calibrated with its excitation in phase with the voltage, by altering r a small amount, r', and noting the change in deflection. Then

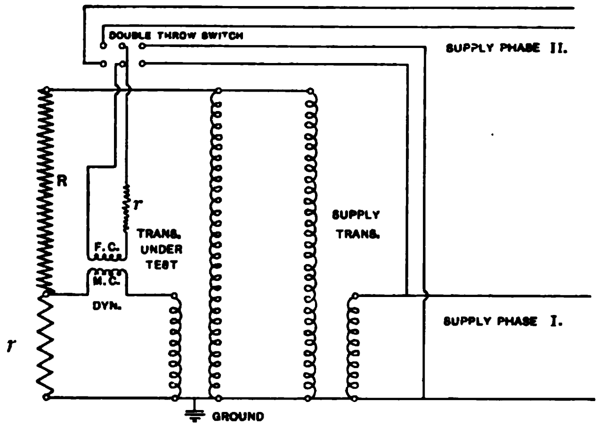

FIG. 16—Measurement of voltage transformer ratio and phase angle using electrodynamometer

$$\tan\beta = \frac{d''}{d'}\ \frac{r'}{r}\ \frac{R}{R+r}$$

where d'' and d' are the deflections under test and calibration conditions respectively.

Means of Loading Transformers at Various Power Factors. In the testing of voltage transformers, it is necessary to obtain various loads at various power factors representing the equivalent of the instruments to which the transformers are to be connected in use. The method given here was devised to permit any load at any desired power factor to be obtained without the necessity of constructing a large number of inductance coils of various values. The connections are shown in Fig. 17. Two transformers are required which have approximately the same ratio. Transformer No. 2 is connected to one phase of a two-phase circuit and is used as a step-down transformer to supply energy to transformer No. 1, which is under test. A load on transformer No 1. at unity power factor is obtained by means of a lamp bank connected directly across its terminals. The load at zero power factor is obtained by introducing the second phase of the two-phase circuit between the points P, and P^1, in series with a lamp bank. If the transformers are connected with the proper polarity, these points are at the same potential so that the current flowing is determined purely by the voltage of phase two. The ammeters A_1 and A_2 respectively measure the power and wattless components of the load current, enabling their independent adjustment. The wattmeter M furnishes a check on the power factor. This method of loading is suggested as a possibility for the loading of power transformers for regulation tests, etc., at various power factors. The pumping back method could be used and the load current caused to circulate by two low voltage transformers connected to the two phases.

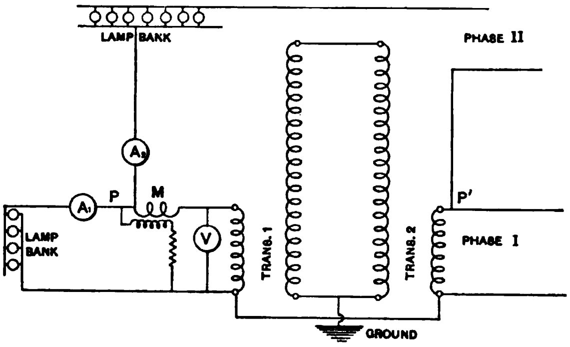

FIG. 17—Method of loading transformer at various power factors

Voltage Ratio of Current Transformers. It is often necessary when analyzing the results of current transformer tests, to know the ratio between the primary and secondary turns and it is important to be able to determine this value by test, since due to errors in manufacture, the number of turns may differ from that intended.

The ratio of turns is determined by measuring the voltage ratio in the same manner as for voltage transformers. Four or five volts is impressed on the secondary and a fraction of this is balanced against the e.m.f. induced in the primary.

To obtain the true ratio of turns, it is necessary to correct for the drop in the low-current winding due to the magnetizing current. If no magnetizing current determination has been made, an approximate value may be obtained by the following procedure. With the connections shown in Fig. 18, the milliammeter indicates the resultant of the magnetizing current and of the current taken by the voltmeter. The phase relation of this current to the voltage is not known. Referring to Fig. 19, it may be considered to be represented by a vector from the point *O*, whose end is somewhere in the arc *A B C*, which is laid out to a suitable scale. *O X* represents the voltage.

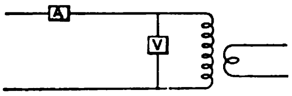

FIG. 18

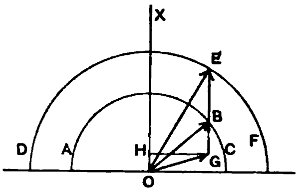

FIG. 19

A known non-inductive resistance is connected in parallel with the voltmeter and the increased current indicated by the ammeter is observed. The arc *D E F* is laid off with a radius equal to this current. The vector difference between this current and the initial current will be the current taken by the non-inductive resistance which is in phase with *O X*. Finding a point where the vertical distance between the two curves is equal to the computed value of the current in the added resistance, the points *B* and *E* are determined. *O B* is then the initial current. By subtracting from this the current taken by the voltmeter (equal to *B G*) the magnetizing current *O G* is determined. *O H* is then the component in phase with the voltage and this, together with the resistance of the winding, enables computing the correction to the observed ratio.

THE ALTERNATING-CURRENT POTENTIOMETER.

The amount of energy required by alternating-current indicating instruments prohibits their use directly in measuring very low alternating voltages. A separate circuit may, however, be obtained from the same generator and the unknown voltage measured by balancing it against a known fraction of a higher voltage which can be measured accurately by means of indicating instruments. The connections are shown in Fig. 20, in which the " standard voltage " is obtained on the line *C D*, and the unknown voltage on the line *A B*. A balance is obtained by adjusting r_1 and the phase relation. The unknown voltage is then

$$\frac{r_1}{r_1 + r_2} \quad \text{of the voltage on } C\ D.$$

The sensitiveness of the rectifier is sufficient to enable a voltage of a few millivolts to be measured quite accurately. The same method may be used to measure alternating currents of any desired magnitude by the use of a non-inductive shunt, and has the advantage that the necessary drop in the shunt is very small.

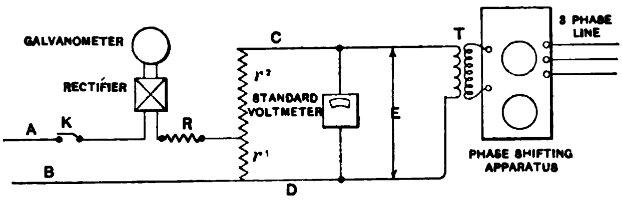

FIG. 20—Alternating current potentiometer

Methods of Adjusting Phase Relations. For obtaining a varying phase relation such as is needed in the alternating-current potentiometer arrangement, and in many other classes of tests notably test of wattmeters and watt-hour meters on low power-factors, the following methods have been found convenient. Using a three-phase circuit, (Fig. 21) a slide-wire rheostat is connected across two of the phases. The voltage circuit is obtained from the third phase and from the sliding contact on the rheostat. This arrangement furnishes a gradual shift of 60 deg. and phase relations beyond this range may be obtained by connecting the rheostat to the different phases. The method is not suited to cases where the voltage circuit draws a large tally on the top of the containing case. A series of bars, *a*, *b*, *c*, etc. are silver soldered to the terminal blocks, alternate bars being attached to the positive and negative terminals respectively. These bars extend directly downward into the oil bath. Each sheet of resistance metal is folded double and its ends attached to two adjacent bars of opposite polarity. By this arrangement, each sheet is made non-inductive, and any desired number of sheets may be connected in parallel.

In order to bring out taps at fractional values, tongues are cut in one of the sheets to which the potential binding posts are attached. The arrangement of these potential leads to avoid loops susceptible to stray fields, is equally important with the non-inductive construction of the shunt itself. A double concentric binding post is used for the potential terminals.

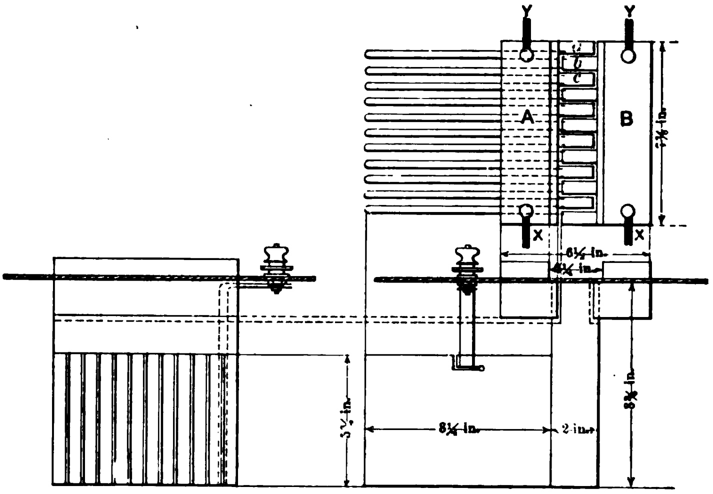

Fig. 23—5,000 ampere non-inductive shunt

The resistances are immersed in oil and cooled by a water jacket in the usual manner.

After some difficulty in determining the proper treatment for manganin sheets, pickling for 20 seconds in 50 per cent nitric acid has been found to remove the oxide and scale and give satisfactory results as regards temperature coefficient. The sheets are removed from the pickling solution, rinsed in warm water, dried in an air blast, and immediately shellacked. Before installing the insulating material and mechanical parts, the resistances are baked for 48 hours at 150 deg. cent.

Figs. 24 and 25 are photographs of the shunts assembled and taken apart, respectively.

Terminal blocks of the above described form introduce changes in resistance depending on the position of the current leads. The variations could be largely obviated by bringing out the potential taps from the middle sheet, but this is prevented by mechanical difficulties.

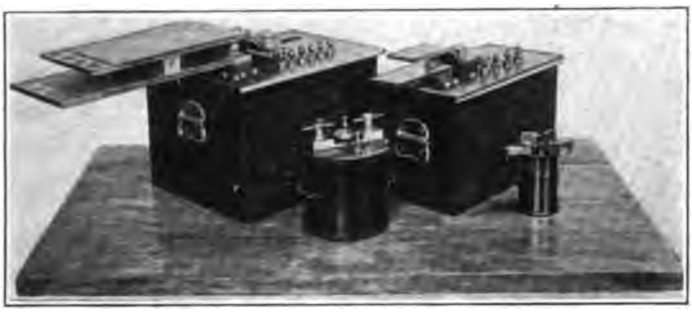

FIG. 24

The phase angle between the current and the potential drop also varies with the position of the leads; in the 5000 ampere resistance which has 11 resistance sheets in parallel, the phase angle at 60 cycles varied from +1 deg. to —1 deg., depending on whether the connections were placed in position *XX* or *YY*, Fig. 23. In order to remedy the variations in resistance and phase angles, a pair of extended connection plates, which may be clearly seen in Fig. 24 and 25, were installed. Using these plates

FIG. 25

no variation in phase angle was found as long as the heavy current leads did not form a large loop near the resistance.

Comparison of Inductances of Heavy Current Resistances. The measurement of the residual inductance of an approximately non-inductive resistance is dependent upon comparison with resistances which are assumed to be non-inductive. In the case of very low resistances, this comparison is difficult because the only " non-inductive " resistances whose residual inductances can safely be neglected, are those of a comparatively high value (0.1 ohm or more). However, if a sufficiently accurate method is available, a series of comparisons starting from a resistance of high value and working toward the low resistances, will enable the desired results to be obtained. The method of comparing inductances by connecting two resistances in series, exciting the fixed coil of an electrodynamometer in quadrature with the current, and transferring the moving coil from one resistance to the other, was found unsatisfactory due to the fact that the phase relation between the excitation and the current in the resistances would not remain sufficiently constant for an accurate measurement. In this connection, it may be remarked that in order to obtain with sufficient certainty the phase angle of the 0.00002 tap of the 0.0002 ohm, 5000 ampere resistance, it is necessary to have a method capable of comparing phase angles to within 0.1 to 1 minute.

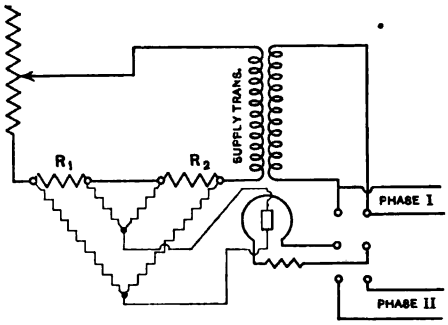

FIG. 26—Connections for measuring phase angles of shunts

The second method tried was the use of the Kelvin double bridge with two equal variable self inductances inserted in series with the bridge arms. This method was found to be so susceptible to stray field effects that without the design of special apparatus, it could not be applied in practice.

The method which was finally adopted was that shown in Fig. 26. A Kelvin double bridge is used, but no attempt is made to balance the inductive effect. A Rowland electrodynamometer with separate excitation is used as a galvanometer. The resistances of the bridge are balanced with the excitation in phase with the current in the resistances under comparison. The excitation is then placed in quadrature with the current in the resistances and the deflection is noted. This deflection is a measure of the difference in phase angle between the two resistances. The rectifier and galvanometer might be used in the same manner.

The electrodynamometer is best calibrated by observing its sensitiveness to change in resistance when the excitation is in phase with the current. The inductance of the resistance under test is then obtained from the following formula.

$$\frac{X_1}{R_1} - \frac{X_2}{R_2} = \frac{d_1}{d_2}\,\frac{r}{R_0}$$

where

X_1 = inductive reactance of R_1

X_2 = inductive reactance of R_2

d_1 = deflection obtained in test

d_2 = deflection obtained in calibration

r = change in variable bridge arms corresponding to deflection d_2

R_0 = resistance of one of the variable arms of the bridge.

The sensitiveness of the Rowland electrodynamometer is such that using a Kelvin double bridge having 100 ohms in each fixed arm and 100 to 1000 ohms in the variable arms, and pushing the excitation to the limit, resistances having a drop of 0.1 volt may be compared to within 20 parts of reactance in 100,000 of resistance; or in other words, within about 0.6 minute. With a larger drop, a proportionately smaller phase angle may be measured.

This method has the advantage that it is independent of steadiness of the test circuit and is free from stray field effects. It is, however, essential to take precautions against leakage effects.

It is believed that the above described methods represent at least a small advance in the art of practical alternating-current measurements and that the results obtained by them will be of value to the engineer.

DISCUSSION ON "SOME RECENT DEVELOPMENTS IN EXACT ALTERNATING CURRENT MEASUREMENTS". JEFFERSON, N. H., JULY 1, 1910.

V. Karapetoff: There are four classes of measuring instruments for measuring alternating current; the soft-iron type, of which the well-known Thomson inclined-coil ammeters represent possibly the best practice. Then the hot-wire instruments, the dynamometer type instruments, and the induction instruments, based on the principle of revolving field. All these classes of instruments are in common use, all possess certain advantages and disadvantages, but hardly any of them are adapted for precise measurements. Considerable effort has been devoted for a long time to adapt the d'Arsonval type of galvanometer, that is, an instrument consisting of a coil moving in the field of a permanent magnet, for alternating-current measurements. Dr. Sharp's instrument represents one of the possible methods of using direct-current galvanometer for alternating current measurements, namely, by rectifying the alternating current. However, there are other methods for obtaining the same end, and I wish to mention here those that I know, with a view of getting Dr. Sharp's criticisms in regard to these methods. Since he had to devise a new method, we are justified in assuming that the methods known heretofore did not possess sufficient accuracy, or for some reason were not convenient for his purpose.

The methods used so far for measuring alternating currents with direct-current precision instruments are based chiefly upon the thermal effect of alternating currents, either through a direct heating of wires, or by heating a thermo-couple. We have had before our Institute a paper by our friend Dr. Northrup on his "Comparator," an instrument devised for measuring alternating currents with great precision (TRANSACTIONS, Vol. 24, page 741). The instrument consists of two parallel wires connected by a mirror. Alternating current is sent through one wire; the heat generated expands the wire and deflects the mirror. Then direct current is sent through the other wire, so that the other wire is also expanded until the mirror returns to its first position. The direct current is measured accurately with a precision instrument, for instance a potentiometer; The effective value of the alternating current is equal to that of the direct current.

Another instrument is Professor Duddell's "Thermo-galvanometer." There you have an ordinary suspension type coil, the ends of which are connected to a thermo-couple. The alternating current to be measured is sent through a stationary heater; the heater heats the thermo-couple, and the current generated turns the moving coil; so you can calibrate the instrument with direct current, and use it to measure alternating currents. One might naturally think that this type of galvanometer is too delicate for ordinary measurements; but I lately saw it advertised in the form of a portable instrument for industrial work. Generally speaking, the disadvantage of this type of measuring instrument is that only a small and rather indefinite part of the heat generated in the alternating-current heater is transmitted to the thermo-couple.

This drawback has been recently eliminated in an instrument developed by Dr. Guggenheimer, in Germany. He ingeniously combines the alternating current and the direct current in the same circuit. The internal connections are similar to those of the Wheatstone bridge. Two opposite points of the bridge are connected to a non-inductive ammeter shunt, in the alternating current circuit. Two other points are connected to a direct-current milli-voltmeter. Four thermo-couples are connected in the four branches of the bridge in such a way that they are in opposition (by pairs) with respect to the alternating current circuit, and act in parallel with regard to the direct-current circuit. In this wise, alternating currents and direct currents both flow in the same circuit, and the full extent of the heat developed by alternating currents in thermo-couples contributes to the deflection of the direct-current instrument. The apparatus is made in a form similar to that of ordinary portable instruments. The Wheatstone bridge is in the base of the instrument, and the instrument, when used as an ammeter, can be provided with any number of external shunts, from one-half ampere to several thousand. The sensitiveness of the instrument is limited only by the sensitiveness of the direct-current milli-voltmeter used in it.

I should like to know what objections Dr. Sharp has to this or to any other devices used for precise alternating current measurement, and what advantage his synchronous rectifier has as compared to these?

L. T. Robinson: The necessity and the advantages of zero methods are brought out in the paper quite clearly. We all appreciate that these zero methods are always to be preferred if they do not introduce other complications that more than offset their advantages. The use of a direct current instrument as the detector is spoken of as distinguished from the use of the electro-dynamometer for the same purpose. In my experience, we have had no difficulty with the electro-dynamometer with separate excitation, and did get, as described, good results, and do now; therefore, we see no objections to it. There may be advantages in introducing the further complications, and these advantages may become more apparent as time goes on, but they are not yet fully apparent to me.

The difficulties with dynamometer instruments, due to suspensions springs, scales, etc., are also referred to, but for moderate currents, at least, we still find that this method is convenient, satisfactory and accurate, and while I still hope, as I expressed the hope a year ago, that some of the other methods would ultimately win for the work in connection with the current transformer. We still find it more satisfactory to stick to the first method which was described a year ago and which we are still using.

In connection with electro dynamometers, there are certain difficulties which come up in the measurement of very large current; I think that if these difficulties which seem to be inherent in large alternating-current precision dynamometers can be removed and they are in a fair way to be removed, the ratio determination by dynamometers will still remain a formidable competitor of more complicated methods. As far as accuracy goes, there is, I think, nothing to be desired. If we can determine the ratio and phase angle of instrument transformers with a degree of precision which is well beyond the limits of accuracy which can be had with the instruments that they are to be used with, there certainly is no use in going further. It is an unnecessary refinement, and I do not think that any one would want to use these methods of measurement for truly precision work. When we come to such work we would need to use the dynamometer instruments or other instruments which Professor Karapetoff has referred to, directly on the work. Thus, there is hardly any use in carrying the refinement in instrument transformer testing beyond a certain point. I think Dr. Sharp's improvements in the contact making key are, of course, very important and satisfactory, and such a rectifier may ultimately be the right thing to use. As I had it at first, it would do the work, but as he has improved it, it certainly does a great deal better, and to show him that I mean what I say, I have copied his device as nearly as I can and incorporated it with mine, and have used it in that form for some time. I cannot testify any more strongly to the value of the device.

I think from the statements in the paper, it is apparent that some of the things I have spoken of as difficulties with these indirect methods have come up. It is only fair to say that we have been working for some time with the method which Dr. Sharp has described - have been doing this for more than a year—and I have come in contact with some of these same difficulties myself, and also some others that are not mentioned, but I think that ultimately the method will be worked out in satisfactory shape. The author of the paper refers to obtaining of average value of alternating currents by means of these reversing commutators. I think this will ultimately be something that will be of considerable value, and in that connection I would say that I have experimented somewhat with an instrument in which the reversing commutator and other means are made use of to determine directly the average current, the root mean square current is also used in the same instrument, so that the instrument determines directly the ratio between the two, and in that way the form factor, which is an important thing in connection with transformer losses and also for several other purposes. In shifting the phase in the determination of the ratio of transformers, I think Dr. Sharp brings out quite clearly the points for which I have previously contended, that is, that it was hardly necessary in commercially good transformers to take this into account; when the phase angle is less than two degrees the correction term in the ratio formula may be neglected. Of course, it is true that we have had transformers where this phase angle is more than two degrees, but the demand for good transformers which is now well established, and which we cannot stop, and which should not be stopped, will certainly result in the production of transformers in which phase angles, like two degrees, will be unknown, and if such are offered for sale, I think they will be refused promptly.

The method of determining the distortion of wave form to which Dr. Sharp refers is most ingenious and satisfactory, and I think this will undoubtedly lead to some practical way of determining whether the wave form of a certain alternator comes within the requirements of the Institute standards or not —that is, to a short and direct way which will not involve the necessity of taking the wave with oscillograph or in some other way, to see if it comes within the requirements or not. It also seems to me that some way will be devised to handle the problem referred to, of obtaining Fig. 5 from Fig. 4, of the paper by direct measurement.

I would also emphasize the importance of being able to obtain tests of current transformers, by using a low value of impedance, in the secondary circuit. The method referred to of using mutual inductances is compared with similar methods using resistances, and then several advantages are given, but it seems to me that other methods have these same advantages, and others as well. I have not yet given up the idea that some method using thermo-couples will be the ultimate method, as no questions of wave form or phase displacement in determining the ratio can possibly modify the results. Thermal instruments have some peculiarities, and there are some difficulties in their employment, but at the same time, primarily, it is the correct principle, and I think that some means will be found ultimately so that they will be very generally employed.

In regard to the statement, " The magnetizing current is measured on open circuit the voltage being adjusted to the value corresponding to a given load of the transformer.. It is best measured by supplying the current to the secondary or low current winding and computing the results in terms of the primary." This is undoubtedly true, but at the same time I am not prepared to accept this at present as the universal statement. It appears to me that this should be the correct way to do it, but at the same time, as I showed last year in my paper, in some transformers we have been able to do it and to get very exact results indeed, but I have since found that in certain other types we do not get this kind of results at all, and there is something wrong with the way we do it, or else we do not understand the situation. I am not prepared to say what it is now—I desired simply to say that this statement, while it appears that it should be true, I do not think should be accepted, without more experimental proof, as absolutely covering all cases.

In regard to the statement, " It has been found possible to simplify these methods by the employment of one electro-dynamometer only, in phase angle test whereas previously two electro-dynamometers have been employed." In justice to what has been written on this subject, I revert to page 731, of the TRANSACTIONS of the Institute for 1906, where you will see the method using one dynamometer described in a discussion which I offered at that time on Mr. Curtiss's paper on Current Transformers. In fact, we have now been around the circle—I think I started with one, but finished with two, and Dr. Sharp started with two and finished with one. It is unimportant and it makes very little difference. The reason I prefer two instruments is that you can bring one instrument to zero, and have some one hold it there, and you can correct most variations in the circuit while the measurement on the second dynamometer is being made and thus determine the phase angle from one measurement. The way it is done in the paper is good, and in some cases perhaps is to be preferred. It seems to me, ordinarily viewed, it would be a little more direct to take one reading proportional to the sine of the phase angle then to take one proportional to the sine and another to the cosine, and from these readings determine the tangent.

In regard to loading transformers at various power factors, I am well satisfied with the arrangements which we have, but this, again, is a matter largely of what one can do handiest. We had plenty of reactances, and have simply taken meter parts and combined them with switches, etc.—there is little to say about the speed of using, and the convenience is about the same in either case.

The point referred to about determining the ratio of turns in current transformers, is good and could be given quite useful application. Of course, in my own work it is not often necessary to do this, as we have access to construction records, and it is only necessary to determine the ratio of turns in examining transformers of other makes.

The phase shifter illustrated in the paper I consider to be a very ingenious and satisfactory device, and I take this opportunity of complimenting the authors on the production of it.

With regard to the large current shunts, I do not approve of the construction as shown. It seems to me that they are of necessity somewhat inductive and I think a moment's consideration of the loops which are formed within these shunts, and the statement which Dr. Sharp made, that the phase angle is twenty minutes—would support this view. It is only necessary to squeeze the two sides of the circuit closer together to remove the phase angle altogether, and with it the necessity of determining what the phase angle is, and the correction for it in the measurement. This would simplify the whole matter very greatly. I have recently devised a line of shunts with these features, but which I will not describe now.

The remainder of the paper is of interest to me, but I do not think you would be particularly interested in any remarks I could offer about it. In regard to the whole paper, I want to testify to my appreciation of what has been done, and to say that it pleases me very much to note that a subject which is of real importance, although it does not directly come into the field of all of us, still the results obtained are important to all, is being considered. I feel quite sure that if this development of methods and proof of results can be continued and we can be made acquainted with the work which is done, that we will all be benefited by it.

W. H. Pratt: Allusion has been made to recent work done in directly measuring large alternating currents and large quantities of alternating current power by direct methods as opposed to the zero methods. In the first place, I have always felt doubt about the zero methods of measurement, unless we have a very close approximation to the sine wave. The distortion in the current transformer may be taken care of all right, but it is necessary to have a close approximation to the sine wave to start with.

As to these direct measurements, we have recently found it necessary to make measurements of alternating-current power and to make them with a degree of accuracy that precludes the use of current transformers.

The great source of error in alternating current instruments of large current carrying capacity has been the eddy currents induced in the massive copper conductors. Previous attempts to minimize this trouble have consisted in using stranded cable, often flattened. This procedure helps a great deal but comes far from curing the trouble.

In the twisted cable, the individual conductors are not all similarly located, and, consequently, as the cable heats, the distribution of current flow is altered.

I believe that long ago the possibility of water-cooling instruments was mentioned, but I have never seen it applied until very recently, when we constructed a water cooled watt-dynamometer of the reflected type.

In the water-cooled instrument, the trouble from uncertain current distribution is entirely taken care of. The amount of current that can be carried in the water-cooled conductor is surprisingly great. The conductor that we employed in the dynamometer, I referred to, was a copper tube 5/32 in. internal diameter and only 7/32 in. external diameter, *i.e.*, the walls of the tube are only 1/32 in. thick. City water pressure is applied at one end so as to get a heavy flow of water through the tube. Under these conditions, this very small cross section of copper will carry with about 6 deg. cent. rise a current of 1000 amperes. The flow of current could be easily doubled without causing excessive heating. At 1000 amperes, the current density in the copper is approximately 55,000 amperes per square inch.

It can be readily seen that by using a tube of the dimensions which I have just mentioned, that it is possible to make an instrument of very large current carrying capacity, having characteristics almost identical with instruments of 50 amperes capacity or thereabouts.

Of course in many places water-cooling cannot be applied, and to avoid the troubles that accompany the use of stranded cable, as ordinarily employed, we have used flat hand-braided conductors. Every individual strand is located similarly to every other strand and trouble from unequal conductivity, due to heating as well as eddy currents, are simultaneously avoided. It has been found possible to employ coils made in this way in portable instruments, obtaining thereby very high accuracy.

For some alternating current measurements, we have employed current shunts. Here again we have used direct measurements and have not stinted in the power consumed, often using, even for large currents, drops as high as 50 volts. By so doing, it is possible to proportion the apparatus so there is no question as to the relative distribution of the alternating current used in measuring and the direct current used in standardizing.

C. P. Steinmetz: There is one modification of the method of measuring alternating current which I do not see described,

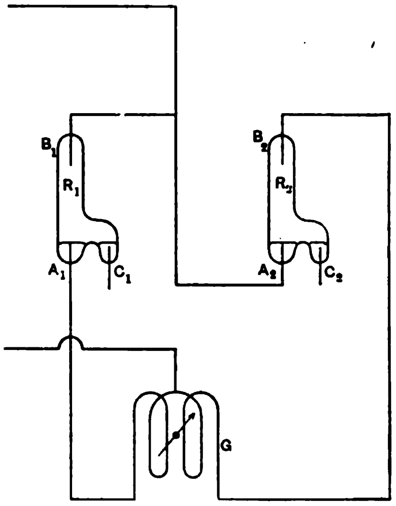

Fig. 1

and which appears to me to lend itself specifically to the measurement of the mean value of extremely small alternating currents of very high frequency—frequencies beyond those where mechanical rectification is possible. It is by the use of an arc rectifier, as diagrammatically sketched in Fig. 1. Let R_1 and R_2 be two rectifiers, with negative terminals A_1 and A_2, positive terminals B_1 and B_2, and auxiliary terminals C_1 and C_2, and assume, as not shown here, that between A_1, C_1, and between A_2, C_2, an auxiliary direct current arc is maintained to supply the conducting vapor stream for the main arc. The incoming alternating current connects to terminals B_1 and A_2, while the rectifier terminals A_1 and B_2 connect to the two terminals of the galvanometer G, and the center of the galvanometer coil connects to the outgoing current, as shown in Fig. 1. In this case the galvanometer measures as direct current the mean value of the alternating current. The arrangement, which can be modified in various ways, is, as you see, that these two rectifiers completely rectify the successive half waves of the alternating current, irrespective of how small they are, and how high their frequency is.

Clayton H. Sharp: Mr. Karapetoff wanted to know what the criticism was of the old method and of the apparatus which is at present available. I would say to him there is not any criticism made. The purpose of the paper was not to criticise old methods, but to present something that is a modification of these older methods, or has some elements of novelty in it. I would, however, call his attention to the fact that this paper deals chiefly with zero methods, and that the instruments of which he spoke are deflection instruments, also that, being thermal instruments, they would not be well adapted to zero measurement work.

Mr. Robinson spoke of the complication of the method here presented as compared with electro-dynamometers. When electro-dynamometers are available and the work is done in the laboratory, rather than under service conditions, there is no complication in their use except that involved in any non-zero method. I maintain however that there is no complication in the method which has here been presented, and if one has not a row of electro-dynamometers, it hardly admits of question that the rectifier and direct-current galvanometer and shunts represent even less complication than is involved in the construction of the whole line of electro-dynamometers, especially as they are subject, particularly in the higher values, to difficulties of their own. Moreover shunts can be constructed for much larger currents than electro-dynamometers can be constructed for.

I want to take issue with Mr. Robinson in another matter, and that is his statement that it is unnecessary to go into the measurement of these transformers to any higher degree of refinement than the instrument which is to be used in the secondary side is capable of. I do not think he is right in that statement. I think we want to do something better than direct reading instruments will do. If our transformer is capable of better work through its constants being determined to a higher degree of accuracy, we ought to do it, and then to bring up the instrument on the secondary side to a higher standard of accuracy to correspond thereto.

As to Mr. Robinson's contention that the phase angle is a negligible quantity in determining the ratio, undoubtedly the ratio can be determined, even though the phase angle is neglected. However, the phase angle needs to be known for accurate reading with watt hour meters and wattmeters, and the method presented here includes determination of that angle without introducing any complication into the work.

L. T. Robinson: I fear Dr. Sharp misunderstood me. I appreciate the importance of the measurement of the phase angle, and brought that out in a previous paper. It was the importance of the lag—the necessity of taking into account the phase—in determining the ratio, and I would also say I fully appreciate, and described the advantages of most of the zero methods in the paper which I presented a year ago. That is not the point—it is simply the particular method of carrying out these zero methods that seems to me a little more complicated than is necessary.

Clayton H. Sharp: Regarding Mr. Robinson's reference to the paper of a year ago, I want to say that this work has been in active progress in our laboratories for well on to three years, and the method described is not a new thing with us. I described it briefly at our last convention.

William W. Crawford: I have very few points to add to what Dr. Sharp has said. In answer to Professor Karapetoff's inquiry as to the particular advantages of the rectifier, as used with the direct-current galvanometer, I would like to say that by rectifying the alternating current, the entire energy available in the galvanometer circuit can be applied to the galvanometer. A device which converts the available energy into heat, and then, by means of a thermal or some similar effect, regenerates a very small proportion of this energy into current, cannot have as great sensitiveness.

In the measurement, by deflections, of moderately large quantities, the use of a direct current instrument with a synchronous reversing key is not as accurate as the ordinary alternating current instruments.

Mr. Robinson has referred to the difficulties encountered in this method. In the article we have described in full the difficulties we have encountered in this method, such as leakage between the motor circuit and the galvanometer circuit, and imperfections in the mechanical actions of the rectifier. It has been my experience, however, that with equal sensitiveness in the electro-dynamometer and the direct-current galvanometer, the leakage effects would be nearly equal. Of course, that may be contrary to the experience of others.

Mr. Robinson has suggested an alteration in the design of the heavy capacity shunt—that designed for 5,000 amperes.

The calculated phase displacement at 60 cycles of this shunt, based on the distance between the outgoing and returning leaves of the plate, amounts to about eight minutes, whereas the measured value is twenty-two minutes. That eight minutes is the amount we could probably get rid of by squeezing the plates together. There is an amount of fourteen minutes there which is introduced by the terminal blocks, which form a considerable loop in such a manner as to affect the plates unequally. It therefore is necessary to measure the phase angle of the shunt, and I think this is a desirable precaution, even though all indications of design would point to the shunt having a zero phase displacement.

A Paper presented at the 252nd meeting of the American Institute of Electrical Engineers, New York, October 14, 1910.

POTENTIAL STRESSES IN DIELECTRICS

BY HAROLD S. OSBORNE

HIGH VOLTAGE INSULATION

The property of a dielectric in which one is particularly interested in the design of high voltage insulation is its ability to resist the stresses exerted upon it by the voltage, tending to disrupt it, and to force a large current through the puncture.

The fundamental assumption which is made with regard to this property is that the force tending to disrupt the material at any point is measured by the electric intensity at that point, that is, by the force which would act upon a unit charge placed at that point. Thus Maxwell makes this statement:[1]

" If the electromotive intensity at any point in a dielectric is gradually increased, a limit is at length reached at which there is a sudden electrical discharge through the dielectric. The electromotive intensity when this takes place is a measure of what we may call the electric strength of the dielectric."

This critical value of the electric intensity in a dielectric is itself called, in common parlance, the electric strength of the dielectric.

Granting the existence of this definite physical constant, the electric strength of a dielectric, that is, a definite value of electric intensity which cannot be continuously or repeatedly exceeded without disrupting the dielectric, the voltage required to break down a given design of insulation depends evidently upon two factors:

1. The electric strength of the dielectric.
2. The distribution of the electric intensity, or, as one may now call it, the electric stress, in the dielectric.

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[1] *Electricity and Magnetism*, Vol. I, Art. 55.

With regard to the electric strength of the dielectric it need only be remarked that if one could devise materials of any desired electric strength, and possessing the necessary mechanical properties, insulation problems would be at an end. There seems little prospect, however, of the production of materials having greatly increased electric strengths until our knowledge of the constitution of matter is much more intimate than it is at present.

The second factor, the distribution of electric stress in the dielectric, depends upon its configuration. With an ideal distribution, the stress would be uniform throughout the dielectric, but in a homogeneous material this distribution can, unfortunately, occur only between infinite parallel conducting planes, which of course are not to be found in practice. When a conductor is insulated by surrounding it with a homogeneous dielectric, the stress is greatest at the surface of the conductor and less on the outer layers of insulation. Because of this non-uniformity in the distribution of the stress, the breakdown voltage of the wall of insulation is less than the product of its electric strength and its thickness. In high voltage insulation, the thickness of the wall required is relatively great, and the non-uniformity in the distribution of stress is so great that it becomes important to increase, by some device, the stress on the outer layers of insulation, so that they may be stressed equally with the inner layers.

In considering methods of accomplishing this result, those methods applicable to apparatus for alternating-current working are of primary importance. If one imagines the insulation to be divided into layers, it may then be considered as a set of capacities in series, the inner capacities being the smaller and hence supporting the greater stress. Two general methods are employed to equalize the stress on the layers. This equalization is accomplished either:

1. By connecting layers of metal foil, separating the layers of insulation, to points of suitable potential.
2. By increasing the capacity of the inner layers.

These same methods may be applied to apparatus for direct-current working, if it be borne in mind, in applying the second method, that in direct-current working the final stresses on the different layers are determined by their relative conductances instead of by their relative capacities.

The first method, requiring sources of various potentials, is not adapted to many cases, but can be conveniently applied in the insulation of a transformer, where any desired voltage may be tapped from the high tension winding. In England a patent[2] has been granted to the Siemens Bros. Dynamo Works, Ltd., covering this method of insulating high voltage transformers. Substantially the same expedient has been suggested[3] by Professor H. J. Ryan for protecting the minor insulation of high-voltage windings against excessive stresses.

The most obvious way of applying the second method of equalizing the stress, that of increasing the capacity of the inner layers, is to separate the layers by metal foil, and connect additional condensers across the inner layers. This method has been suggested for underground cables, but it has the disadvantage that it requires apparatus external to the cables themselves. This method has, however, been applied very ingeniously and successfully to the design of the condenser type of transformer terminal, which has been recently described[4] by Mr. A. B. Reynders in a paper presented to the American Institute of Electrical Engineers.

A method of increasing the capacity of the inner layers which is capable of a broader application, and which does not require the insertion of metallic layers, is the *grading* of the specific capacity (also called the dielectric constant) of the dielectric, making it higher in the inner layers than in the outer. This method has the advantage that it does not require the insertion of metallic layers between the layers of insulation. It is this method which is being applied in the manufacture of extra-high tension cables.

THE GRADING OF CABLES

The grading of cables seems to be worthy of a detailed consideration for three reasons:

1. The single-conductor concentric cable is of sufficiently simple configuration to permit of mathematical treatment by the ordinary methods of analysis, which lead to a complete theoretical solution of the problem of so grading the cable as to give a maximum voltage strength.

2. The manufacture of high voltage cables is now of commercial importance, and it seems certain that the demand for graded cables will increase with further development of high-voltage underground transmission.

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[2] British Patent 21860 of 1907. Engineering, July 17, 1908.

[3] *Some Elements in the Design of High Pressure Insulation.* International Electrical Congress of St. Louis, 1904.

[4] PROCEEDINGS of the American Institute of Electrical Engineers, March, 1909.

3. It is worth while for engineers, who frequently specify the thickness of insulation on their cables, to understand the possibilities offered by grading. In a rubber-insulated cable which was recently manufactured, the thickness of insulation specified by the purchasing engineer was so great that the manufacturer found it expedient to put the rubber on in two layers, though these layers were ungraded. If those layers had been properly graded, the cable could have been built with one-fourth the volume of insulation actually specified, and operated with the same maximum stresses.

Historical. The grading of cables has been discussed in several papers, the more notable of which are mentioned below.

It seems to have been first pointed out[5] to engineers by Mr. J. Swinburne, in 1897, that the electric stress in concentric cables is not uniform, but varies inversely as the distance from the axis of the cable. Mr. M. O'Gorman, in 1901, suggested[6] remedying this defect by *grading* the electrical constants of the wrappings, so that the outer layers should be stressed equally with the inner. In particular, he proposed to increase the conductivity of the inner layers of direct-current, impregnated paper cables by adding small portions of linseed oil, or of a similar oil, to the impregnating compound.

Mr. E. Jona, of Pirelli & Co., Milan, discussed the grading of cables in a classical paper[7] presented to the International Electrical Congress in 1904. Among other things, this paper describes a graded rubber-paper cable which was built by Pirelli & Co., gives the results of a theoretical investigation of the effect on the stress of stranding the conductor, and recounts some experiments made by Mr. Jona, to which frequent reference is made later in this paper.

Still more recently, Professor A. Russell has presented[8] this subject to the Institution of Electrical Engineers. Professor Russell's paper discusses methods of determining the electric strength of materials, and a number of interesting questions, such as the effect of temperature and of conductance on the distribution of the stress. In this paper are also presented

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[5] In a paper on *Electrical Transformation* before the Eng. Society. See Mr. O'Gorman's paper, Note (6).

[6] Journal of the Institution of Electrical Engineers, Vol. 30, p. 608. 1901.

[7] Transactions of the International Electrical Congress of St. Louis, 1904. Vol. II, p. 550.

[8] Journal of the Institution of Electrical Engineers. Vol. 40, p. 6. 1908.

formulæ for grading concentric cables, derived on the assumption that all the layers of insulation should be subjected to the same maximum and minimum stresses.

Grading Formulæ. For heavy walls of insulation Professor Russell's formulæ do not give the best possible designs. The problem of determining the constants of a graded single-conductor cable of a given type in such proportions as to give the maximum possible voltage strength can be solved in the manner indicated below.

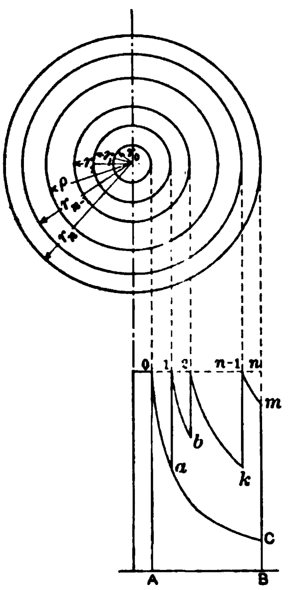

FIG. 1.—Potential gradient in a single-conductor cable

The electric intensity near a long, uniformly charged wire which is surrounded by concentric layers of insulation is found, by a simple integration, to be equal to

$$F = \frac{2\,Q}{\epsilon\,\rho} \tag{1}$$

where Q is the charge on the wire per unit length, ϵ is the specific capacity of the dielectric at the point considered, and ρ is the distance of that point from the axis of the wire.

If the conductor has a radius r_0. and is surrounded by a homogeneous insulation of outer radius r_n, and by a conducting sheath, the expression for the electric stress becomes

$$F = \frac{V_0}{\rho \, ln \, \frac{r_n}{r_0}} \tag{2}$$

where V_0 is the potential difference between the conductor and the sheath.

The distribution of stress is then represented by the curve $O\,a\,C$, Fig. 1, and if $O\,A$ represents the electric strength of the dielectric, the area $A\,O\,a\,C\,B$ represents the highest voltage which can be impressed upon the conductor without rupturing a part, at least, of the wall of insulation. If the stress were uniform throughout the wall of insulation, the rupturing voltage would be represented by the rectangle $A\,O\,n\,B$.

If now the insulation be divided into layers having outer radii r_1, r_2, etc., and specific capacities ϵ_1, ϵ_2, etc., respectively so graded that the stress at the inside of each layer is brought up to the value $A\ O$, or to the electric strength of the material, the rupturing voltage of the cable is evidently represented by the area $O\ a\ 1\ b\ 2\ .\ .\ .\ .\ .\ .\ k\ (n-1)\ m\ B\ A$, and approaches nearer and nearer to the maximum value, rectangle $A\ o\ n\ B$, the greater the number of layers.

In such a graded cable the equation for the stress becomes

$$F = \frac{1}{\varepsilon \rho} \cdot \frac{V_0}{\frac{1}{\varepsilon_1} ln \frac{r_1}{r_0} + \frac{1}{\varepsilon_2} ln \frac{r_2}{r_1} + . . . + \frac{1}{\varepsilon_n} ln \frac{r_n}{r_{n-1}}} \qquad (3)$$

Since the maximum stress on each layer is at its inner radius, the voltage which will just cause breakdown of the inner layer is

$$V_0 = F_1 \varepsilon_1 r_0 \left[\sum_1^n \frac{1}{\varepsilon_k} ln \frac{r_k}{r_{k-1}} \right] \qquad (4)$$

where F_1 represents the electric strength of the inner layer.

If all the layers are to be stressed to the point of disruption by the same voltage, we must evidently make

$$F_1 \varepsilon_1 r_0 = F_2 \varepsilon_2 r_1 = \ . \ . \ . \ . = F_n \varepsilon_n r_{n-1} \ . \qquad (5)$$

where F_k is the electric strength of the kth layer.

Under these conditions formula (4) for the disrupting voltage is

$$V_0 = F_1 \varepsilon_1 r_0 \left[\sum_1^{n-1} \frac{1}{\varepsilon_k} ln \frac{F_k \varepsilon_k}{F_{k+1} \varepsilon_{k+1}} + \frac{1}{\varepsilon_n} ln \frac{F_n \varepsilon_n r_n}{F_1 \varepsilon_1 r_0} \right] \qquad (6)$$

The problem now becomes that of finding the maximum value of V_0 in equation (6) under any given conditions and under simultaneous variation of all its variable factors. It is evident that V_0 increases indefinitely with r_n, so that quantity cannot be considered variable in obtaining a mathematical maximum. V_0 also increases indefinitely, in general, with the electric strengths. However, since these electric strengths are limited at present, in the manufacture of cables, to a very few values, they are not properly considered variable.

The specific capacities can be varied throughout a certain range, both in impregnated paper and in rubber compounds, without materially affecting the electric strength of the material.

We may then determine a mathematical maximum of V_0 for any of these conditions:

1. The outside diameter, $2\,r_n$, alone fixed. V_0 depends in this case upon the n independent variables $r_0, \frac{\varepsilon_1}{\varepsilon_2}, \frac{\varepsilon_1}{\varepsilon_3}, \ldots \frac{\varepsilon_1}{\varepsilon_n}$ and its maximum value is the maximum voltage which can be insulated by a given external diameter of the given materials.

2. The outside diameter, $2\,r_n$, and the diameter of the conductor, $2\,r_0$, fixed. V_0 is then a function of the $(n-1)$ independent variables $\frac{\varepsilon_1}{\varepsilon_2}, \frac{\varepsilon_1}{\varepsilon_3}, \ldots \frac{\varepsilon_1}{\varepsilon_n}$. The conditions for maximum V_0 give the constants of a cable which will insulate a given conductor for a given voltage with the smallest possible outside diameter of insulation.

3. The extreme radii (r_n and r_0) fixed, and also the extreme ratio of specific capacities, $\frac{\varepsilon_1}{\varepsilon_n}$. This last limitation is imposed in many cases by the present commercial limit in the variability of the specific capacities. V_0 then depends upon the $n-2$ independent variables $\frac{\varepsilon_1}{\varepsilon_2}, \frac{\varepsilon_1}{\varepsilon_3}, \ldots \frac{\varepsilon_1}{\varepsilon_{n-1}}$. The conditions for maximum V_0 give the same results as those for the second case. but under this added restricting condition.

Design Curves. The formulæ[9] expressing these conditions, and the resulting design formulæ for graded cables, are implicit logarithmic equations. From them, however, may be plotted curves from which the best designs may be read directly. Figures 2, 3, 4, and 5 show these design curves for four different types of cable. If one wishes to insulate a given size of conductor for a given voltage, he takes the required ratio of diameter of insulation to diameter of conductor from curve B, that ratio being read from curve A if one wishes to design for a given voltage an insulation with a given outside diameter. With a determined value of $\frac{r_n}{r_0}$ the other quantities of the design are read directly

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[9] See Appendix, Note 1.

from the curves. The values of the intermediate radii of the layers are obtained by remembering that

$$F_1 \varepsilon_1 r_0 = F_2 \varepsilon_2 r_1 = \,.\,.\,.\,.\,.\,. = F_n \varepsilon_n r_{n-1} \qquad (5)$$

The solid line marked *Max.* gives the value of $\frac{r_n}{r_0}$ for the largest ratio of voltage to outside diameter. The vertical dot-and-dash line cuts the curves at that value of $\frac{r_n}{r_0}$ which calls for a ratio of specific capacities which seems to be the present commercial limit. For larger values of $\frac{r_n}{r_0}$ we must introduce the condition that the value of $\frac{\varepsilon_1}{\varepsilon_n}$ is kept constant at this maximum value. The design under this added condition is represented by the dotted curves, and *Max'* represents the highest ratio of voltage to outside diameter which can then be obtained.

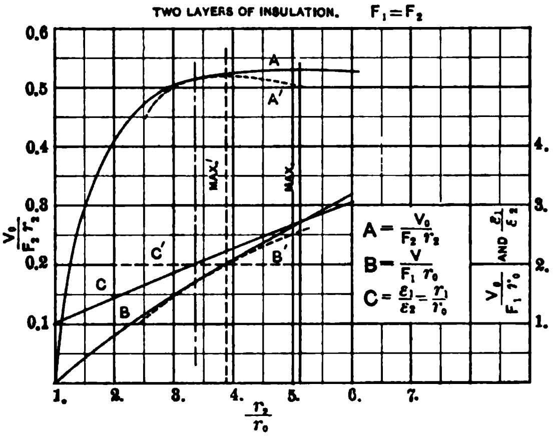

Fig. 2.—Design curves of a single-conductor cable

Figs. 2 and 4 are for cables of two layers and three layers respectively, the layers being all of the same strength. The maximum ratio of specific capacities attainable at present is taken to be two, which seems to be about correct for either rubber or impregnated paper insulations.

Figs. 3 and 5 give the curves for two-layer and three-layer cables respectively, in which the outside layer has an electric strength equal to two-thirds that of the inside layer. This is about the ratio between the electric strengths of impregnated paper and rubber, and these curves may be used for the design of cables having inside layers of rubber and an outside layer of paper. The commercial range of specific capacities for this case seems at present to be about 2.4, and curves have been drawn for this maximum value of $\frac{\varepsilon_1}{\varepsilon_n}$.

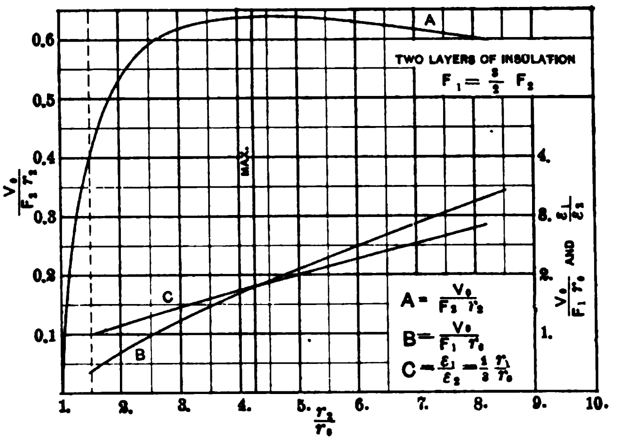

FIG. 3.—Design curves of a single-conductor cable

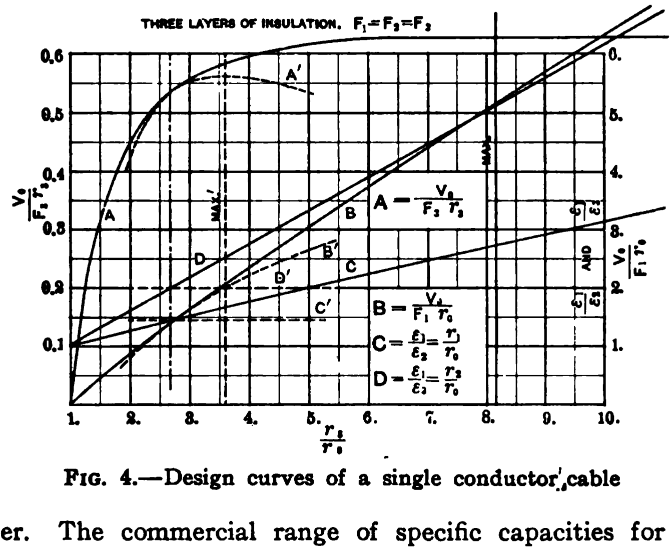

FIG. 4.—Design curves of a single conductor cable

It is interesting to note the greatest voltage which can be applied to cables of different designs having a diameter over the insulation of 70 mm. (about the largest that can be drawn, when sheathed, into a standard duct), the allowable stress in the rubber

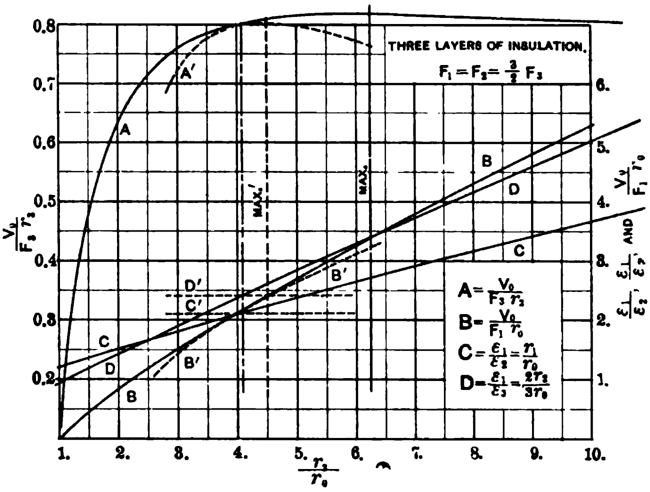

FIG. 5.—Design curves of a single-conductor cable

being assumed to be 6 kv. per mm. (effective), and that on the paper 4 kv. per mm. It is assumed that the available variation in specific capacities is sufficient to allow the best designs. The results obtainable are shown in table I.

TABLE I

No. layers	Insulation	Rad. of core mm.	Circular mils	V_0 (kilovolts)
1	All rubber....................	12.9	1030000	78
2	All rubber....................	6.85	290000	112
3	All rubber....................	4.29	114000	132
2	Rubber-paper................	8.24	420000	90
3	Rubber-rubber-paper..........	5.59	194000	115

Fig. 6 compares what may be called the voltage efficiencies of the different designs, that is to say, the voltage sufficient to overstress a given cable is expressed as a fraction of the voltage which would puncture a uniformly stressed layer of insulation having a thickness equal to the outside radius of the insulation of the cable. The maxima are indicated by short vertical lines, and it is noticeable that the graded cables not only show maxima which are higher and at greater values of $\frac{r_n}{r_0}$ than that for the ungraded cable, but that the curves are much flatter at the maxima than the curve for an ungraded cable. The circles indicate the points at which the present commercial limits in the ratios of specific capacities are passed. The curves for cables having larger values of $\frac{r_n}{r_0}$, and using the commercial limits of $\frac{\varepsilon_1}{\varepsilon_n}$ are somewhat lower than those in Fig. 6.

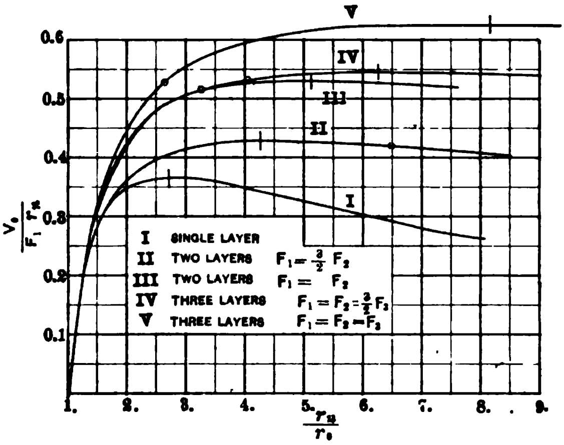

FIG. 6.—Maximum voltage efficiencies of cables

Fig. 7 gives the results of Fig. 6 plotted as percentages of the voltage strength of an ungraded cable. This figure then shows the increase in voltage strength to be gained by grading a cable of given dimensions. Curve I represents in this instance the values for an ideally graded cable, *i.e.*, one having a uniform stress throughout. Curves III and IV so nearly coincide that curve IV has been omitted.

Fig. 8 shows the volume of insulation to be saved by grading a cable of fixed voltage strength and size of conductor. The ordinates are the volumes of insulation required by graded cables expressed in per cents of the volumes required by the ungraded cable. The circles on the curves have the same significance as those in Fig. 6.

Figs. 2 to 8 are sufficient to show the results which can be obtained by the best designs under certain conditions. Formulæ can be derived from the general equations for cables of any desired types. In cases where especial conditions are imposed by the properties of the materials available or by the conditions of manufacture, the best design can be determined from the general equations.

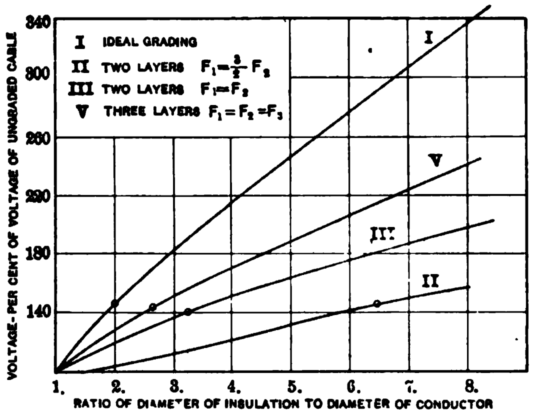

Fig. 7.—Voltage strength of graded cables

Conductance of the Dielectric. The results noted above depend on the assumption that no conductance current flows in the dielectric. This is not true, and it has been pointed out[10] by Professor Russell that the conductance may influence the distribution of stress.

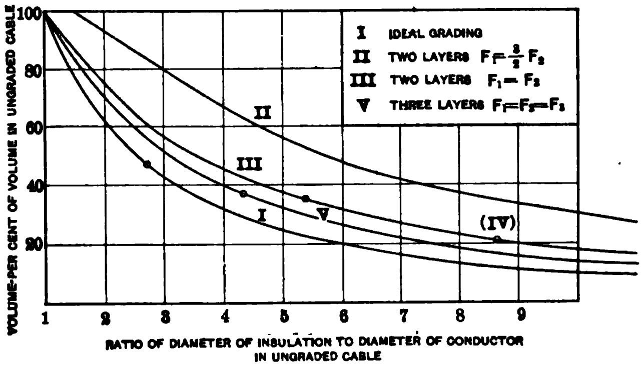

Fig. 8.—Volume of insulation in graded cables

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[10] See note (8).

If the conductance of the different layers be taken into account equation (3) for the stress in the dielectric becomes in complex notation

$$F = \frac{1}{\rho\left[\varepsilon - j\,\dfrac{18\,(10)^{11} g}{n}\right]} \cdot \frac{V_0}{\displaystyle\sum_1^n \frac{1}{\varepsilon_k - j\,\dfrac{18\,(10)^{11} g_k}{n}}\, ln\, \frac{r_k}{r_{k-1}}} \qquad (7)$$

where g_k is the conductivity of the kth layer in mhos per cm., and n is the frequency of the impressed sinusoidal electromotive force.

This equation reduces to equation (3) under any of the three conditions

$$\left.\begin{array}{l} n = \infty \\ g_1 = g_2 = \; . \; . \; . \; . \; = g_n = 0 \\ \dfrac{g_1}{\varepsilon_1} = \dfrac{g_2}{\varepsilon_2} = \; . \; . \; . \; . \; = \dfrac{g_n}{\varepsilon_n} \; . \end{array}\right\} \qquad (8)$$

In case $n = 0$ (direct-current working), the equation reduces exactly to the form of (3), with the values of ε_1, ε_2, etc., replaced by g_1, g_2, etc., respectively.

From equation (7) it may be computed that in any case the effect of conductance is less than five per cent if

$$R\, n\, \varepsilon > 5.6\, (10)^6 \qquad (9)$$

where R is the insulation resistivity in megohm-cm.

This condition, (9), is well met by any ordinary frequencies and insulating materials. The complete negligibility of the conductance of the dielectric in ordinary cases is well illustrated by Fig. 9, which shows the effect of low insulation resistance in the inner layer on the charging current of a particular two-layer condenser. It is seen that at commercial frequencies anything having an insulation resistivity of less than 50 megohm-cm. acts as a perfect conductor, while any resistivity greater than 40,000 megohm-cm. acts as a perfect insulator. The insulation resistivity of impregnated paper is ordinarily stated to be about 10 million megohm-cm., and that of rubber about 800 million megohms-cm.

The effect of conductivity increases with decreasing frequency, and with continuous pressures the final stresses are determined by the relative conductivities of the layers just as they are determined for alternating pressures by the specific capacities.

Temperature. Professor Russell has pointed out that the temperature gradient in the insulation may, by its effect on the conductivity, have a large influence on the distribution of stress in direct-current cables. The effect of the temperature on the specific capacities of ordinary materials is smaller, and in such a direction that it tends to reduce the stress on the inner layers of the insulation.

Multi-Conductor Cables. Cables with two and four, and particularly those with three round conductors inside a sheath are of such commercial importance that formulæ for grading them are much to be desired. Unfortunately they are like almost every other piece of electrical apparatus in that the potential gradient in the insulation cannot be exactly expressed in simple mathematical language.

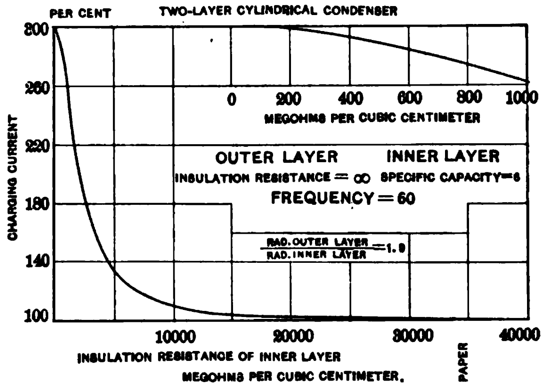

FIG. 9.—Effect of leakage conductance on charging current

A familiar approximate solution[11] is obtained by considering the charge on each conductor to be concentrated either at the centre of the conductor or at the appropriate inverse point relative to the sheath. The results obtained by such an approximation are far from exact if the conductors are large relative to the sheath. In cables for very high voltages, however, the conductors must be small relative to the sheath, and in such cases the approximation is very good. It seems probable, then, that rational grading formulæ for multi-conductor cables can be developed from the approximate solution.

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[11] See Appendix, Note 2.

CORONA IN SOLID DIELECTRICS

The theoretical results which are outlined above rest upon the fundamental assumption concerning electric strength which was mentioned at the beginning of this paper. It has been assumed that the electric strength of a dielectric is a real physical constant, measured by the electric intensity which, continuously or repeatedly applied, disrupts the dielectric. As this assumption has been assailed, notably in the discussion[12] of Professor Russell's paper, to which reference is made above, it may be worth while to consider it in some detail.

Maxwell laid a foundation for this assumption in the words already quoted: "The electromotive intensity when this (sudden electrical discharge through the dielectric) takes place is a measure of what we may call the electric strength of the dielectric."

Under certain circumstances this disruption extends through only that part of the dielectric which is near the conductors, as is the case in the familiar corona in air, and does not extend through the entire mass of insulation. Reasoning probably from the familiar and undisputed cases of corona, Professor Russell has advanced the hypothesis that there exists in solid dielectrics a corona similar to that in air, which disrupts, the entire overstressed portion uniformly, charring it and rendering it worthless as insulation.

For instance, the insulation about a wire which is insulated to more than 2.7 times its diameter will, according to this hypothesis, as the stress upon it is increased, first break down in a little uniform layer around the conductor. The breakdown of this layer will be insufficient to overstress the rest of the dielectric, so as the voltage is further increased, a zone of uniformly disrupted dielectric will extend out from the wire, within which zone the insulation is valueless, and at the surface of which the stress on the insulation is just equal to its electric strength. After this corona reaches a radius equal to 10/27th of the outside radius of the insulation, any further increase in voltage will overstress the rest of the insulation, and it will puncture.

According to this hypothesis, then, small wires insulated to a large outside diameter with a homogeneous dielectric will all

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[12] Journal of the Institution of Electrical Engineers, 1908, Vol. 40, p. 33. Professor Russell's paper and this discussion are referred to repeatedly in the following pages.

be expected to puncture, irrespective of the actual size of the wire, at a voltage to be computed by replacing with a conductor all the insulation within 10/27th of the outside diameter of the insulation.

In support of this theory, Professor Russell quoted one of two careful experiments performed by Mr. Jona. He insulated two wires, one of 1 mm. diameter and one of 29 mm. diameter with the same thickness, 14 mm., of paper, and punctured the two cables thus formed. Two similar cables were made with rubber insulation. From the puncturing voltages of the larger cables can be computed the voltages at which the smaller cables should puncture according to Professor Russell's hypothesis. The results observed, and those thus computed, are given in Table II.

TABLE II

Type of insulation	Puncture voltage, Kilovolts	
	computed	observed
Paper	43	40
Rubber	31	22

The agreement in the case of the paper cable is very good. It is interesting to note that in both cases the observed values are even lower than those called for by Professor Russell's hypothesis.

Accepting this hypothesis as correct, one would expect to find a visible change in the layers of insulation which have been subject to corona. Professor Russell quoted several men who have observed the partial destruction of a wall of insulation, but it is not clear in any case that the deterioration observed can be attributed to corona. A visible change in the dielectric is, however, perhaps not a necessary result of the complete destruction of its insulating properties. Professor Russell remarked in closing the discussion of his paper:

" Whether charring occurs or not, I think that once the dielectric has been broken down, it will never prove of much future use, mechanically or electrically, as a covering."

Corona in Air. In absence of experimental proof, it appears that the idea of corona in solid dielectrics has its chief basis on the familiar occurrence of corona in gases. The present state of our knowledge of corona in air is admirably summed up by Mr. E. A. Watson in a paper[13] recently presented to the Institution of Electrical Engineers. Mr. Watson has supplemented the very complete determinations made in this country, notably

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13. *Electrician*, London, Feb. 11, 1910.

by Mr. R. D. Mershon,[14] of the corona loss from wires under alternating pressures, by a very valuable series of tests with continuous pressures. His conclusions regarding the character of corona in air may be briefly summarized as follows:

The fact that a loss does occur with direct pressures shows that it is incorrect to consider the alternating current loss to be due to the flow of charging current through the disrupted strata of air, neither can it be considered to be due to the conversion into heat of the electrostatic energy stored in the air when breakdown occurs. Experiments of Rhigi and others have shown that the discharge of electricity from steadily electrified points consists in a stream of gaseous ions moving with a velocity of about 1.5 cm. per second for a field of one volt per cm. Mr. Watson's computations, based on this fact, indicate that the discharge from the wire is carried by certain agglomerations of molecules, and not by the whole mass of air. Tests of the corona in air from different sizes of wire indicate that the electric strength of the air is not constant, but varies inversely with the diameter of the wire, dropping from a value of 81.4 kv. per cm. for a diameter of wire of 0.70 mm., to about 39 kv. per cm. for diameters of 12 mm. or larger. Mr. Watson considers the most reasonable explanation of this to be the assumption that the layers of air next to the wire have a higher electric strength than the main body of air. This is an old idea, suggested by Steinmetz, Ryan and others, and one which seems to have some experimental basis.

These ideas concerning the nature of corona in air, as summed up by Mr. Watson, are of such a nature that it may well be questioned whether there is a similar effect in solid dielectrics. The discussion of Professor Russell's paper before the Institution of Electrical Engineers produced a good deal of opposition to his views on this subject, based largely on the fact that the charring effect of partial breakdown of the dielectric does not seem to have been definitely observed. The opinion of a good many men seems to be typified by a remark of Mr. George H. Nisbett in discussing Professor Russell's paper:

" I am further strongly of the opinion that no such effect has been observed as a partial breakdown of a solid dielectric where a layer of air has been entirely absent. I have never seen anything of the sort."

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[14] Proceedings of the American Institute of Electrical Engineers, June 1908.

Mr. Jona, whose opinion on this subject is important, remarked in the same discussion:

"I have been engaged for over ten years upon this subject, and my present conclusion is that unfortunately the experiment is most difficult, and often gives results which are not in accord, owing perhaps to the non-homogeniety of the dielectrics, and that theories based solely on the gradient of the potential are deficient. Such theories are partially true, but they do not represent the whole truth."

In support of his views Mr. Jona tells of an experiment with an especial cable. A copper wire 4 mm. in diameter was insulated with jute to 8 mm., surrounded with a thin brass tape, and then with 3 mm. of rubber. With a potential of 8000 volts across this cable, the stress on the jute (3300 volts) was sufficient to puncture it, charging current flowed through to the brass tape, and the entire stress was thrown upon the rubber. This is as one would expect. A second cable was then constructed identical with the first, except that the brass tape was omitted, there being then no conducting layer between the jute and the rubber. On Professor Russell's corona hypothesis one would expect the jute to carbonize at voltages above 8000, and the capacity of the cable to increase eventually to that of the layer of rubber. As a matter of fact no such effect was observed. Mr. Jona found the capacity to be practically constant between 5000 and 15,000 volts. No carbonizing of the jute was observed. This result is distinctly not in accord with the corona hypothesis and may be due, Mr. Jona suggests, to a supporting action of some sort between the jute and the rubber.

Results similar to those of Mr. Jona's experiment have been obtained with a piece of No. 14 wire, insulated to 8.5 times its diameter with rubber. Tests of the electric strength of the rubber with which it is insulated show that at voltages higher than 35,000, the inner part of the rubber is overstressed, and hence, according to the corona hypothesis, the charging current should increase along the curve A of Fig. 10. As a matter of fact, it increased along curve B. At each point of the curve the voltage was held constant until the capacity stopped increasing. As is indicated by the double points, a slight increase with time was noted; thus at the highest point observed the charging current increased between the two values indicated in two minutes, and then was constant for five minutes. Above 44 kilovolts the cable punctured above the surface of the water in which it was immersed, at a deep gash which ozone had eaten in it. Another piece of the same cable punctured under the water at 50 kilovolts.

Experiments with Cylindrical Condensers. In the attempt to get a more definite indication of the real condition of an overstressed dielectric, a special two-layer cylindrical condenser was constructed. As indicated in Fig. 11 it consisted essentially of a heavy glass tube, or tubes, G, into which was drawn a rubber insulated wire, R. Paraffin terminal pieces, T, were melted onto the ends to prevent end leakage, and to prevent puncturing at the edges of the outer electrode, which consisted of tinfoil wrapped tightly about the tube and about the inner cones of the terminal pieces.

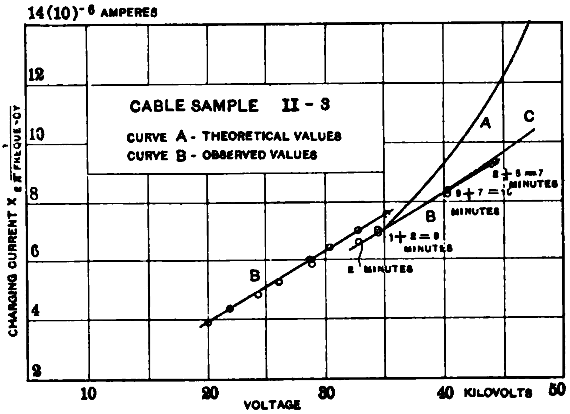

FIG. 10.—Charging Current at high voltages

The method of measuring the charging current is also indicated in Fig. 11. C_0 is a standard condenser, variable between 0.001 and 1 microfarad, connected in a series with the test condenser, E is an electrostatic voltmeter for measuring the voltage drop across C_0, and P is a protective device. This method was used not only in these experiments, but also in determining the specific capacities of the dielectrics used in the experiments. These constants were thus determined under the conditions ruling during the tests of partial breakdown.

A representative set of constants for the apparatus follows:

Rubber, $\varepsilon_1 = 6.3$ $F_1 = 18.3$

Glass, $\varepsilon_2 = 8.5$ $F_2 = 35+$

The combination therefore forms an inversely graded cylindrical condenser, in which the inner layer is overstressed by voltages which stress the outer layer but slightly.

From the constants of the apparatus it can be computed that at 24 kilovolts the rubber begins to be overstressed, and the charging current should increase, according to the corona hypothesis, along the curve A of Fig. 12, assuming, at 27 kilovolts the value due to the capacity of the glass cylinder alone. The curves B-1 and B-2 represent the values of charging current observed during two successive tests. It is seen that between 24 kilovolts and puncture at 28 kilovolts, the apparent capacity increased but slightly, and by no means as much as is called for by the corona hypothesis, that is, by the complete breakdown of the insulation in the overstressed region.

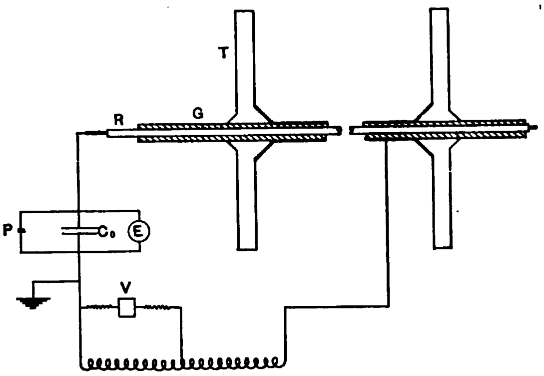

Fig. 11.—Apparatus for measuring charging-current at high voltages

A second, and unexpected, result is that the whole apparatus punctured at 28 kilovolts though the glass tubes alone were capable of withstanding twice that voltage. At this puncturing voltage the potential across the glass tubes, as computed by ordinary methods, was about 10 kilovolts, while that across the rubber was about 16 kilovolts, a little higher than the voltage (13.8 kilovolts) at which the rubber punctures alone.

A third result was obtained by withdrawing the wire from the tubes after the voltage had been applied, and examining it for insulating properties. In appearance, even under the microscope, the rubber was sound. Mechanical tests failed to indicate any deterioration. The insulation resistance of the short lengths used in the test could not be very satisfactorily tested, but it was certainly more than 100 megohms per 1000 meters. When a voltage test was applied, however, the insulation was found to be markedly deteriorated. Rubber which had been highly overstressed could not withstand at any point a voltage readable on the high-tension apparatus, and rubber which had been but slightly overstressed showed numerous very weak spots.

A difficulty in accepting these results as wholly conclusive arises from the fact that the thin layer of dielectric between the glass and the rubber, where the two did not fit exactly together, was itself disrupted by the voltage stresses. After the first tests had been made with air between the rubber and the glass an unsuccessful search was made for an insulating liquid which would not be overstressed during the experiment. Castor oil was used in some of the tests, but under the stresses exerted upon it, it evolved little bubbles of gas, even when it had been put under an air-pump directly before the experiment. A test was finally made with a mineral oil which, though it was overstressed during the experiment, showed no bubbles or visible signs of deterioration. The tests with the different insulating liquids all indicate the same results. In the tests the results of which are represented in Fig. 12 castor oil was used between the rubber and the glass.

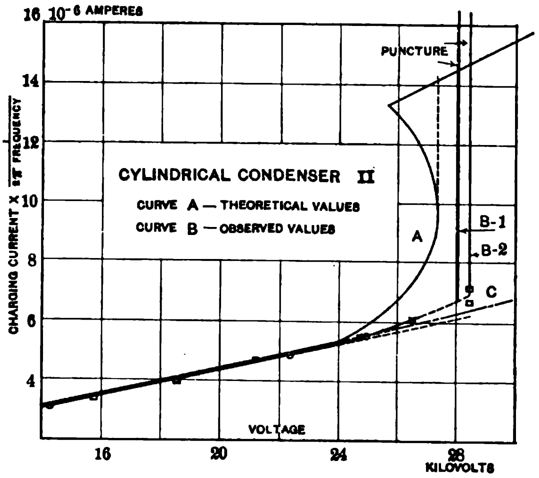

FIG. 12.—Charging current at high voltages

The possibility remains that if one could introduce between the rubber and the glass an insulating liquid which would not be overstressed during the experiment, the results noted here would not be observed. Such a possibility seems remote, however, in view of the fact that all the effects observed are explained by a very simple and convincing hypothesis concerning the nature of this partial breakdown.

Let us accept the assumption that an excessive potential gradient at any point always disrupts the dielectric at that point. It seems evident upon consideration that, even in a perfectly homogeneous dielectric, the uniform breakdown required by the Russell hypothesis would be a condition of unstable equilibrium, for if the breakdown proceeds a little farther at one point than at the points around it, the charge flowing into that advanced point will reduce the stress on the surrounding points, and the more intense field at the end of the advanced point will tend to push the breakdown farther and farther into the dielectric. Commercial dielectrics, which cannot be perfectly homogeneous, should then be certainly expected to break down not uniformly, but at a number of points, so that the incipient breakdown produces much the same effect as a number of needlepoints thrust into the insulation.

This simple hypothesis seems to explain all the results of the experiments noted here. When, in the rubber-glass condenser, the needlepoints of disrupted rubber reach the glass, they will tend to puncture it at a much lower voltage than would be required were the inner surface of the glass an equipotential surface. The apparatus punctured in these tests at about 28 kilovolts, though when alone the glass could withstand more than 50 kilovolts. When subjected to potential from an actual steel needlepoint surrounded by insulation, the same tube punctured at about 25 kilovolts. The needlepoints must push their way into the rubber in a sufficient number of places to keep the stress in the rubber down to its electric strength. They must take some additional charging current, but not nearly as much as would be required were the entire inner layer disrupted, and in a conducting condition. A general idea of the magnitude of this charging current might be obtained by considering that portion of the dielectric which would have become, according to Professor Russell's hypothesis, uniformly disrupted, to support a stress which is uniform and equal to the electric strength of the material. The charging current curves corresponding to this assumption have been drawn in Figures 10 and 12 (Curves *C*). In the test of the cable the curve so computed is in substantial agreement with the observed values. In the experiment with the rubber-glass condenser the observed values are somewhat greater than those of curve *C*, partly, perhaps, because some of the needlepoints carried charging current to little bubbles of gas in the castor oil which separated the rubber and the glass.

This idea of the needle-point character of corona in solid dielectrics explains also the results of the experiments quoted by Mr. Jona, making it easy to see how his thick insulations could puncture at voltages even lower than those called for by Professor Russell's hypothesis. It even seems probable that corona in gases is of the same general character, as this idea makes it easier to explain some of the phenomena of that corona. Therefore, though the needlepoint nature of partial breakdown in a dielectric may not be conclusively proved, the substantial accuracy of that idea seems highly probable, because it harmonizes the results of experiment with the fundamental assumption concerning electric stress.

In view of the needlepoint effect, it is particularly desirable to design an insulation for high voltages in such a way that no part of it will be overstressed, for it is apparent from the experiments reported in this paper that an overstressed insulation may be much worse than no insulation at all. It might even pay cable manufacturers who have occasion to make ungraded cables with thick walls of insulation, to fill the space within a radius of 10/27th of the outside diameter of their cables, in case it is not wanted for copper, with some material having a conductivity high enough to protect it from excessive voltage gradients, if such a material, having the requisite mechanical properties, is available.

It is desirable to have the results which have been mentioned checked with other apparatus and materials. An attempt was made to do so with a parallel plate condenser, consisting essentially of two glass plates, separated by a weaker dielectric, and separating the two electrodes, one of which was provided with an ample guard ring.

A preliminary test of the apparatus, in which air was the disrupted dielectric, gave the results shown in Fig. 13. The bend in curve I is due to the fact that, owing to irregularities in the glass plates, some air remained between them when they were pressed together. The variations of curve II from the dotted line seem to be largely due to the element of time, and it is not improbable that, were all the other variables eliminated, the voltage across the disrupted air would be found to be sensibly constant, and the current flowing through it largely a displacement current. Mr. A. W. Ewell has conducted an extensive series of tests[15] similar to this, but with plates which were vertical and open to a free supply of air. He found that for large gaps and high voltages, the voltage for a given charging current tended toward a constant value, independent of the width of the air-gap.

A condenser built with paraffin as the weaker dielectric was rejected because of the great contraction of the paraffin on solidifying. A condenser was finally built of a compound[16] which did not contract on solidifying. In testing this condenser the difficulties of insulation were found to be great, and were not surmounted in the short time which remained for the work.

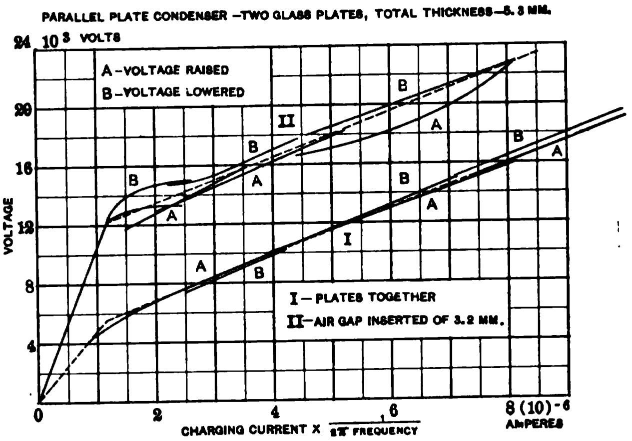

FIG. 13.—Charging current at high voltages

SUMMARY

In the design of high-voltage insulation, resort is frequently made to certain expedients which tend to equalize the stresses in the different parts of a thick wall of dielectric. In transformers metallic layers, separating layers of dielectric, are connected to points of suitable potentials. In the condenser-type of transformer terminal the capacities of the inner layers of insulation are increased by increasing their lengths; and in graded underground

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[15] *American Journal of Science*, November 1906.

[16] The compound consisted in 4 parts of shellac, one part of resin, and 2 parts of venice turpentine. It is recommended by Professor L. T. Moore in an article on *Dielectric Strain along the Lines of Force*, Phil. Mag., December, 1905.

cables the capacities of the inner layers are increased by increasing their specific capacities.

Formulæ have been developed which give the best theoretical designs of graded single-conductor cables of certain given types for any given conditions. The effect of the conductivity of the dielectric is found to be entirely negligible for ordinary materials and ordinary frequencies of alternating-current working.

Results of experiment indicate that a solid dielectric, when overstressed, is not disrupted uniformly, but that the material is affected as though it had been pricked by a number of needlepoints. By this hypothesis these results, and those of earlier experiments, are explained without violating the assumption with regard to the electric strength of a dielectric which is the basis of all analytical work on the subject.

It seems probable, then, that these analytical results are based on proper assumptions; but when dealing with cases of partial breakdown, account must be taken of the true character of that breakdown.

The experiments reported in this paper were performed in the Electrical Engineering Laboratories of the Massachusetts Institute of Technology. The author wishes to acknowledge his indebtedness to the Simplex Electrical Company for samples of insulated wire, and particularly to thank Professors H. E. Clifford and Harold Pender for their assistance. Professor Clifford suggested that this investigation be undertaken, and it was commenced under his direction and completed under the direction of Professor Pender.

APPENDIX

NOTE 1. Grading formulæ for concentric cables.

$$V_0 = F_1 \varepsilon_1 r_0 \left[\sum_{1}^{n-1} \frac{1}{\varepsilon_k} \, ln \frac{F_k \, \varepsilon_k}{F_{k+1} \, \varepsilon_{k+1}} + \frac{1}{\varepsilon_n} \, ln \frac{F_n \, \varepsilon_n \, r_n}{F_1 \, \varepsilon_1 \, r_0} \right] \qquad (6)$$

A. If V_0 is a function of the $n-2$ independent variables $\frac{\varepsilon_1}{\varepsilon_2}, \frac{\varepsilon_1}{\varepsilon_3} \; . \; . \; . \; . \; \frac{\varepsilon_1}{\varepsilon_{n-1}}$, the conditions for a mathematical maximum are

$$\frac{1}{\varepsilon_k} \, ln \frac{F_k \, \varepsilon_k}{F_{k+1} \, \varepsilon_{k+1}} = \frac{1}{\varepsilon_k} - \frac{1}{\varepsilon_{k-1}} \qquad (10)$$

k having all values between and including 2 and $n-1$

B. If $\frac{\varepsilon_1}{\varepsilon_n}$ is variable, in addition to the variables of case A, the maximum of V_0 is given by the $n-2$ conditions of case A, and by the added condition

$$ln\frac{F_n\,\varepsilon_n\,r_n}{F_1\,\varepsilon_1\,r_0} = 1 - \frac{\varepsilon_n}{\varepsilon_{n-1}} \tag{11}$$

C. If r_0 is variable, in addition to the variables of case B, the maximum of V_0 is given by the $n-1$ conditions of case B, and by the added condition

$$ln\frac{F_1\,\varepsilon_1}{F_2\,\varepsilon_2} = 1. \tag{12}$$

The equations derived from these different sets of conditions for the design of graded cables of certain types follow.

I. $n = 2.\quad F_1 = F_2$

A. $$V_0 = F_1 r_0\left[\frac{\varepsilon_1}{\varepsilon_2}\,ln\frac{r_2}{r_0} - ln\frac{\varepsilon_1}{\varepsilon_2}\left(\frac{\varepsilon_1}{\varepsilon_2} - 1\right)\right]$$

B. $$V_0 = F_1 r_0\left[\frac{\varepsilon_1}{\varepsilon_2} + ln\frac{\varepsilon_1}{\varepsilon_2} - 1\right]$$

$$ln\frac{r_2}{r_0} = 1 - \frac{\varepsilon_2}{\varepsilon_1} + ln\frac{\varepsilon_1}{\varepsilon_2}$$

II. $n = 2.\quad F_1 = \frac{3}{2}F_2$

A. Not derived.

B. $$V_0 = F_1 r_0\left[\frac{\varepsilon_1}{\varepsilon_2} + ln\frac{3\,\varepsilon_1}{2\,\varepsilon_2} - 1\right]$$

$$ln\frac{r_2}{r_0} = 1 - \frac{\varepsilon_2}{\varepsilon_1} + ln\frac{3\,\varepsilon_1}{2\,\varepsilon_2}$$

III. $n = 3.\quad F_1 = F_2 = F_3.$

A. $$V_0 = F_1 r_0\left[ln\frac{\varepsilon_1}{\varepsilon_2} - 1 + \frac{\varepsilon_1}{\varepsilon_2} + \frac{\varepsilon_1}{\varepsilon_3}\,ln\frac{\varepsilon_3\,r_3}{\varepsilon_1\,r_0}\right]$$

$$ln\frac{\varepsilon_1}{\varepsilon_3} = 1 - \frac{\varepsilon_2}{\varepsilon_1} + ln\frac{\varepsilon_1}{\varepsilon_2}$$

B. $$V_0 = F_1 r_0 \left[\frac{\varepsilon_1}{\varepsilon_3} + ln\frac{\varepsilon_1}{\varepsilon_2} - 1\right]$$

$$ln\frac{r_3}{r_0} = 1 - \frac{\varepsilon_3}{\varepsilon_2} + ln\frac{\varepsilon_2}{\varepsilon_3} + ln\left[\frac{1}{1 - ln\frac{\varepsilon_2}{\varepsilon_3}}\right]$$

$$\frac{\varepsilon_1}{\varepsilon_2} = \frac{1}{1 - ln\frac{\varepsilon_2}{\varepsilon_3}}$$

IV. $n = 3 \qquad F_1 = F_2 = \frac{3}{2} F_3$

A. $$V_0 = F_1 r_0 \left[ln\frac{\varepsilon_1}{\varepsilon_2} + \frac{\varepsilon_1}{\varepsilon_2} - 1 + \frac{\varepsilon_1}{\varepsilon_3}\, ln\frac{2}{3}\frac{\varepsilon_3}{\varepsilon_1}\frac{r_3}{r_0}\right]$$

$$ln\frac{3}{2}\frac{\varepsilon_1}{\varepsilon_3} = 1 - \frac{\varepsilon_1}{\varepsilon_2} + ln\frac{\varepsilon_1}{\varepsilon_2}.$$

B. $$V_0 = F_1 r_0 \left[\frac{\varepsilon_1}{\varepsilon_3} + ln\frac{\varepsilon_1}{\varepsilon_2} - 1\right]$$

$$ln\frac{r_3}{r_0} = 1 - \frac{\varepsilon_3}{\varepsilon_2} + ln\frac{3}{2}\frac{\varepsilon_2}{\varepsilon_3} + ln\left[\frac{1}{1 - ln\frac{3}{2}\frac{\varepsilon_2}{\varepsilon_3}}\right]$$

$$\frac{\varepsilon_1}{\varepsilon_2} = \frac{1}{1 - ln\frac{3}{2}\frac{\varepsilon_2}{\varepsilon_3}}.$$

The results of case *C* may be tabulated, and are shown in Table III.

TABLE III

Type of cable	$\frac{r_1}{r_0}$	$\frac{r_2}{r_0}$	$\frac{r_3}{r_0}$	$\frac{\varepsilon_2}{\varepsilon_1}$	$\frac{\varepsilon_3}{\varepsilon_1}$	$\frac{V_0}{F_n r_n}$
Single layer...............	2.72	—	—	—	—	0.368
I.........................	2.72	5.11	—	0.368	—	0.531
II........................	2.72	4.25	—	0.552	—	0.640
III.......................	2.72	5.11	8.18	0.368	0.196	0.626
IV........................	2.72	5.11	6.26	0.368	0.294	0.817
Ideal grading..............	—	—	—	—	—	1.000

NOTE 2. Approximate solution for multi-conductor cable.

If a charge of Q units per cm. is considered concentrated along a line having the cylindrical coördinates (d_0, π), the origin being the centre of a sheath of radius R which is at zero potential, the potential function within the sheath is, by the method of images

$$V = -Q \, ln \frac{\rho^2 + 2\, d_0 \, \rho \cos \theta + d_0^2}{\frac{d_0^2}{R^2} \, \rho^2 + 2\, d_0 \, \rho \cos \theta + R^2} \tag{13}$$

The equipotential surfaces of equation (**13**) are circular cylinders whose axes have the coördinates

$$\rho = d_0 \frac{R^2 \, (1 - c^2)}{R^2 - c^2 \, d^2}, \qquad \theta = \pi$$

and whose radii are equal to

$$r = R \, c \, \frac{R^2 - d_0^2}{R^2 - c^2 \, d_0^2}$$

where c equals the base of natural logarithms raised to the $-\frac{V}{2\,Q}$ power, V being the potential of the cylinder in question.

When more conductors than one are placed symmetrically in the same sheath, the potential function may be found approximately by adding terms of the form (**13**), the angle θ being changed to correspond to the position of the new conductors.

NOTE 3. Bibliography.

Below are given some references in addition to those given in the foot-notes of the paper.

(*a*) High Voltage Insulation

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(*c*) Insulating Materials

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22. The Mechanism of Disruptive Discharge. M. Langevin. *Soc. International des Electriciens. Bull.* Feb., 1906.
23. Dielectric Losses. B. Monasch. *Electrician.* June 28, July 5, 1907.
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DISCUSSION ON "POTENTIAL STRESSES IN DIELECTRICS". NEW YORK, OCTOBER 14, 1910.

J. B. Whitehead: The language of the ionization theory is conspicuously lacking in this interesting paper. Since this theory is now widely accepted, and since practically all of the phenomena of the conductivity of gases and many of those of liquids and metals may be explained in terms of this theory, it is worth while to consider in the same light some of the questions raised in the authors' valuable summary and discussion of the nature of the processes involved in the break-down of cable insulation. First as to the possibility of corona in solid dielectrics it must be remembered that the term " corona " has arisen in connection with the phenomenon in gases and that the structure of the solid is radically different as viewed by the firmly established kinetic theory of matter and its offspring the ionization theory. The important differences in the present instance are the greater number of free ions in a gas, the greater length of their free paths, and above all the possibility of an ion attaching itself to one or more molecules and dragging them through the gas under the influence of an electric field. Thus in the corona in gases it is certain that disruption or ionization occurs only within the bounds of the corona itself, yet beyond the corona there is motion of charged molecules the charges originating as free ions in the corona. Moreover it is highly probable that the gas even in the corona is not disrupted at all in the sense that the term means the separation under the electric field of the two component charges of an atom of molecule, but that these latter are split apart by the impact of a free ion of which there are always a certain average number present.

In the case of the solid dielectric on the other hand there is little, if any, evidence of the existence of free ions. The mean free path of the molecules is much shorter than that of the gas and it is certain that agglomerations of molecules attached to a free ion cannot move freely through the body of the substance. Further, it seems highly probable that the break-down of a dielectric is an actual disruption or tearing apart of the opposite charges of a molecule under the stress of the electric field. The long accepted view that the dielectric properties are due to an elastic structure of a molecule in which the two component charges are held together up to the point of disruption, is not in conflict with the ionization theory which simply states that there is no extended motion of free ions with consequent possibility of ionization by collision, and resulting conductivity.

What then does the theory offer in explanation of the facts observed in the behavior of cable insulation? These facts are: (*a*) The insulating material may be overstressed without breakdown. (*b*) There is no evidence of corona or charring of insulation. (*c*) There is no evidence of conductivity after overstress or consequent increase of capacity due to such conductivity. (*d*) The material after overstress is, however, weaker.

There is no difficulty in the idea of a strain of dielectric material beyond the electrical elastic limit with no resulting structural break-down and resulting conductivity. In a single conductor cable, we may think of a string of molecules stretched radially along a line of electric force. When the interior portion of the insulation is overstressed, but the insulation as a whole unbroken we may think of the component charges of a molecule in the stressed region as drawn apart, and a tendency on the part of opposite charges of two adjacent molecules to combine. If this tendency could take place along the whole line of force there would be combination throughout and resulting discharge. The phenomenon would then be similar to conduction in a metal. In the case as supposed, however, the outer portions of the insulation are not overstressed, consequently proceeding outward from the conductor along the line of force there comes a region where there is a molecule which is not overstressed, which therefore successfully resists the tendency of one of its charges to pass to the adjacent overstressed molecule. This restraining influence is therefore propagated backward toward the center and serves to keep the overstressed portion from breaking down entirely. In this way the region of safe stress may be said to aid that in which this stress is exceeded. Referring to fact (*b*) it should be noted that the corona as it is known in gases with its evolution of heat is probably due to the rapid motion of charged particles or ions through the body of the gas. There is not the possibility of such motion in dielectrics and it is not therefore a necessity of overstress that there should be the carbonization usually resulting, in dielectrics from the passage of current. As to fact (*c*) it is evident that if there is no break-down and resulting conductivity there is no reason why increase of capacity should be looked for. There remains the fact (*d*) that the material is weakened electrically after being overstressed. In explanation of this it may be pointed out that slight impurities of material, particularly if such impurities have large conductivity, would serve to enable the opposite charges of adjacent overstrained molecules of the dielectric to be neutralized thus leaving an unbalanced molecule and a consequent region of weakness. This action would naturally take place in the method ingeneously described by the author with the term " needle point ".

With regards the question of the constancy of the electric strength of dielectrics it may be pointed out that there is plentiful evidence that in gases the electric stress may be carried far beyond the value which is taken as constant for the material for the great majority of circumstances. In those instances in which the gas seems to present abnormal strength it may be shown that the conductor applying the electric strain has dimensions so small as to be comparable with the mean free paths of the ions which are involved in the break-down of the gas itself. Extending this idea to the case of dielectrics we are faced with the fact that the distances between the ions which enter into the phenomenon of disruption are very much smaller than those involved in the phenomena occurring in gases. It would therefore seem probable that by steadily decreasing the size of wire any tendency of the electric strength to present an apparent increase must occur at very much smaller diameters than those obtaining in the case of a gas. It is worth mentioning also that for the same reasons one might expect an alteration in the value of the specific capacity of the material for very small wires.

The paper has presented in valuable fashion the problems connected with the strains in the insulation of cables. It leaves the field in excellent shape as a point of departure for promising experimental work. It is to be regretted that the author could not supplement his own deductions with more experimental evidence. The field, however, is notoriously a difficult one.

Milton Franklin: The subject of this evening's paper is of great interest to me inasmuch as I have done some work along these lines myself. I have prepared a paper on the analytical discussion of the physical dimensions of cylindrical dielectrics. My paper is mathematical rather than practical, though only the simplest mathematics are involved. The author has applied these principles to commercial design, which is, after all, the ultimate aim of all such investigations.

My analyses, however, are fairly exhaustive and will enable any one to comprehend the principles involved and to extend their application to many cases other than the insulation of cables, and to cases of this, other than to those here treated, for example: the determination of the minimum mass of material that may be used in any case, etc.

The paper this evening is a very practical one, and in my opinion admits of very little criticism. The attempt to explain the cause of dielectric failure seems to me to be a description of observed cases rather than an explanation.

I have shown in the paper referred to, and in some subsequent experiments, that the dielectric stress corresponds to a mechanical stress similar to a hydrostatic pressure and accompanied by a proportionate strain, and have given an equation expressing the values of this stress, for various conditions in pounds per square inch. I am led to the conclusion that the failure is due to the periodic application of this stress, and the ultimate fatigue of the material. It is true that the stress and the consequent strain are small, but the number of blows is enormous, *e.g.*, at 60 cycles per second there are one hundred and twenty blows per second, 7200 blows per minute, 432,000 blows per hour, 10,368,000 blows per day, etc. This I think explains the cause of failure, the needle point result being due to lack of homogeneity and constituting the prodromata of an unstable equilibrium. The delay, or time lag, observed is not incompatible with this hypothesis.

With respect to the cases given for multi-conductor cables, I cannot agree with the assumption of the author with regard to the distribution of charge. He seems to ignore the influence of electrical images and the oscillating character of the alternating current, for which, in the main, these cables are designed. With respect to images it should be noted that in cables the conductors are very near the ground, *i.e.*, the images, and the skin effect tends to a peripheral distribution of the charge. The moments of these quantities are not amenable to mathematical analysis and evaluation, but I am satisfied from observation of practical cases that the assumption of uniform peripheral distribution, while probably not exact, will lead to minimum errors. This applies also to practical cases of transmission.

A. E. Kennelly: The subject of this paper is of great practical importance owing to the rapidity with which voltages have been rising recently in electrical engineering.

The facts are very clearly presented in the paper. The paper has, moreover, the special merit of presenting curves, by means of which the advantages, theoretically obtainable from the grading of cable insulation can be read off on inspection. We should however, carefully distinguish between the advantages that may be theoretically obtainable, and those that may be practically obtainable, through grading. Many considerations, such as mechanical strength, elasticity, permanence, cost, etc., must be taken into account, besides the dielectric strength, in selecting gradings.

We all know that a joint in the magnetic circuit gives rise to a certain extra magnetic reluctance and c.m.m.f. But the paper shows that a joint in the electrostatic circuit may not merely be the seat of additional electrostatic reluctance, but also of a dangerous local electric gradient. Such electrostatic joints may be inimical, by introducing equivalent point conductors, where the dielectric may break down, as little spherical particles into conducting material, whence electric flux and electric equipotential surfaces may diverge anew with powerful local intensities into the adjoining layers of dielectric. For this reason also the paper indicates that a grading of insulation may be detrimental instead of helpful.

It must be admitted, however, that the particular kind of grading experimented with—the grading of rubber and glass—is more than usually dangerous in regard to weak electrostatic jointing. When a rubber-covered wire is pulled into a glass tube, there is sure to be a layer of air included between the two. This air has not only a relatively high electrostatic reluctivity, thereby establishing a relatively large drop of potential across the layer, but it has also a relatively low breaking stress. Once it breaks electrically, it is able to precipitate high local stresses near the broken down spots, as is described very clearly in the paper.

In making computations of graded electrostatic reluctances, "semi-log" paper has special advantages, that is, paper ruled to logarithmic coördinates along the axis of abscissas, but to ordinary uniform spacing along the axis of ordinates. "Semi-log" paper can be constructed by taking ordinary cross-section paper, and laying off the spacings, from the face of a slide rule, along the horizontal axis. The long denominator in formula (3), which is virtually a summation of electrostatic reluctances in series, is then presented on "semi-log" paper in the form of a simple series of juxtaposed rectangles. The total area of all the rectangles is thus easily determined, and defines the total electrostatic reluctance of the graded insulation. The potential in the layers insulation also reveals itself on the "semi-log" diagram, as a series of connected straight lines.

In regard to the effect upon the electrostatic capacity of dielectrically stressing cable insulation layers, I may mention a case that came to my notice a few years ago. A stranded copper conductor 2.3 mm. in diameter, was covered with a layer of Para rubber to a wall thickness of about 1 mm. and then covered with vulcanized rubber, containing over 40 per cent of rubber, to a total diameter of 7.15 mm. About one hundred 5-mile lengths of this core were tested. The tests included electrostatic capacity, and dielectric stress at 5 kilovolts r.m.s. pressure between conductor and outside salt water, for 5 minutes, at 60 ~. It was found that the core easily withstood this pressure, and no injury could be detected in the insulation after this application. The linear electrostatic capacity, however, which, before applying the dielectric test, averaged approximately 0.4 microfarad per nautical mile, was distinctly increased after applying the test. The increase was most noticeable immediately after the test, and partly disappeared with time; but an increase of about 5 per cent was found to persist, at least for months. In some cases the increase in linear capacity immediately after the test was 15 per cent. The capacity was measured by direct current methods, using (1) galvanometer deflections on charge; (2) galvanometer deflections on discharge; (3) the method of zero resulting charge by mixture.

W. S. Franklin: In discussing a theoretical paper on engineering one should attempt first of all to estimate the significance and value of the paper. In the present instance this duty is a pleasing one because in my opinion the paper constitutes an unusually important and really practicable application of theory to electrical engineering.

I have always looked upon the grading of cable insulation as an extremely simple matter, which indeed it is from the theoretical point of view. But the grading of cable insulation is not wholly a theoretical matter; the facts as to the electric strengths and inductivities of available materials are of some importance, to say the least, and Mr. Osborne is the first, as far as I know, adequately to consider the question of grading on the basis of these facts.

The case mentioned by the author of a cable which contained four times the necessary volume of insulating material shows indeed the importance of the paper, and the fact that a person perfectly familiar with Maxwell's theory would be unable to point out this glaring case of bad design shows that something besides Maxwell's theory is necessary.

There is a close analogy between the mechanical cracking of strained glass and the electric rupture of a dielectric. The author seems to have this analogy in mind when he speaks of the " needle-point " theory. This analogy is developed in Nichols & Franklin's *Elements of Physics*, Vol. II, pages 154-157. The analogy holds for the ordinary spark discharge and also for the brush discharge or " corona," and it is not inconsistent with the electron theory provided one does not look upon the " needle-point " fracture as a mathematical line.

A difficulty in forming a mechanical conception of the influence of inductivity on the distribution of electric stress is that a mechanical arrangement *in parallel* must be compared with an electrical arrangement of dielectrics *in series*. Thus a number of helical springs of different degrees of stiffness are placed in parallel between two parallel metal bars. When these bars are moved towards each other every spring is subjected to the same strain or yield and the stress or compressing force is great in the stiff springs and small in the springs which yield easily. When a number of layers of dielectric are placed between two charged flat metal plates, they are all subjected to the same electrical yield (electrical flux density or displacement), the dielectrics which have great electrical stiffness (small inductivity) are subjected to great stress in volts per centimeter and those which have small electrical stiffness (large inductivity) are subjected to small stress in volts per centimeter.

The modern built-up cannon furnishes a close analogue to the graded cable. Indeed, if one could use highly elastic or easily yielding steel for the inner portions of the gun tube and less elastic or stiffer steel for the outer portions (ultimate strength of steel being the same in both cases) then the analogue would be complete. The interior portions of such a graded steel tube would yield greatly in being brought to their maximum permissible tension and this great yield would stretch the outer and less yielding portions of the steel tube sufficiently to bring the tension in these portions to the permissible limit. So it is in the graded cable; the inner portions of the insulation have high inductivity, that is to say, the inner portions are made of material which is electrically yielding, as it were, and the great yield (electrical flux density or electrical displacement) which is produced in the inner layers as compared with the outer layers of insulation causes inner and outer layers to be stressed simultaneously to their maximum strength in volts per centimeter.

W. I. Middleton: Considerable is to be gained by the grading of insulation of cables for very high voltages, say above

15 kilovolts, as it tends to decrease the wall of insulation and so reduce the cost of outside covering; but on lower voltages its advantage is doubtful, where grading might reduce the insulating wall to such an extent that for mechanical reasons it would be dangerous. Cables carrying from 10 to 15 kilovolts, where the copper runs from No. 1 to No. 4/0 B. & S., can easily be made with a good grade of rubber without putting too great a strain on the dielectric. Owing to the difficulty of making insulations of different specific inductive capacities when only one kind of dielectric is used, it would seem best in making graded cables to use a combination of two or more materials, such as rubber, cambric, and paper.

I am most interested in what the speaker terms " Corona in Solid Dielectrics.". I do not believe any of us knows what actually takes place in the dielectric, but as far as Professor Russell's hypothesis, that the dielectric near the conductor breaks down and becomes charred, is concerned, I do not believe it. In eight years in the testing room of a cable factory, I have never seen a cable that has shown mechanical change due to excessive voltage in either rubber or cambric insulation. I do not say that some cables may not be injured electrically by overstraining, but cables that are easily injured by voltage stress are to be avoided, as this injury shows that they have not been as well made as is possible. There is a vast difference in the characteristics of rubber compounds, which is not important for low-voltage cables, but is very important for high-voltage cables.

Now to come directly to the corona law and its application to cables, I agree to the commonly accepted formula

$$V = K\, d \log \frac{D}{d}$$

where V = test pressure.
K = voltage constant of the dielectric.
d = copper diameter.
D = diameter over insulation.

so long as the copper diameter is greater than 10/27 of the diameter over the insulation, that is, to the point where d equals $\frac{D}{2.72}$. Taking D and d in mils, we have tables showing the values of $d \log \frac{D}{d}$ for all sizes from No. 18 B. & S. to 1,000,000 cm., with walls from 1/32 to 20/32 in. on each size. We have used these tables to the critical point where d equals $\frac{D}{2.72}$, or approximately where the copper diameter and insulating wall are equal, but beyond this point the formula does not apply.

For example, when the formula demands 45/32-in. wall on a No. 14 B. & S. wire for a voltage, on which 5/32-in. wall is adequate on a No. 4/0, we know this wall is not necessary. If the formula beyond this point does not apply, what formula does apply?

Having in mind the law for corona in air and the possibility of its application to solid dielectrics, I suggested that results be worked out with a modified formula, where d is changed to d_c

and $d_c = \frac{D}{2.72}$

$$\text{so that } V = K\, d_c \log \frac{D}{d_c}$$

This necessitated working out new values for our tables, and we began on No. 6 B. & S. for walls from 5/32 to 20/32 in., 5/32 in. being the point at which the wall of insulation is equal to the copper diameter. Inspection of the new tables shows a surprising feature, namely that the new values for $d_c \log \frac{D}{d_c}$ increased about 10 for each thirty-second added to the wall, while in the old table these values showed a gradual decreasing increment. As soon as we noted this feature, we made a further study of our formula, and saw immediately that the increase in value for 1/32-in. increased wall was a constant, regardless of the size of the cable, and calculation showed this constant to be 9.9855.

The two formulas agree that there is a minimum outside diameter for a given voltage, but they do not agree in the fact that while the old formula calls for an increase in the outside diameter with a reduction of copper, the modified formula allows for a reduction of the copper with the same outside diameter.

In a previous attempt to check up the old formula, we had made tests on a series of small conductors insulated with relatively thick walls of rubber, but the results did not agree at all with our calculations. On making a comparison of figures obtained by the modified formula with the old tests, we found that they checked up in a most satisfactory manner, and the modified formula has agreed with the results of subsequent tests.

It may be interesting to mention that instead of the 45/32-in. wall required on the No. 14 wire in the example given above, we now figure that only 9/32 in. wall is necessary.

Henry A. Morss: I would like to explain in a little more general way than Mr. Middleton has done, why he has developed his formula. When we first made cables, we had no means of knowing the necessary thicknesses of insulation except by experience, and if we wanted to determine the thickness for a cable on which we had no experience, we could only guess. Then we began to learn about this formula $d \log D/d$, and found that by taking its values and multiplying by a constant, which we could determine by experiment, we could arrive at a suitable thickness of insulation for any voltage. This worked very well, and we were much pleased with it until we began to figure small wires for high voltages. Then, as Mr. Middleton said, we came to absurdities; that is, they were absurdities to the extent that we knew we needed no such thicknesses. What we have been working toward, and have been trying to get, is some rule by which our calculated thicknesses will compare properly with the thicknesses obtained by experience, and this modified formula which Mr. Middleton has developed, seems according to our experience to date to enable us to figure these thicknesses which we could not figure before.

R. W. Atkinson: Assume as true (as seems probable) the author's theory that the overstressed portion of the dielectric is punctured in " needle points " and that the potential across this portion remains equal to that required to cause breakdown. Now the current across this portion is greater than the charging current at this voltage. The extra current is conduction current and is at right angles with the charging current and in phase with the voltage across this portion. The resultant current is then less than 90 degrees ahead of the voltage. Hence when this voltage combines with the voltage across the remainder of the insulation, the resultant is less than the numerical sum. The net result is that the capacity is greater than would be calculated by the method suggested by the author and used as a basis for curve *c* in Figs. 10 and 12. This difference would not however be marked until the voltage is considerably higher than that which causes partial breakdown and would not be observable at all on ordinary cables with the usual insulation thicknesses, since there is not so marked a difference in the maximum and minimum stress as to make it possible to raise the voltage greatly above that causing partial breakdown.

Another thing which might be expected in the test is an increased dielectric loss when the conduction begins. It would be impossible to predict the amount of this since it is quite possible that the voltage across the needlepoint punctures is reduced considerably below that originally causing them. The destruction or carbonizing of the insulation by corona cannot be due to heat when the dielectric is uniform. Were it sufficient for this, the whole cable would heat extremely rapidly and the loss would have readily been observed in the wattmeter measurements both by the author and by Höchstädter. (In *Elec. Zeit.*) The charring of insulation by discharges where there are air spaces is of a different nature.

H. W. Fisher: I will not attempt at this time to discuss the mathematics of the paper, but rather the experimental part in the light of recent investigations and reason.

During considerable experimental research work, I have never had any evidence which would lead me to the belief that the insulation next to the conductor in an overstressed cable becomes charred. It has been impossible to manufacture a cable whose insulation at all points will have an equal resistance to disruptive voltages. Hence, for sometime, I have believed that breakdowns of over-stressed cables must be caused, in the first place, by a gradual puncturing of the insulation around the conductor at the weakest point.

A knowledge of the characteristics of manufactured insulations leads one to the belief that an absolutely continuous disintegration of overstressed portions is impossible, and therefore, until an actual breakdown between conductor and sheath occurs, this action of isolated discharges must take place more or less all along the conductor.

I have noticed for many years that glass, overstressed at points by local discharges, breaks down under voltages much below what would ordinarily be considered safe. Generally, but not necessarily so, the glass is found to be cracked and I have been inclined to believe that the localized stress started a small crack through which a puncture immediately followed. The behavior of glass under localized electric stress very strongly accentuates my belief in the correctness of the author's conclusions as to isolated discharges along the conductor.

Had other materials, such as a paper insulated conductor inside of a hard rubber tube, been used, I doubt very much if the difference between the normal puncture voltage of the hard rubber tube and that of the improvised cable would have shown anything like the difference found in the case of the glass tube specimen.

It must be remembered that in the tests under consideration, the materials used were chosen so as to accentuate the stress on the insulation next to the conductor. Therefore, in the case of a regular high-voltage cable, it is more difficult to determine what actually happens to the insulation if overstressed.

In a series of papers recently published in the *Elektrotechnische Zeitschrift*, Mr. M. Höchstädter gives the results of tests which show that the power factor increased very slightly with increase in the applied voltage, and that even at the puncturing voltage, there was no sudden increase of dielectric loss, which we would expect if there were a large number of discharges through the insulation near the conductor. Moreover, the general properties of the cable did not seem to be changed up to the instant when a puncture occurred. In the cable under consideration, the size of the conductor and thickness of insulation were such that the stresses on the insulation at the conductor would not be abnormally high compared with those on the insulation near the lead, and this may be the cause of the results obtained.

It would be interesting to make tests on an ungraded cable having a small conductor and considerable thickness of insulation and note if the dielectric loss increased rapidly when the insulation near the conductor began to be overstressed. Such a test I have had under consideration for some time.

One important fact must not be lost sight of, namely, that for mechanical reasons cables often have a thicker insulation than might seem necessary for the voltages under consideration.

The proper grading of the insulation of high-voltage cables is certainly of the highest importance and every up-to-date manufacturer will have his own way of doing this.

Percy Thomas: I will only add one suggestion. So far in the present discussion one of the very important elements governing the actual breakdown of insulating material has been practically omitted, that is the effect of temperature. Broadly speaking, in insulating materials, especially in some sorts of insulating material, an increase in temperature beyond a certain point, not far above ordinary atmospheric temperature, means a very great decrease in insulation resistance and more troublesome still a very considerable increase in the energy loss within the insulating material itself. The results of this fact may or may not actually be a serious matter, depending upon conditions.

Take for instance a comparison between the breaking down strength of a sheet of varnish covered paper one one-hundredth of an inch thick and the breaking down strength of fifty of those sheets piled together. The single sheet will stand perhaps 10,000 volts without trouble if the electrodes have not too sharp edges. Fifty of these sheets may very likely stand continuously not over 50,000 volts. This value might be a little higher if the material were well dried. Now as the number of sheets is multiplied by fifty and the breaking down voltage only by five there is a loss of possibly ten to one in the capacity of each sheet to withstand voltage. This effect is largely a result of the increase in temperature within the body of the material, not necessarily throughout the material, but at some particular spot or spots or layer. The higher temperature means that the energy loss will be larger which larger loss will cause the temperature to rise and this rise in temperature again increases the local loss of energy at that particular location and so on up and up. The heat resisting character of the material prevents the dissipation of heat fast enough to keep the temperature down. The result may be the entirely confined to one portion of the insulating material near the center, while the rest may be entirely uninjured. I have often observed such effects. Of course, extreme results are to be expected only under favorable conditions as where the insulation is very thick and has naturally a high energy loss under voltage stress.

This trouble is not met with in cables with the usual thicknesses of insulation under ordinary conditions, because they are used so far below the breaking down point of the insulation that the energy losses are not sufficient to produce a material rise in temperature. It is only as we approach very close to the puncture point that the critical rise in temperature is found.

I think that it may be very likely that in the experiments described in this paper this local heating had a very important part in the final result, but it would be practically impossible to trace out this fact afterwards. I am not familiar with the thicknesses of material used, nor with other conditions of the test.

In tests of this sort, the time of application is of course extremely important as a certain elapse of time is necessary to cause a rise of temperature. The difference between the application of a static stress lasting but momentarily and a continuous application of alternating voltage is of course extreme.

The phenomena accompanying the case of two or more layers of insulation with a slight enclosed amount of air between, is a difficult one; but doesn't it seem probable that the heat generated in the thin layer of air by the fact that its insulation strength is overcome and the ions and corpuscles are freely moving therein and therefore generating heat, has much to do with the very serious weakening the total insulating strength of the combination found to accompany the presence of air layers?

If we were nearer the breaking down strain in cables, the effect of I^2R in the cable itself, due to the useful current flowing through the copper might be important. Fortunately, however, the cable has too good a radiating power for this loss to be critical, except possibly in the case where the grounding of one leg of the circuit occurs or excess voltage from some other cause subjects the cable to almost the puncture stress.

Possibly the effectiveness of the needle points in puncturing glass is very much emphasized by the point Professor Franklin has brought out, namely that we may easily have a minute crack started in this material. Now this crack is very likely due to the concentrated generation of heat, due to the extremely local application of potential by the needlepoint. Rapid heating of the glass at one spot would be almost sure to crack the glass at this point, the physical weakness of glass in that respect making it particularly vulnerable. This difficulty would not be found to the same extent in rubber or paper or cambric.

C. J. Fechheimer: The conditions which obtain in alternators are somewhat different from those which apply to cables, bushings and transformers, inasmuch as, due to mechanical considerations, we are practically compelled to place the conductor in a slot which is usually rectangular in section. The ideal condition, from the standpoint of insulation only, would be that of a round slot by means of which we would eliminate sharp corners on the coils. This, however, is impracticable.

In order that we may use as economically as possible the most valuable space in high voltage generators—that is, the stator slots—we often use conductors which are square or rectangular in section and to avoid the stress in the dielectric at the corners of the coil reaching too great a value, the corners of the conductor are usually rounded.

It has often been contended that it is inadvisable to use mica for slot insulation and many engineers prefer only the use of cloth treated with some form of insulating varnish, but, as has been shown so well in this paper, it is extremely advisable to grade the insulation; that is, place mica or some other dielectric having a high specific inductive capacity near to the conductor and some other dielectric, such as varnished cloth, having a specific inductive capacity of about half that of mica, on the outside of the coil.

This grading of insulation enables us to use a smaller quantity and we thus can place more copper in the same size slot than we could if we used only varnished cloth for insulation. This also has the additional advantage that with a thinner insulation the heat can flow more rapidly from the conductor to the outside of the coil; and furthermore the mica, being near to the copper, is subjected to the highest temperature, and this material has the inherent property of being able to withstand high temperature far better than any kind of cloth.

The great advantage to be gained by placing the material having high dielectric strength, as well as high specific inductive capacity, next to the copper was brought out by Professor H. J. Ryan in his paper on " High Pressure Insulation " at the Electrical Congress in 1904, although he is inclined to believe that " structural requirements make impracticable . . . . . the placing of the most powerful dielectric next to the conductor ".

We have since found, however, that we can without great difficulty surround the conductors with flexible mica and then use as a binder the varnished cloth or linen tape. A coil which was recently made on this principle in accordance with Mr. H. Pikler's advice, was wound with No. 8 B. & S. square wire having a radius on the corners of 0.026 in. The coil, after winding, was vacuum treated and was then wrapped with two layers of 0.012 in. flexible mica and then with two layers of 0.009-in. varnished cloth and one layer of linen tape. The coil was dipped in insulating varnish a number of times between wrappings. When subjected to a high-voltage test, this coil withstood a puncture test on one side of 29,000 volts and on the other side of 30,000 volts, these being effective values of voltage with a sine wave.

I was in hopes that I might reduce the density of dielectric flux at the corners, and thus increase the break-down voltage by placing tinfoil around the conductor, and also between the mica and varnished cloth and therefore had a coil wound similar to the one described above with the exception of placing tinfoil as stated, but found that this coil broke down at 16,000 volts; and another coil, which had tinfoil between the conductor and mica only, broke down at 20,000 volts. Violent brush discharge indicated that the insulation was highly stressed before breakdown.

It would appear to me that the tinfoil has the effect of increasing the electrostatic capacity of the layer of mica and decreases that of the varnished cloth as implied in this paper, thus raising the potential gradient in the varnished cloth and decreasing it in the mica, causing the varnished cloth to break down, which resulted in the mica taking all the stress, and this broke down soon afterward. Had the tinfoil between layers of insulation proven a success as far as increasing the breakdown voltage was concerned, I would have expected trouble from eddy currents in the tinfoil due to changing in interlinkages with magnetic flux. This I thought I might be able to overcome.

In this connection I would call attention to the following statement in the paper: " Since these electric strengths are limited at present, in the manufacture of cables to very few values, they are not properly considered variable ". From the data which I have available, it is my impression that the dielectric strength of. mica in volts per millimeter is nearly twice that of varnished cloth; so that for the ideal grading of potential we should be able to have the stress in the mica, in volts per millimeter, practically twice as great as in the varnished cloth. In fact, it appears to me that for ideal grading of insulation we should have the ***maximum potential stress in each dielectric proportional to its breakdown voltage.***

I would call attention at this time to a slightly different conception of the problem than that given by the author in his paper. As stated by Professor Ryan and others, the breakdown of insulation results from the density of dielectric flux reaching a certain critical value just as in the case of material in tension or compression, a rupture occurs when the stress expressed in pounds per square inch, or similar units, reaches a certain critical value. It would seem that this view would give a clearer physical conception of the phenomenon than that of considering the breakdown to be due to the potential per unit thickness reaching a critical value. After all, as Dr. Steinmetz states in his book on " Transient Phenomena ", the potential is merely a mathematical fiction which is taken to be a measure of the electrostatic field, and we should therefore consider the stress in insulation to be due to the dielectric field rather than to the potential. Of course, for mathematical analysis it is far easier at present to treat the subject from the standpoint of potential rather than from that of dielectric flux.

From my point of view it appears that two dielectrics having equal strength expressed in volts per millimeter, but having different specific inductive capacities, the dielectric having the higher specific inductive capacity transmits more dielectric flux for the same difference of potential per millimeter and therefore its stress expressed in lines of dielectric flux per square centimeter is the greater.

If, as in the case of cables, we place a dielectric having a high specific inductive capacity next to the conductor and a somewhat lower specific inductive capacity dielectric outside of this first dielectric, then the first dielectric has the greater stress expressed in lines per square centimeter, although the volts per millimeter may be the same as in the outer layer of insulation. The effect of the outer layer in addition to taking part of the stress, is (due to its lower specific inductive capacity) to prevent as great a flow of dielectric flux as would be the case if all of the insulation were made up of the insulation having the higher specific inductive capacity.

G. I. Rhodes: This paper on potential stresses brings out three points to which I wish to call attention: the so-called corona effect, the value of graded insulation and the effect of heating by the load.

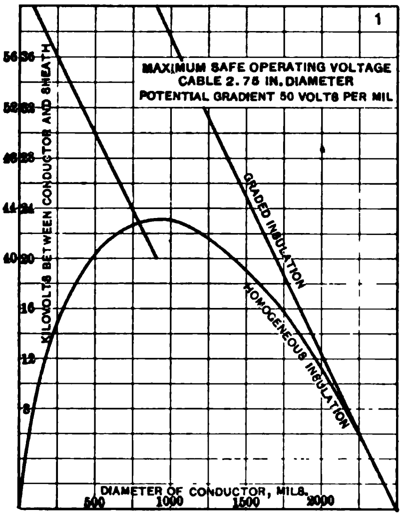

FIG. 1

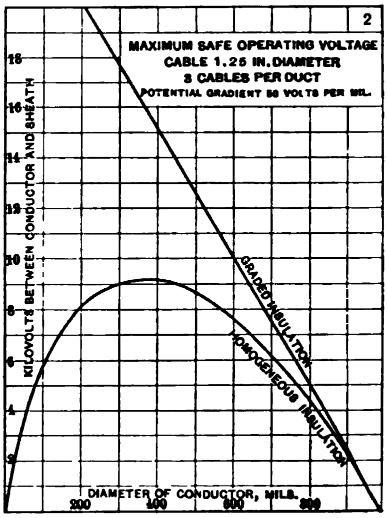

FIG. 2

The theory offered in the paper for the deterioration of insulation under excessive voltages, has an interesting bearing on the test voltages which should be applied to cables. These over-voltage tests are now applied on high tension cables at twice the working voltage for a period of 60 seconds.

When underground cables were first used, dielectric tests were frequently applied at voltages as high as three times normal for periods as long as half an hour. Breakdowns occurring during these tests usually happened within the first minute, but at times the cable held up for almost the entire test period. These breakdowns occurred with no apparent weakening of the rest of the cable.

The needle point deterioration, as explained in the paper, accounts for this phenomenon. If the deterioration was general these high voltage tests would have weakened the entire cable. The theory of failure in a gradually extending needle point explains both the time element and the apparent absence of damage to the rest of the cable.

In Table I the author gives an idea of the maximum voltages for which cables can be built. The limit of size is the maximum that can be drawn into a three-inch duct. I wish to call attention to the fact that high voltage is not necessarily the criterion by which to judge the value of a cable. In the future development of high tension underground transmission, it is probable that in addition to high voltage, a large safe load per duct will be called for. A small percentage loss will also be a factor. The cable will then be valued in proportion to its ability to carry load and inversely as the percentage loss at the maximum safe load.

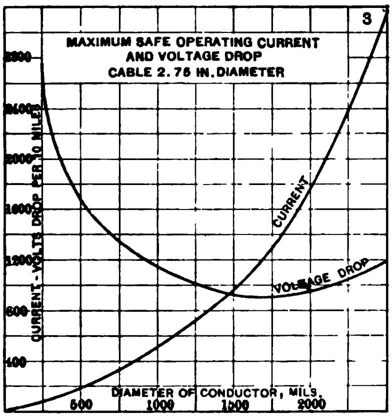

FIG. 3

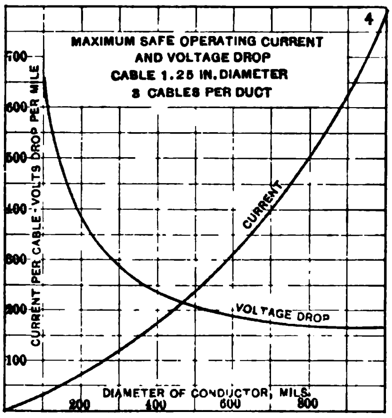

FIG. 4

I have prepared some curves, showing roughly the voltages, loads, losses, etc., in cables. The first type of cable considered is as large a single conductor as can be drawn into a standard duct. The second type is a single conductor, so large that three can just be pulled into a standard duct.

Fig. I shows the relation between permissible operating voltage and diameter of conductor in a cable of the first type. The figures are based on equation (2) of the paper. The voltage gradient of 50 volts per mil is safe for paper insulation. Curves are shown both for homogeneous insulation and for the ideal grading. It will be observed that there is a definite maximum voltage for homogeneous insulation, which obtains with a conductor diameter about 40 per cent of the total outside diameter of insulation.

Fig. 2 shows the same curve for the second type of cable, three to a duct. This type of cable was taken rather than the usual three-conductor cable, to simplify calculations. The results should not be very far different. It will be observed that the maximum voltage for homogeneous insulation again occurs at a conductor diameter of 40 per cent. The total actual value of the maximum is reduced by the small diameter of the cable.

Fig. 3 shows the maximum safe current in the 2.75-in. cable and the voltage drop due to this current. The effect of the relatively low heat conductivity of the insulation is taken into account. These curves are only roughly approximate.

Fig. 4 shows similar curves for the 1.25-in. cable. Here the currents are smaller, but current densities larger than in the previous case, principally on account of the thinner insulation.

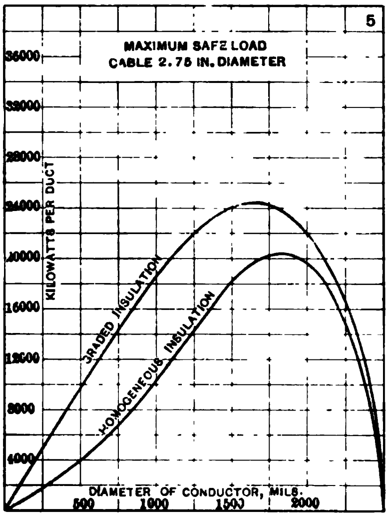

FIG. 5

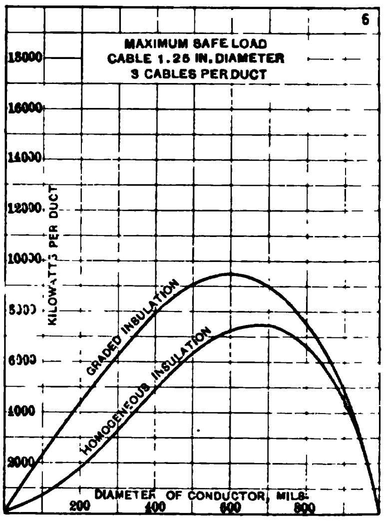

FIG. 6

Fig. 5 shows the relation between conductor diameter and maximum safe load on a 2.75-in. cable for the two kinds of insulation. It will be observed that the improvement due to grading the insulation is less here than on the voltage curves. The maximum loads require larger conductor diameters than the maximum voltage. This best diameter is approximately 70 per cent, instead of 40 per cent.

Fig. 6 shows similar curves for the smaller cables, three in a duct. Here the same general characteristics are seen as for the larger cable, except that the best conductor diameters are slightly lower.

Fig. 7 shows the percentage heating losses per mile in the large cable for the two types of insulation. Here the best conductor diameters are lower than for maximum load.

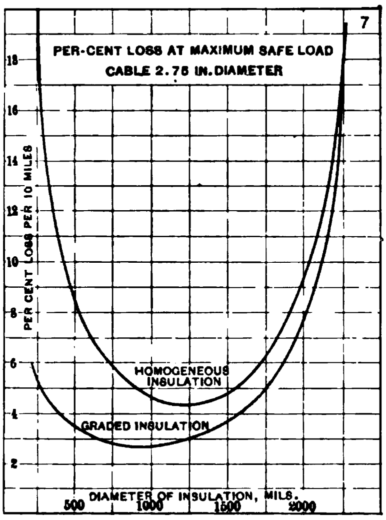

FIG. 7

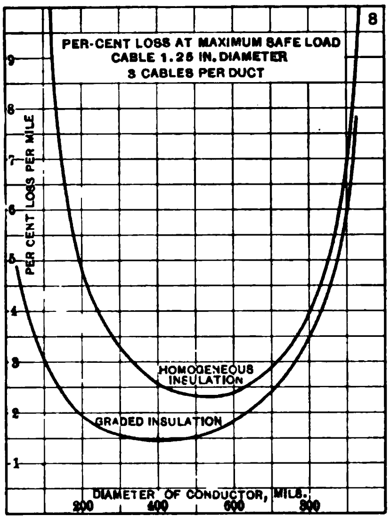

FIG. 8

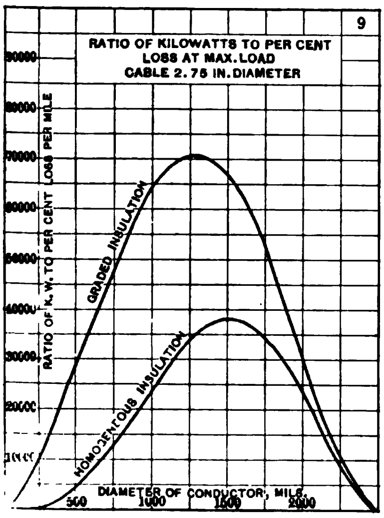

FIG. 9

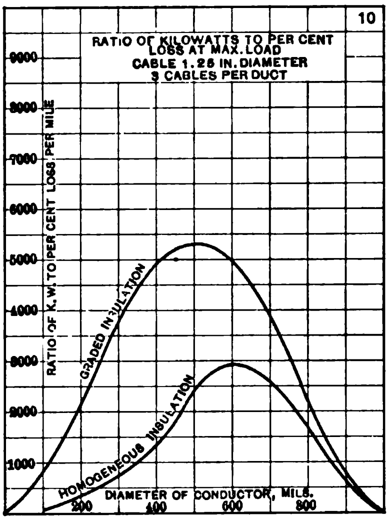

FIG. 10

Fig. 8 shows these same curves for the smaller cables. The effect of the high current density and the low voltage make the losses relatively high.

In Fig. 9 there are combined the loads and the losses, to get the measure of the value of the cable described at the beginning of this contribution. It is seen that the best diameter of conductor is from 50 per cent to 60 per cent of the total. Grading the insulation improves the cable about 80 per cent.

Fig. 10 gives similar curves for the smaller cables. It is seen that small cables are very much less desirable than the large. This is due to the lower maximum load and the larger losses.

To summarize the curves, it thus appears that the voltage to give the maximum capacity per duct is that corresponding to conductor diameter 70 per cent of the total, allowing 6,500 volts for the three cables per duct and 18,000 volts for the large cable. The benefit from grading the insulation is small. For minimum drop the conductor diameter is about 45 per cent, corresponding approximately to the highest voltage permissible with uniform insulation, 9,000 volts for the three phase cables and 23,000 for the large, single conductor cable; the improvement due to grading being 60 per cent in such case. The best all-round cable is assured with a conductor diameter of about 55 per cent, corresponding to voltages of 8,000 for the three small cables, and 20,000 for the large single cables. The gain, due to grading is about 80 per cent.

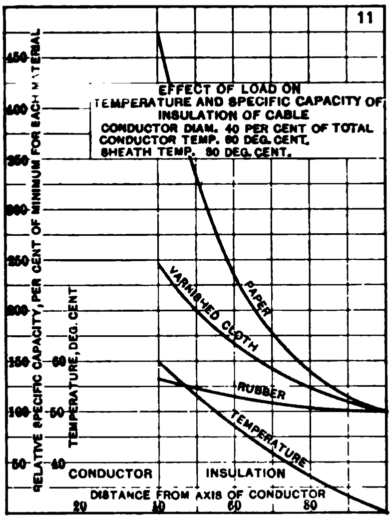

Fig. 11

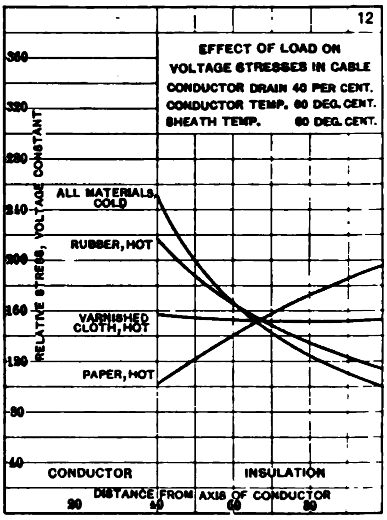

Fig. 12

If other than the maximum loads are to be considered, curves of somewhat different characteristics are obtained. These curves show only maximum conditions. They show the cable that will transmit the maximum amount of power per duct with the minimum loss. Other considerations are neglected.

In the paper the effect of the temperature gradient in the insulation is mentioned, but no figures are given. Figs. 11 and 12 show the magnitude of this effect. They are based on data published by one of the large manufacturers of cables. Fig. 11 shows the variation of temperature and specific capacity of the dielectric with distance from the sheath.

The material used has a very great effect on the capacity distribution. Fig. 12 shows corresponding voltage stresses with a constant potential difference between conductor and sheath. The three materials considered show very well the effect of the temperature on the distribution of the strains. Rubber, which has a very small capacity temperature coefficient, shows very little change. Varnished cloth, which has a considerably larger coefficient, has a potential distribution corresponding closely to that in a perfectly graded cable. Paper, which has a still larger coefficient, shows a reversal of stress, so that the greater potential gradients are near the exterior of the insulation. This effect represents overgrading. If the safe voltage with a cold cable is taken as 100 per cent the safe voltages, after heating due to load as shown in the curves, are 118 per cent for rubber, 160 per cent for cloth, and 128 per cent for paper. It is thus evident that the cable is safer when cold, the factor of safety being greatest where the thickness and the capacity temperature coefficient of the insulation combine to produce ideal grading. If the temperature coefficient is too great, the stresses are inverted and then there is less improvement due to load.

If the cables are to be graded at all, this grading should take into account the temperature distribution in the dielectric, so as to produce the safest cable under conditions of full load.

Armin Henry Pikler: The author in his very interesting paper properly started with quoting Maxwell. The fundamental phenomena in connection with dielectrics were observed by Faraday and the laws of distribution of the electrostatic flux in the dielectric of condensers of various configurations and finally the capacities of condensers of various configurations were given by Maxwell.

The results which Maxwell arrived at were not utilized for practical purposes until the necessity arose for them. It seems natural that the cable manufacturers, who were most pressed for room for insulation of cables, made first use of them. It was Professor Jona of Italy, who first made practical use of the idea of potential gradient and the grading of the insulation of cable.

From the analysis of two equations, the practical requirements for insulation between conductors arranged concentrically can be seen at once. From the equation: Potential difference equals charge divided by capacity, it will be seen that in condensers connected in series the one having the smallest capacity will have the greatest difference of potential between its conducting surfaces. From the equation giving the capacity of a cylindrical condenser $C = \dfrac{K\,l}{2 \log \dfrac{r_2}{r_1}}$ it will be seen that if the dielectric between the inner and outer conducting surfaces of the cylindrical condenser be divided into concentric layers of equal thickness, the inner layers—that is, the layers of the smaller radius—offer a smaller surface to the dielectric flux than the outer layers, when a charge passes from the inner to the outer wall of the cylindrical condenser. This results in a greater dielectric flux density per unit area on the inner layers. These layers will then have a greater difference of potential between the limiting walls and will be subjected to a greater stress. If the inner conductor is of very small radius, the stress in the layer of the dielectric close to this conductor will be enormous and there may be no insulating material sufficiently strong to withstand the stresses when this conductor carries a current of high voltage.

It is the above considerations which will lead to the design of the most efficient transformer insulation. I wish to discuss this subject more particularly from the point of view of the insulation and construction of high-voltage power transformers. The ability of transformers to transmit high voltages and to withstand very high voltage strains has developed practically during the last six or eight years and I dare say that this is due, not so much to a more thorough knowledge of insulating materials and the use of new materials, as to the recognition of the great dangers of moisture in the insulation, the capability of extracting this moisture and afterwards keeping it out of the insulation.

I wish to state that I do not consider it practical to use graded insulation in transformers between the high- and low-tension windings or between the windings and the core. The introduction of metallic layers between high- and low-tension windings would result in very great complications as regards manufacturing, and the connection of these metallic layers to taps of the high-voltage winding would add a number of high-tension leads, the placing of which would be cumbersome and the insulation of which would require a great deal of room and involve expense.

The grading of the insulation of a high-voltage cable is a matter of necessity because the unequal distribution of the dielectric flux and the great difference in density of the dielectric flux between points on the inner layers and the outer layers of the cable cannot be eliminated.

In high-voltage transformers, if properly designed, this unequal distribution of the dielectric flux density can be almost entirely eliminated and therefore the grading will become unnecessary.

Moreover, while in cable insulation economy of space is highly desirable, particularly from the point of view of cutting down the thickness and weight of the dielectric, the most expensive of the materials; in transformers a certain minimum space must be allowed between high- and low-tension windings and between windings and core to serve as ventilating ducts, admitting the circulation of oil between these parts. This results in low heating and consequently reduction in weight of copper, the most expensive of the materials used in transformers. This space, which is necessary for the purpose of cooling, is in most cases of ample size for the purpose of insulating the present commercial transformers of the very highest voltages, if properly designed and constructed.

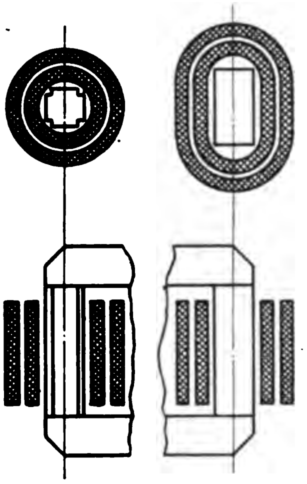

FIG. 1

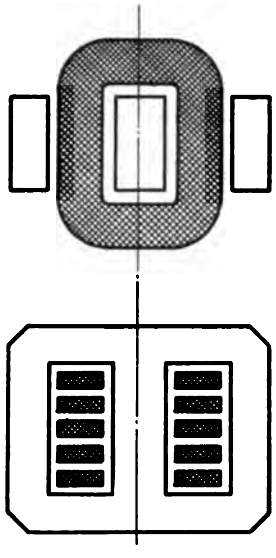

FIG. 2

The type of transformer where the distribution of the dielectric flux between high- and low-tension windings is most uniform is the one where the coils are arranged as concentric cylinders, either of circular or oval cross section. These two cylinders are placed over the sheet steel core in such a manner that the high-tension winding is outside of the low-tension winding. The opposing surfaces of these cylinders are either parallel walls or concentric circles of large radii. The percentage increase between the inner and outer radii being very small, the distribution of the dielectric flux between these surfaces will be fairly uniform and every cubic inch of dielectric will withstand the static strains in the same measure. The results will be a high factor of safety against breakdowns and economy in space and insulating material.

It will be only at the ends of these comparatively long cylinders that the density of the dielectric flux will be greater and its distribution irregular. These ends, however, being accessible, may be easily protected from breakdowns.

The type of transformer particularly adapted to employ coils and insulation as described above is the so-called core type transformer shown in Fig. 1. In contrast to this type, Fig. 2 shows another type of transformer winding, the so-called shell type. In this, the number of edges and sharp corners exposed between adjacent high- and low-tension windings and between windings and core are numerous. The dielectric flux density at these places is very great and it is difficult to insulate such windings. Nevertheless there is a great number of transformers, which employ coils of this type. The necessary insulation, however, and the space occupied by it is much greater than in the previously described core type transformer. For instance, in a 25-cycle, 2000-kw., 50,000-volt transformer of the core type construction the space factor of the windings—that is, the ratio between the total section of copper conductors to the total available winding space—will be about 27 per cent, whereas in the shell type transformer this space factor is only about 16 to 18 per cent. The consequence of this is a heavier and more expensive transformer for the shell type, about one-third more than in the case of the core type transformer. With this there also goes a lower efficiency and a worse regulation for the shell type transformer on account of the larger spacings required.

C. P. Steinmetz: This paper deals with a subject which has become very important, since the development of the electrical industry has led to the use of cables of 20,000 volts and more, and of transmission lines of 100,000 volts and over, and thereby made it necessary for us to seriously consider the phenomena of the electrostatic field. I entirely agree with Dr. Franklin, that it is of the utmost importance that we should endeavor to explain all phenomena in the simplest possible manner, and in such a manner as to get a clear physical conception of them, since only hereby it becomes possible intelligently and safely to use them. It is regretted therefore that the nomenclature and to the conceptions of the electrostatic field, electric intensity, electrostatic quantity, etc., are so cumbersome and so unamenable to giving a clear physical conception that we find it much more difficult to understand phenomena of electrostatic fields than for instance phenomena of the electromagnetic field. You can get a very simple and clear conception even of a very complicated magnetic field by Faraday's physical picture of the lines of magnetic force, and there is no reason why we should not get the same clear conception of the electrostatic field by a corresponding picture of the lines of dielectric force.

The first part of this paper deals with the question of grading in relation to cables, and the results and data given in the paper are very suggestive. But I believe we would make a mistake if we should use them as given, for the design of cables, for the reason that the conditions are much more complex than they appear from the discussion in the paper.

High-voltage cables probably never break down by their operating voltage, but they break down at a weak spot, an air bubble, a lack of homogeneity in the insulating material; or they break down by a transient over-voltage, an electric impulse of limited power but more or less unlimited voltage.

As regards the first, you see that fundamentally important in the design of cable insulation is the mechanical character of the insulating material, as thereon depends the probability of applying it without getting any weak spots or defects in it. An insulating material may have a very high specific capacity and high disruptive strength, and may therefore appear very suitable for the inner core of a cable, and still be entirely unsuitable, due to its mechanical characteristics which make it less safe to rely upon the absence of weak spots or defects in it. This very greatly limits the variety of materials which can be used.

As regards the second feature, when the breakdown is due to a transient voltage, it means that of equal importance with the two quantities considered in the paper—the specific capacity and the dielectric voltage—the *dielectric energy* of the insulating material enters into the design of a graded cable. It takes a finite amount of energy to break down a dielectric and the dielectric may be exposed to an electrostatic gradient far above the break-down gradient without breaking down or deteriorating, if the application of voltage is sufficiently short that the energy of the field is less than the break-down energy.

This makes the problem of grading very much more complex than it appears on the surface, when we consider that this latter quantity, the dielectric energy, is of equal importance to the two quantities considered, while quantitatively we know practically nothing about it.

The explanation of the deterioration of insulation when stressed beyond its dielectric strength, by the formation of pinholes, I do not consider as a hypothesis, but rather as a fact, fairly well known for some years. In the early days of the application of high-voltage cables it was suspected from the life history of these cables, that a deterioration of the insulation took place by the formation of pin holes, and evidence of this phenomenon was afforded by the investigation and study of the insulation in very high-voltage transmission systems. In those cases where the insulation had been locally strained beyond its dielectric strength under conditions where no secondary phenomena, as short circuiting arcs, had destroyed the evidence, it is common to find the surface perforated by innumerable pin holes which, in the case of a very high voltage transmission line, where the electrostatic energy is large, may reach visible size. If then the over strained insulation is perforated by pin holes, either microscopic or visible, the electrostatic field is brought to bear on the outer insulation in a concentrated form and the outer insulation is exposed to what we may call an electrostatic shearing strain. That explains the described break down of the glass tube at a voltage far below that which it would stand when exposed to a uniform static field.

This phenomenon has been described a number of times in recent years. It is shown best if you test a thin sheet of mica between a point and a plate. The mica sheet breaks down at a certain voltage. If now you put a drop of oil on the point, even a very small drop of oil, you find the mica sheet breaks down at a much lower voltage. In the first case, brush discharges spread from the point over the mica and give a gradual slope of the potential gradient. In the last case the drop of oil, by its much higher dielectric strength, cuts off the formation of the brush and brings the voltage localized to bear on the dielectric and the electrostatic shearing strain, if I may use that term, cuts through at a much lower voltage than a more uniform field would. You know that this phenomenon is guarded against in cable installations by avoiding sharp edges of the dielectric; by tapering it at the cable ends.

I agree with the author of the paper that probably the phenomena leading to the corona in air are of the same nature as the deterioration of the solid dielectric by overstrain. The corona, my experience led me to believe, also is a disruptive effect and consists of innumerable minute streamers, the same as the pin points which perforate the solid dielectrics, the difference being merely that with the air those pin holes heal again, but they do not heal in the solid dielectric.

In discussing the break down of a dielectric by an overstrain we generally assume, and I believe correctly, that there is a finite dielectric strength to air, to solid dielectrics, etc. Usually the break down is explained by assuming that if at any point in the electrostatic field, the electrostatic gradient exceeds the dielectric strength of the material, a break down occurs at that point, and then may spread further if the conditions are favorable. Since on conducting wires the maximum potential grading is at the surface of the wire, the break down should occur at the wire surface as soon as the electrostatic gradient at this surface exceeds the dielectric strength of air. Calculating, however, the electrostatic gradient at the conductor surface from the voltage at which corona formation begins—and this voltage can be determined with great accuracy—we find that this electrostatic gradient is not constant but increases very greatly with decreasing size of wires. This has been explained by assuming a layer of condensed air on the surface of the conductor. I believe I am responsible for this explanation which I gave seventeen years ago in a paper on the dielectric strength of air, and I am the more sorry to say that investigations which we made during the last months have led me to doubt this explanation.

In the pursuit of a very extensive investigation of the phenomena of the electrostatic field in air and other dielectrics —of which we may be able to communicate some of the results at the next annual convention—I began to question whether the break down in the electrostatic field does take place as soon as the potential gradient exceeds the breakdown strength of the dielectric at any point. The results rather led me to suspect a different law. "In an electrostatic field a break down of the dielectric occurs as soon as the potential gradient has exceeded the dielectric strength of the material within a volume sufficiently large that the discharge current within that volume has an appreciable value. Corona thus forms at a conductor not as soon as the dielectric strength is exceeded at the surface, but only after the potential gradient has exceeded the break-down strength up to a certain distance from the conductor which is sufficiently large that the current charging and discharging the volume of air within this distance has an appreciable, though minute value."

This explains the increase of the potential gradient with a small conductor and also agrees with other phenomena which apparently contradict the assumption of the constant break-down gradient of dielectrics.

When there is an explanation suggested as the result of experimental evidence, it is always well for a moment to set aside the experimental results and reason what we should expect from the known properties of things.

When a break down occurs in a dielectric it means that in that broken down space a current flows. Now what are laws of current flow in air or other gases or in those materials which are used as insulating materials, in solid dielectrics. We find that the effective resistance is not a constant but is a function of the current density and has an enormous negative coefficient; that is, the resistance increases enormously with decreasing current density, approaching or tending towards infinity for zero current.

Now you see what could follow from this. If the break-down strength is exceeded at one point or a very small volume, the dielectric may be stressed beyond breakdown, but there can not yet be a current flow, since that current would be so small that the resistance of the material is too high, that is, gives a higher potential consumption than the potential gradient available in that space. You must first break down a sufficiently large volume to bring the resistance of the dielectric down sufficiently to pass the current. Thus the very phenomena which I outlined above should be expected from the laws of gas conduction and from the laws of the conduction of those dielectrics which are used as insulating material.

To conclude, I desire to congratulate the author, not only on the very important results which he has communicated to us, but also on the very scientific manner in which he has given the results of his investigation by stating the experimental facts, as such and without detracting from their value by giving instead of the facts their interpretation by some prevailing theory or speculative hypothesis.

C. O. Mailloux: The remarks made by Mr. Thomas caused me to recollect some interesting experiments which I made thirteen years ago. I had gone to Vienna to investigate a certain insulating compound. I utilized there the facilities placed at my disposal by Professor Grau of the Technical High School of Vienna. Together, we made some experiments for the purpose of demonstrating and determining approximately, (which was all that was possible, with the crude methods and knowledge at that time available to us), the relative resistance to puncture of different insulating substances. The particular compound which I was investigating specially was a mixture intended to replace and to constitute a substitute for gutta-percha. Hence I naturally compared it with gutta-percha. Inasmuch as that compound was intended to be used largely for making cables, I also compared it with several other compounds which were then on the market, notably the " wax " compounds used by Siemens & Halske for high-tension cable insulation. We made some experiments by taking sample sheets of the material of varying thickness, from a half a millimeter to seven or eight or even ten millimeters thick, and maybe from ten to fifteen centimeters square. We subjected these samples to puncture tests by placing them in the spark-gap of an electrostatic machine. As nearly as we could estimate, with the facilities we had, we were able to raise the pressure to as high as 50,000 or 60,000 volts, and to reduce it to 10,000 or 15,000.

The usual method of procedure was to lay the plate of material flat on a plate of metal forming one electrode or sometimes on a point, that is, allowing it to rest on one of the electrodes. We used vertical electrodes of various forms, some of the needle-point variety, some of the " knob " variety. We placed the electrodes near to or far away from the sample, according to the case, but always had the conditions the same for each set of experiments. By raising the voltage we could increase the stress; and, usually we would keep up the stress until puncture took place or until we found that the voltage was insufficient for the particular case. It should be stated that the pressure used was usually sufficient to cause brush discharge and sparking discharges over and around the edges of the sample. Now, I observed repeatedly that before puncture took place in any of the waxy materials, or in any compound, (*i.e.*, any " made-up " compound) there was always a slight preliminary *pitting* produced at the point where the puncture was to occur. After that pitting action began the puncture would occur generally (perhaps invariably), in a very short time. The idea occurred to me that there must be two actions here—a mechanical action, and a thermic action. So we tried the experiment of stopping the test before the puncture took place. First, by a series of experiments we determined that a puncture would take place in so many seconds or minutes, as the case night be, with the application of a certain voltage; *i.e.*, we had found out what pressure was requisite and how long it must be kept up in order to produce punctures. I came to the conclusion that the puncture took place at a certain point which was first ***heated*** either by the passing of a very weak current resulting from dielectric hysteresis or by some slight conduction-current actually passing through the plate, which had the effect of heating it slightly. The moment it heated, the resistance decreased very greatly as is the case with all insulating materials of that kind, thereby allowing a still greater amount of current to pass through. Suspicious that this might be the explanation, we tried the experiment of removing the stress. After subjecting the plate to a high voltage for a certain short time, we would stop just short of puncture. We did that many times, and we noticed that if we allowed the plate to cool it would eventually recover very nearly if not all of its power to resist to puncture. Of course whenever pitting had already occurred the total thickness of the sample was diminished at the pitted point and consequently less pressure and less time were required to produce puncture. This led me to believe that the puncture took place, when it did occur, as the result of a lowering of the resistance which allowed the dielectric resistance to fall to such a point that actual conduction took the place of electrostatic conduction.

Another point which I wish to call attention to is that, in Europe, at least, there is a quantitative estimate or measure made of the difference in the breaking down ability of alternating current and direct current. At the Marseilles Electrical Congress in 1908 the question came up before the Section at which I presided, and, at the request of one of the members, I appointed a committee to interview the various cable manufacturers represented at the exposition or at the congress and ascertain from them what difference, if any, they would make in the margin of allowable potential if the current used were a direct or continuous current instead of an alternating current. One of the reasons which led to the discussion of this subject and to the appointment of the committee was an interesting exhibit made at Marseilles in which an alternating current of very high potential, something like 100,000 volts, was commutated and then applied to a cable. I believe the manufacturers dared anybody else to try such a voltage on their cables and especially to try it in the alternating-current form. The next day after the committee was appointed it reported at the meeting of the session; and my recollection is that every cable manufacturer had stated that a much higher voltage would be allowed if the voltage were "direct-current." The figures are probably to be found in the official report of the discussions before that section (*i.e.*, Section II) of the Congress. My recollection is that the figures ranged from one and one-half to two or more times the voltage. In other words, the cable manufacturers were willing to allow from fifty per cent to one hundred and fifty per cent more voltage in the form of direct current than of alternating current. The discussion of the report of the committee led to an expression of opinion by several members familiar with this subject, to the effect that the strain produced by an alternating e.m.f. is at least proportional to the maximum value of the potential difference during each cycle, if not greater.

Tracy D. Waring: In the development of any theory it is well, and generally necessary, to begin with the simplest assumptions. The simplest theory of graded cables assumes that, for a given insulating material, we may assign to it a *definite* resistivity and a *definite* electric permitivity, or to speak in terms more familiar in the practice of cable engineering, the theory of graded cables requires that we know, for each insulating material, the value of those electric quantities with which the ideas of insulation resistance and of electrostatic capacity of cables are associated.

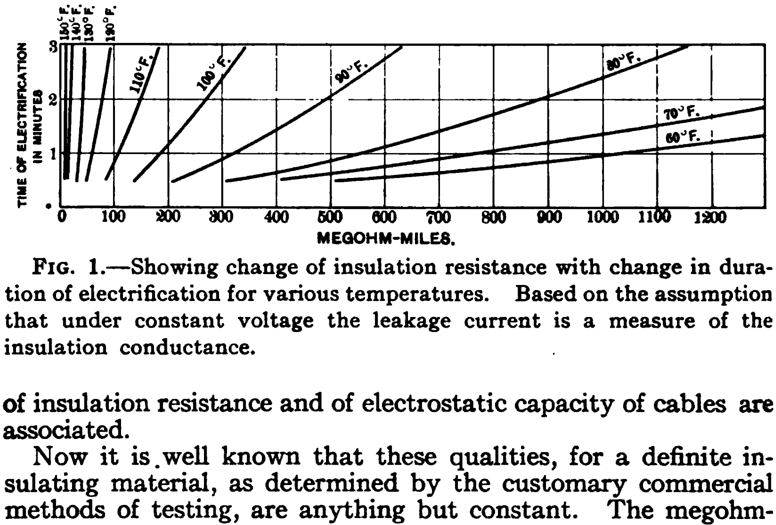

FIG. 1.—Showing change of insulation resistance with change in duration of electrification for various temperatures. Based on the assumption that under constant voltage the leakage current is a measure of the insulation conductance.

Now it is well known that these qualities, for a definite insulating material, as determined by the customary commercial methods of testing, are anything but constant. The megohm-miles and the microfarads per mile for a given cable vary with the time of electrification and with the temperature.

Figs. 1, 2, 3 and 4, derived from tests on rubber insulated wire may be taken as typical of the change of insulation resistance and of electrostatic capacity with change of temperature, and different durations of electrification or charging.

It is worth while to consider how far the electrical qualities thus determined are applicable to the theory of grading, both for direct current and for alternating current voltages.

Under constant voltage the insulation resistance increases very considerably with the duration of electrification, (see Fig. 1) but at a different rate for different insulating materials, so that for a graded cable, made with layers of different materials, the potential gradient from conductor to sheath cannot remain unchanged after the voltage is applied and in fact it may be hours before a steady state sets in. Evidently also, under direct current voltage, the voltage gradient changes with alterations of temperature; for the insulation resistance of different materials have different temperature coefficients, so that, for a graded cable subjected to direct-current voltage, the voltage gradient in the various layers would be different at different temperatures.

Under present industrial conditions, however, the chief practical interest pertains to grading for alternating voltages, and in view of the curves in Fig. 1. it may well be asked whether the insulation resistivity under alternating voltage is of a magnitude any where near that usually ascribed to insulating materials, such, for instance, as the figures given in the paragraph following equation (9) for rubber and for paper.

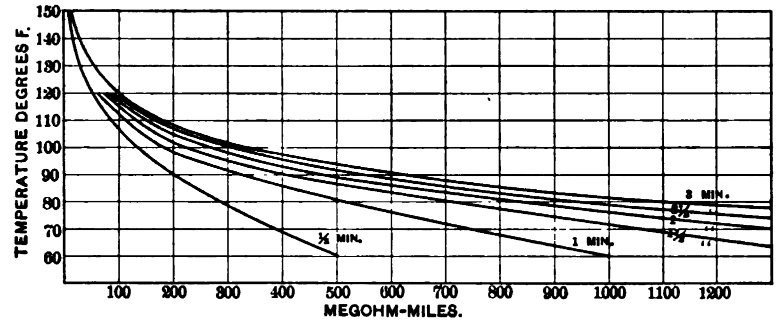

FIG. 2.—Showing change of insulation resistance with change of temperature for various durations of electrification. Based on the assumption that under constant voltage the leakage current is a measure of the insulation conductance.

Note in Fig. 1 how extremely low the resistance is for a short period, say one-half minute, as compared with three minutes. One is tempted to exterpolate at the lower limits of the curves and assume that, for very short intervals of electrification, say for one-half a cycle of alternating current, the resistivity of the dielectric would be extremely low, so low in fact as to make the resistivity and not the electric permitivity the determining factor in the voltage distribution in the dielectric, and thus to contradict the statement, " that in ordinary cases the conductance is negligible."

Exterpolation is, however, extremely dangerous and definite experimental figures for resistivity for short periods of electrification should be demanded to decide this question. A limiting minimum value for the " ohmic " resistance of a cable under alternating-current voltage may be obtained from a consideration of the dielectric energy losses under known voltage and charging current. It is to be borne in mind, however, that the figure thus arrived at is simply the equivalent effective resistance and is not the true resistance, for the greater part of the dielectric losses are hysteresis losses and not generally attributed to the true resistance. The true effective " ohmic " resistance cannot, however, exceed the figure thus obtained. Calculations of specific cases made on this basis generally show that the effective equivalent resistivity, although hundreds of times lower than the " ohmic " resistivity at one minute electrification, is still so high as to indicate that the resistivity is not the determining factor for the voltage gradient under ordinary frequencies.

Although (in view of dielectric hysteresis) the true effective ohmic resistivity cannot exceed the figure thus calculated, it is conceivable that at some critical instant of the alternating cycle that the instantaneous resistivity might be much less than the figures thus arrived at. That this is improbable is beautifully shown in the oscillograph records presented by Höchstädter[1] and as pointed out by him it is an extremely interesting fact that, in spite of dielectric losses during the cycle, that at the exact instant when the applied voltage was at its maximum the current was zero, from which it may be concluded that, at the instant of greatest danger to breakdown, it is not the resistivity of the insulation which determines the voltage gradient.

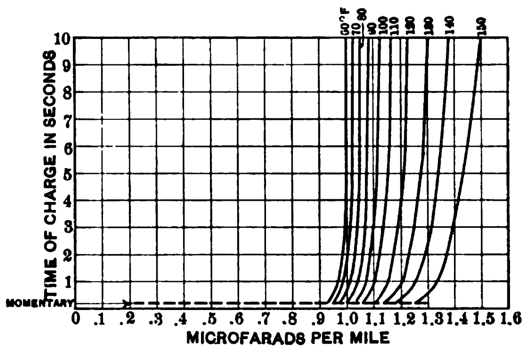

FIG. 3.—Showing change of electrostatic capacity with change in duration of time of charging at various temperatures. Based on the assumption that the discharge measured by the throw of a ballistic galvanometer is a measure of the electrostatic capacity.

I think it may be said, however, that we know very little of the true resistivity of dielectrics under extremely short periods of electrification, the displacement current and the leakage cur-

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[1] *Elek. Zeit.* May 12–19–26 and June 2, 1910. The results referred to were obtained on impregnated paper insulated cables. Tests on other materials might lead to different conclusions.

rent being difficult to differentiate, and I believe the dielectric losses under the same condition have never been analyzed experimentally into conduction losses and hysteresis losses.

Consider next the electrostatic capacity tests as shown in Figs. 3 and 4. The length of time designated as " momentary " refers to the mere tapping of the charging key thus charging the cable for a brief period and immediately discharging it through a ballistic galvanometer.

The capacity thus measured might be expected to give a suitable figure for calculating the charging current under alternating voltage. It has often been remarked however that the capacity calculated from the mean effective charging current and voltage does not accord with the capacity measured ballistically. It has been shown experimentally by Höchstädter, from oscillograph records of tests on paper cables, that the discrepancy disappears if the capacity be calculated from the maximum instantaneous value of the voltage and from the charge in the cable at that instant. This agreement only holds, however, for capacities measured ballistically at rather low temperatures. As a matter of fact the experiments just referred to showed that the electrostatic capacity measured by the charging current is constant, and independent of the temperature. That is, it may be inferred that the electric permitivity is a true constant independent of the temperature and does not change with the temperature at all in the way that is indicated by the ballistic capacity tests.

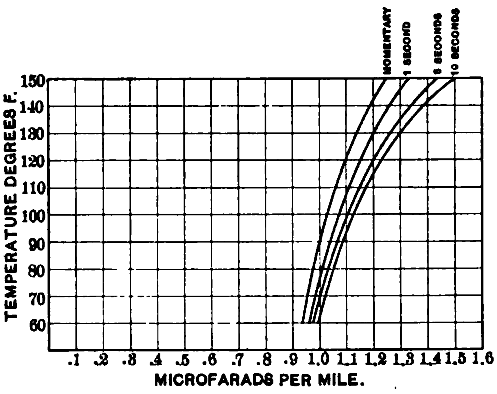


FIG. 4.—Showing change of electrostatic capacity with change of temperature for various durations of time of charging. Based on the assumption that the discharge measured by the throw of a ballistic galvanometer is a measure of the electrostatic capacity.

The bearing of this point on the grading of cable is evident since it has commonly been supposed that the dielectric permitivity varied with the temperature and thus, for instance, an ungraded cable, when heavily loaded would become automatically equivalent to a graded one, since the temperature next the conductor would be higher than at the sheath; but if electric permitivity is independent of temperature this would not be the case, and in any cable the voltage gradient in the insulation, under alternating voltage, would not be influenced by temperature. There can be no doubt that the electrostatic capacity of a cable as measured ballistically is open to grave possibilities of error on account of absorbed charge and by change of the absorption and insulation resistance with the temperature. In any event it is evident, from these and other considerations, that the so-called constants of resistivity and electric permitivity as usually determined in commercial cable testing are, in general, not to be taken as adequate for determining the actual voltage gradient in cables.

The author of the paper under discussion has admirably assisted in opening the way to a wide field of investigation, speculation and practical application.

Wm. A. Del Mar (by letter): The following comments consist of two parts, (1) a discussion of the formula presented by Mr. Middleton, and (2) a discussion of the practical application of the theory of dielectric stresses to the determination of insulation thickness in ungraded cables.

1. Mr. Middleton's discussion of this paper has given rise to a question of the greatest importance, namely, the relation between the corona theory of stresses in dielectrics and the actual phenomena which occur in a stressed solid dielectric, and opinion being somewhat divided as to whether the insulation of a cable can be stressed to destruction internally without puncture, a brief survey of this subject will be attempted.

The author of the paper under discussion gives the following well known formula for the relation between the dielectric stress, the difference of potentials between conductor and sheath and the dimensions of the cable.

$$F = \frac{V}{\rho \ln \frac{R}{r}} \qquad (1)$$

where R = outer radius of insulation.
r = radius of conductor.
ρ = distance from axis of wire to point where dielectric stress is F, when the volts between wire and sheath equal V.

This formula is based upon the assumption that the lines of electrostatic induction extend radially between the conductor and sheath and that therefore their density, or, in other words, the dielectric stress, is the greatest at the surface of the conductor, so that K, the maximum value of F is given by

$$K = \frac{V}{r \, ln \, \frac{R}{r}} \qquad (2)$$

If we keep the applied voltage and outside diameter of the insulation constant and vary the radius of the wire, we obtain

$$\frac{d\,K}{d\,r} = V \frac{\left(1 - ln \, \frac{R}{r}\right)}{\left(r \, ln \frac{R}{r}\right)^2} \qquad (3)$$

An inspection of this equation tells us that if $ln \, \frac{R}{r}$ is greater than one, $\frac{d\,K}{d\,r}$ will be negative, or, in other words, K will decrease as r increases. If we take into consideration the fact that $K = 4\,\pi\,\epsilon$ times the number of lines of induction per square centimeter, a mental picture of the above relations may be obtained by resolving equation (2) into two parts as follows:

$$K = \frac{V}{2 \, ln \, \frac{R}{r}} \times \frac{2}{r} \qquad (4)$$

and dividing by $4\,\pi\,\epsilon$ to obtain N the number of lines of induction per sq. centimeter at the surface of the conductor. Thus

$$N = \frac{V}{2 \, ln \, \frac{R}{r}} \times \frac{2}{r} \times \frac{1}{4\,\pi\,\epsilon}$$

$$= \frac{1}{2 \, ln \frac{R}{r}} \times \frac{V}{\epsilon} \times \frac{1}{2\,\pi\,r} \qquad (5)$$

In this equation the first item represents the capacity of the condenser formed by the conductor and sheath; the product of the first and second terms represents the total number of lines of induction between the conductor and sheath; the third term is reciprocal of the area per unit length of the conductor; and the product of the three terms, the number of lines of induction per sq. centimeter of conductor surface.

In Fig. A, curve *B* gives the relation between the total number of lines of induction between conductor and sheath and the conductor radius; curve *C* is the reciprocal of the conductor surface per unit length, and curve *A* is the number of lines of induction per unit area at the conductor surface, these curves being obtained from equation (5) as described above. It will be noted from Fig. *A* that curve *A* first drops owing to the slowness of the flux increase as compared with the rapidity of its surface attenuation and then rises again owing to the reversal of these conditions. There is therefore a point of minimum flux density and therefore of minimum dielectric stress and this occurs when r is $\frac{1}{2.72}$ of R.

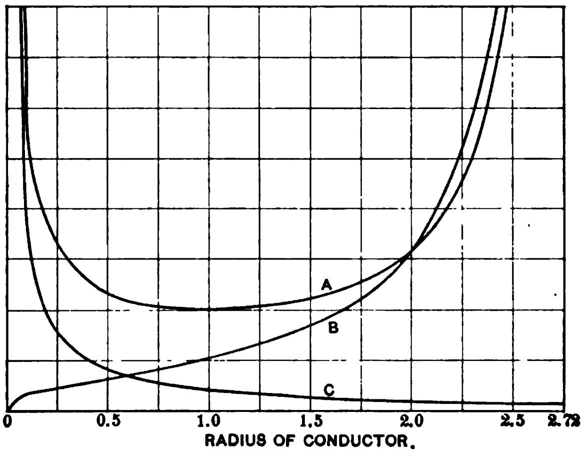


Fig. A.—Curve A: Dielectric stress, or lines of electrostatic induction per unit area. Curve B: Totol number of lines of electrostatic induction or condenser capacity. Curve C: Reciprocal of surface area per unit length

The ordinates of these curves may be regarded either as flux densities or dielectric stresses, these quantities being related by a constant ratio. The ordinates are therefore given without any specified scale in order that the curves may be used for either of these quantities.

This graphical exposition is given in order to emphasize the physical meaning of the equations under discussion. Thus in the case of cables in which $\frac{R}{r}$ is greater than 2.72 we see from curve A, Fig. A, that if the conductor were to grow in diameter, the dielectric stress at its surface would decrease until its diameter became $\frac{1}{2.72}$ of the outside diameter of the insulation, after which $\frac{R}{r}$ being no longer greater than 2.72 the stress would increase. If instead of the conductor growing in diameter, the dielectric at its surface were to break down, the effect would be the same. The stress in the uninjured dielectric where it meets the injured part would decrease until the diameter of the injured part equalled $\frac{1}{2.72}$ of the outside diameter of the insulation, after which the stress would decrease. If, therefore, the applied voltage is just sufficient to break down the layer of insulation nearest the conductors, the next layers of insulation will not necessarily break down, as the virtual increase of conductor diameter due to the breakdown of the layers will have eased the stress to a safe value. Hence in such a cable a partial internal distintegration of dielectric should be possible without a complete puncture.

Considering the case of cables in which $\frac{R}{r}$ is less than 2.72 so that K increases as r increases, a similar line of reasoning leads to the conclusion that if one layer of insulation is disrupted the next layer becomes more greatly stressed than the first and so on to the outside of the insulation, with the net result that the insulation is completely disrupted from the conductor to sheath.

Returning now to the consideration of cables wherein $\frac{R}{r}$ is greater than 2.72 and assuming that the disintegration of inner layers is unobjectionable if the outer layers remain intact, we come to the conclusion that the outside diameter of the insulation is a constant entirely independent of the size of conductor and dependent only on the applied voltage. Referring to equation (2) assume that $\frac{R}{r} = 2.72$ so that $r = \frac{R}{2.72}$ and $ln \frac{R}{r}$ becomes unity. Then

$$K = \frac{2.72\ V}{R}, \text{ or } R = \frac{2.72\ V}{K} \qquad (6)$$

This is what Mr. W. I. Middleton's formula reduces to, when his wire diameter d is replaced by $\frac{D}{2.72}$ as he requires to be done.

Now it will be observed that the establishment of this formula depends upon the admission that the inner layers of insulation are broken down without injury to the outer layers; what, therefore, does Mr. Middleton mean by saying that "as far as Professor Russel's hypothesis that the dielectric near the conductor breaks down and becomes charred, is concerned, I do not believe it. In eight years in the testing room of a cable factory, I have never seen a cable that has shown mechanical change due to excess voltage in either rubber or cambric insulation." Granting that the insulation neither chars nor breaks down visibly it would be interesting to know, first, what kind of change actually occurred in the inner layers of those cables which he tested to check the accuracy of his formula, and second, is there any physical meaning to his formula if it does not assume the partial internal disintegration of the dielectric.

Without wishing in any way to deprecate the value of Mr. Middleton's work or question its originality, I must venture to observe that Professor Alexander Russel gives this formula in his paper read November 7, 1907, before the Institution of Electrical Engineers (JOURNAL I. E. E., Vol. 40, p. 15, line 12) but that Mr. Middleton deserves our thanks for calling attention to its practical value, especially to the fact that for a given voltage the outside diameter is a constant while the copper diameter is a reducible quantity.

2. The application of the theory of potential gradient to the practical design of ungraded cables is a matter of great importance to which we will now turn our attention.

The equation (2) may be reduced, for practical purposes, to the form

$$K = \frac{0.434\ V}{r \log \left(\frac{t+r}{r}\right)}$$

where the logarithm is to the base ten, and t represents the thickness of insulation. This equation may be used to calculate the thickness of insulation required to properly insulate a cylindrical wire of known radius. If, however, the wire is not cylindrical but consists of a strand of several wires, the formula becomes more complicated owing to the irregular distribution of the lines of induction about the wires composing the strand. It has been shown by Professor Levi-Civita that stranding has the effect of increasing the stress by a factor which varies from 1.23 for thick insulation, to 1.46 for thin insulation, an average value being 1.345, so that

$$K = \frac{0.585\ V}{\left(r \log \frac{t+r}{r}\right)} \tag{8}$$

The thickness of insulation calculated by the above formulæ is inadequate because there is always a certain amount of insulation which is not effective as such. In practical cable work, it is found necessary to add an extra thickness to make up for this inevitable deficiency. The useless thickness may be analyzed as follows.

1. Eccentricity of insulation about the wire making the insulation dielectrically stronger on one side of the wire than on the other, the excess on one side over that of the other being useless.

2. Insulation in immediate proximity to the wire being likely to be abraided in bending, etc., is rendered useless.

3. Insulation next to taping being likely to contain depressions due to crinkling of tape is rendered useless.

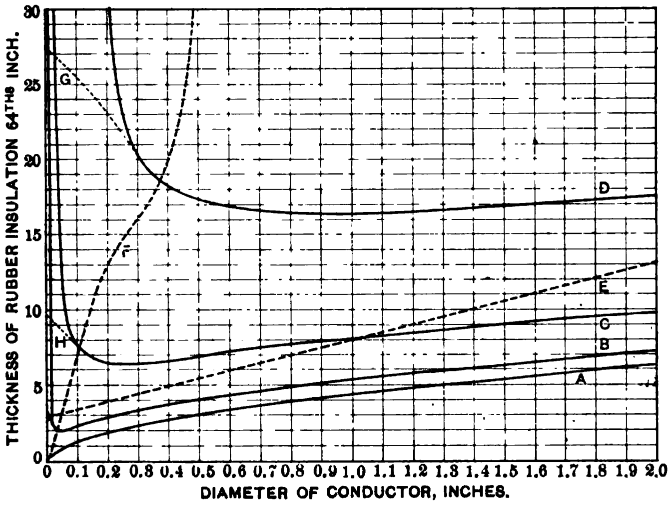


FIG. B

4. When cable is bent, the insulation on the outside of the bend is reduced. Hence, a cable when straight should have an excess of insulation in order that when bent, it may have just sufficient. This excess must, of course, be figured as useless in calculating insulation thickness on a straight conductor.

This "error thickness" as we may call the total of these quantities is a function of the size of conductor and has to be determined by experience. Curve *A* in Fig. B represents what the writer considers to be about the practical magnitude of the error thickness for rubber insulated cable.

Applying the logarithmic formula to the case of a wire insulated with rubber compound for 550 volts alternating current (or say 775 volts direct current) we obtain curve *B*, by assuming a working stress of $K = 57$ kilovolts per inch and plotting the thickness obtained by calculation, upon curve A as base so that curve B represents the electrical thickness plus the error thickness. The thickness of insulation thus obtained is, however, not sufficient to meet the requirements of practical work owing to the severe mechanical stresses to which wires are subjected. It is therefore necessary to add insulation until the amount shown on curve E is reached.

Proceeding in the same way for 2300-volt cables, curve C is obtained, part of which is below and part above curve E. With wires for this voltage the thickness of insulation is therefore partly determined by mechanical and partly by electrical considerations.

Curve D is obtained in the same way for 6700-volt cables, this being used for 11,000 volts three-phase. This curve is entirely above curve E, showing that in this case, if sufficient rubber insulation is supplied to meet the electrical requirements, the cable will have ample mechanical strength.

Curve F is the result of Mr. W. I. Middleton's discussion. It is the line of demarcation between those combinations wherein $\frac{D}{d} > 2.72$ and those where $\frac{D}{d} < 2.72$. According to the theory reviewed above, curves A, B, C and D are worthless for all points on the left hand side of curve F and the special formula which applies to the values to the left of the curve F is shown graphically by curves G, H and I.

The curves B, C, D, G, H and I are based upon a working dielectric stress of 57 kilovolts per inch at the surface of the conductor, using the logarithmic formula modified to allow for the use of a stranded conductor instead of a perfectly cylindrical one. The stress of 57 kilovolts per inch allows a factor of safety of about seven, if an ultimate dielectric strength of 400 kilovolts per inch be assumed. This is about the same factor that is used in common structural design. The curves A and E are taken (by permission of the D. Van Nostrand Co.) from tables in Appendix III of the present writer's "Electric Power Conductors."

Engineers have hitherto avoided the use of small wires with heavy insulation because they cost more than larger wires with less insulation, and it is a curious fact that the curve F, which as explained above, has a purely physical basis, also represents, to a fair degree of approximation the limit of the commercial application of the old logarithmic law, *i.e.*, those portions of the curves B, C and D which are replaced by curves I, H and G respectively give thicknesses of rubber of insulation which are commercially impracticable. The curves G, H and I, may, on the contrary, give commercially practicable thicknesses of insulation and are therefore of more than academic interest, but at present prices ($0.14 per lb. for copper and $2.00 per lb. for rubber) it is cheaper to use copper up to a diameter $\frac{1}{2.72}$ of the outside diameter than to use rubber compound on the expectation of its being disintegrated. In addition to this, the extra copper adds to the carrying capacity and to the scrap value, so that it is usually better engineering to use it instead of rubber.

The practical points brought out above in considering the thickness of ungraded insulation suggest that in designing graded insulation, the theory set forth by Mr. Osborne may have to be materially modified in practical details before it can be adopted by the cable manufacturers.

H. S. Osborne: It has been pointed out in several of the discussions that the design curves which are given in the paper will be modified by mechanical considerations and by manufacturing conditions. The necessity, which Professor Kennelly points out, for good joints between the layers of insulation, in order that excessive local gradients will not appear at those joints, seems to have been met by cable manufacturers, if one may judge from the success of graded cables. That the design may also be influenced by other conditions is suggested by Dr. Steinmetz, whose remarks concerning the effect of transient voltages permit us to hope that he intends to shed some quantitative light on that subject. It is customary to consider that the electric strength of a dielectric depends upon the time duration of the impressed voltage; and it is probable that in designing a cable to withstand transient voltages, values for the electric strengths of the layers of insulation should be used which are quite different from the values determined by ordinary means. It does not appear, however, that the energy necessary to complete the breakdown of a dielectric, after it has been stressed up to the breaking point, would enter into the design of insulation, since the aim should usually be to keep the insulation from all overstress.

Mr. Rhodes has pointed out that the voltage which a cable can withstand is not necessarily the criterion by which it will be judged, and has very clearly shown what advantage may be expected from grading a cable when the aim is for a maximum safe kilowatt capacity per duct. In most cases the aim in designing a cable is for a minimum cost with fixed voltage and current-carrying requirements, and the design is therefore fixed by a consideration of relative costs, of which no analysis is attempted in this paper. In this connection it is interesting to hear from Mr. Middleton that cable manufacturers find grading to be of value for voltages above 15 kv., though theoretically the advantage to be gained depends, not on the voltage for which the cable is designed, but upon the ratio of that voltage to the diameter of the conductor.

It would seem to be a matter for personal preference to decide whether one shall express the stress on the dielectric in terms of the electric flux density, as Mr. Fechheimer suggests, or in terms of the potential gradient. Personally, I prefer to consider the potential gradient to be the measure of the electric stress to which the dielectric is subjected, and the flux density to be the measure of the resulting strain. It is advantageous to deal with what is, from this point of view, the stress, rather than to deal with the strain, because a potential gradient is more easily measured than a flux density, and the electric strengths of dielectrics are ordinarily given in terms of potential gradient. The characteristic of a dielectric which is of primary interest is its volt-resisting ability, rather than its ability to transmit electric flux.

In remarking that " electric strengths are limited at present, in the manufacture of cables, to a very few values," the author did not mean to convey the idea that electric strengths are limited to a single value. The criterion given by Mr. Fechheimer for the ideal grading of cables is expressed in equation 5 of the paper.

Mr. Rhodes and Mr. Waring have discussed the effect of a temperature gradient in the insulation of a cable on the distribution of the electric stress. Mr. Höchstädter, to whose recent researches Mr. Waring refers, found that not only the effective capacity of an impregnated paper cable, but also what he calls the " true " capacity of the cable remained sensibly constant for temperatures between 20 deg. and 60 deg. cent., though the " static " capacity, as measured by a ballistic galvanometer, increased largely. It seems probable, then, that the effect of temperature gradient in equalizing the stress in a cable is very small, if it is indeed appreciable.

The conclusion in the paper with regard to the nature of partial breakdown in solids seems to be generally acceptable; Dr. Steinmetz, indeed, considers it to be a fairly well known fact. It is so simple and obvious an explanation of experimental results that it would be remarkable if some such idea had not been in the minds of some engineers, but it has not before, as far as I am aware, been expressed in public discussions of this subject.

In describing in terms of the electron theory the experiments reported in the paper, Professor Whitehead seems to be mistaken with regard to one of the experimental facts. The experiments in no case indicated that the dielectric could be overstressed without breakdown, but in each case the dielectric broke down when its electric strength was exceeded. Dr. Steinmetz's experiments lead him to conclude, however, that under certain circumstances the electric strength of a dielectric may be exceeded without causing any change in the material.

Mr. Thomas describes the experimental results in terms of local heating. In adopting this point of view one should bear in mind the fact that the " heating " seems to be of a different sort from that due to ohmic resistance, and is accompanied by a disintegration of the material at the point of puncture, however small may be the current which is allowed to flow. In the cases in which the authors have observed the melting and pitting of a dielectric before puncture which was remarked by Mr. Mailloux in substances of low melting point, the heating has evidently been caused by the brush discharge in the air around the electrodes.

Mr. Fisher and Mr. Thomas have both suggested that the experimental results observed would be different, or at least less pronounced, were materials other than glass and rubber used for the experiments. This may well be, and it is to be hoped that experiments will soon be forthcoming which will more completely determine the behavior of overstressed dielectrics. It does not seem probable that the *character* of the partial breakdown was due to the presence of flaws in, or to the lack of homogeneity of the material, as suggested by Professor Whitehead and Mr. Franklin, though doubtless the voltage at which that breakdown occurred was influenced by the lack of absolute homogeneity. The possible effect of a layer of air, suggested by Professor Kennelly and Mr. Thomas, was obviated after the earliest experiments by the use of a liquid dielectric between the rubber and the glass tube.

The curves marked C in Figs. 10 and 12 were intended only to give a very rough idea of the magnitude of charging current which might be expected in those cases of partial breakdown. As the resistance to the passage of current along the lines of incipient disruption is probably low, the change in the phase angle of the current which is suggested by Mr. Atkinson does not necessarily occur, and it was therefore assumed in computing curves C that the phase angle of the current remained unchanged. The increase in " static " capacity which was noted by Professor Kennelly in the testing of some rubber cable would seem to be most readily explained by a rise in the temperature of the dielectric.

It is very interesting to learn from Mr. Middleton that the formula which assumes the complete breakdown of the overstressed zone of a thick wall of insulation gives results which are satisfactory in practice. This fact seems to indicate that in the cases with which Mr. Middleton deals the potential gradient remaining in the partially disrupted zone of insulation approximately compensates for the excessive stresses introduced by the needlepoints.

The inconsistency of the present nomenclature concerning capacity prompts one to wish that the term *permittivity*, which Mr. Waring uses, might come into general use. If Heaviside's rational units were adopted the nomenclature could be simplified in the way indicated in the following. For the sake of simplicity, the case here considered is that of a parallel plate condenser, A representing the effective area of the plates and t the thickness of the dielectric:

Quantity	Present name	Rational name
$\frac{\epsilon A}{t}$	Capacity	Permittance
ϵ	Specific capacity	Permittancy or permittivity

There seems to be little hope of the immediate adoption of a rational system of electric units, but with our present system of units the capacity nomenclature could be made consistent with the rest of electrical nomenclature. For example, the following terms have been suggested:

Quantity	Present name	Consistent name
$\frac{\epsilon A}{4 \pi t}$	Capacity	Capacitance
$\frac{\epsilon}{4 \pi}$	(?)	Capacity, or capacitivity
ϵ	Specific capacity	Permittivity

A paper presented at the 253d Meeting of the American Institute of Electrical Engineers, New York, November 11, 1910.

INTERPOLES IN SYNCHRONOUS CONVERTERS

BY B. G. LAMME AND F. D. NEWBURY

Synchronous converters with interpoles have been used but little in this country, but they have been built to some extent in England and on the continent of Europe, principally by companies which are either directly connected with or very closely allied to the companies which have manufactured the great bulk of the converter apparatus installed in this country. Considering that interpole generators and motors came into extensive use in this country at about the same time as in Europe, the question would naturally be raised why interpole converters have not come into similarly extensive use, especially as the principal designers of converters in this country are in direct touch with the designers of the commutating pole converters in Europe. The reply might be that the introduction of any new type of apparatus is a relatively slow process; but, on the other hand, interpoles on direct current generators and motors came into general use in a relatively short time, especially so in railway motors. This indicates that there has been a more or less pressing need for interpoles in certain classes of apparatus and the greater the need for the change the quicker was the change made. Any important change in design or type must be justified by engineering and commercial reasons, such as improved performance greater economy, or lower cost. In the railway motor, placed under the car, and more or less inaccessible, improved operation at the brushes and commutator, when equipped with interpoles, represented a pressing reason for the change in type, although the cost and efficiency were not appreciably changed. In the direct-current generator with the modern tendency toward higher speeds with lower cost, the interpoles represented a practical necessity. This has been recognized for several years and the change to the interpole type has been made as rapidly as circumstances will permit. Also, in variable-speed direct-current motors interpoles have been in general use for a number of years, simply because the interpoles represent a very definite improvement in a number of ways.

New types of apparatus should only be introduced where they represent some distinct improvement or advance over existing types. Where a new type does not represent such improvement and is simply introduced to gratify a personal whim of the purchaser, or desire on the part of a manufacturing company to produce something different from other companies, the new apparatus, as a rule, will not advance quickly into public favor since there is no real necessity for it.

It is therefore a question whether the slowness in the introduction of interpoles in synchronous converters is due to lack of sufficient advantages, or American engineers do not sufficiently appreciate their advantages. There appears to be room for wide differences in opinion on this subject. The synchronous converter and the direct-current generator are two quite different machines, in their characteristics, and no one can say off hand, that interpoles will give the same results in both. In the following is given a partial analysis of the conditions occurring in the two classes of machines, which will indicate wherein interpoles are of greater advantage on direct-current generators than on converters.

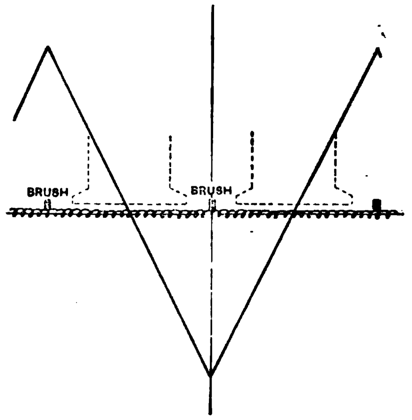


Fig. 1

Taking up first, the direct current generator, it may be considered as containing two sets of magnetizing coils, namely, the armature and the field windings. Considering the armature winding alone, the magnetomotive force of the armature winding has zero values at points midway between two adjacent brush arms or points of collection of current and rises at a uniform rate to the point of the winding which is in contact with the brushes. This is illustrated in Fig. 1. Therefore the armature winding has its maximum magnetizing effect or magnetomotive force at that part of the core surface where the winding is directly in contact with the brushes. However, the magnetic flux set up by the armature winding will not necessarily be a maximum at this point, as this depends upon the arrangement of the magnetic or other material surrounding the armature. If this point occurs midway between two field poles, then, while the magnetizing effect is greatest at this point, the presence of a large air-gap at this same point may mean a relatively small magnetic flux, while a much higher flux may be set up by the armature winding at the edges of the adjacent field poles. In the usual direct-current generator construction without interpoles, the position of commutation is almost midway between two adjacent poles and therefore the point of maximum magnetomotive force of the armature is also practically midway between poles. The absence of good magnetic material over the armature at this point serves to lessen the magnetic flux due to the armature magnetizing effect, but even with the best possible proportions there will necessarily be a slight magnetic flux set up at this point. While this field is usually of small value, yet unfortunately it is of such a polarity as to have a harmful effect on the commutation of the machine. During the operation of commutation, the coil which is being commutated has its two terminals short-circuited by the brushes. If this short circuited coil at this moment is moving across a magnetic flux or field, it will have an e.m.f. set up in it which will tend to cause a local or short circuit current to flow. Such a current is set up by the flux due to the armature magnetomotive force described above and unfortunately this current flows in such a way as to give the same effect as an increased external or working current to be reversed as the coil passes from under the brush. In other words, the e.m.f. set up in the short circuited coil by the above field adds to the e.m.f. of self induction in the coil due to the reversal of the working current.

Another cause of difficulty in the commutation of a direct current machine is the self induction of the armature coils as they individually have the current reversed in them in passing from one side of the brush to the other. Each coil has a local magnetic field around itself, set up by current in itself and its neighboring coils. The value of this local magnetic field depends upon the arrangement of the winding, the disposition of the magnetic structure around the coil, the ampere turns, etc. During the act of commutation, that part of the local field due to the coil which is being commutated must be reversed in direction. It is therefore desirable to make the local field due to any individual coil as small as possible. This means that the number of turns per coil should be as low as possible, the amperes per coil also should be as small as possible, while the magnetic conditions surrounding the coil should be such as to give the highest reluctance. By the proper arrangement of the various parts, it is usually found that the e.m.f. of self induction, due to the reversal of the coil passing under the brush, can be made of comparatively small value so that, if no other conditions interfere, good commutation could be obtained under practically all commercial operating conditions. However, the magnetic field between the poles set up by the armature magnetomotive force as a whole, as described above, adds very greatly to the difficulties of commutation. If the armature magnetomotive force, or the field due to it, could be suppressed, then one of the principal limitations in the design and operation of direct-current generators would be removed, and the commutation limits would be greatly extended. Or, better still, if a magnetic flux in the reverse direction were established at the point of commutation, then the e.m.f. set up by this would be in opposition to the e.m.f. of self induction of the commutated coil and would actually assist in the commutation.

This latter is what is accomplished by interpoles. When these are used the brushes on the commutator are so placed that the short circuited or commutated coils are directly under the interpole. Consequently, the maximum magnetomotive force of the armature is in exact opposition to that of the interpoles. Therefore, the total ampere turns on the interpoles should be equal to the total ampere turns on the armature in order to produce zero magnetic flux under the interpole or at the point of commutation. But, for best conditions there should not be zero field, but a slight field in the opposite direction from that which the armature winding alone would produce. Therefore, the magnetomotive force of the interpole must be greater than that of the armature by an amount sufficient to set up a local field under the interpole which will establish an e.m.f. in the short circuited coils opposite to that set up by the commutated coils themselves and practically equal to it. The excess ampere turns required on the commutated poles is therefore for magnetizing purposes only and the amount of extra ampere turns will depend upon the value of the commutating field required, depth of air-gap under the commutating pole, etc. The commutating field required is obviously a function of the self induction of the commutated coil and evidently the lower the self induction the less commutating field will be required. It is evident therefore that the commutating field under the commutating pole bears no fixed relation to the armature ampere turns or to the main field ampere turns, but is, to a certain extent, dependent upon the proportions of each individual machine.

It is evident that the magnetomotive force of a given armature varies directly with the current delivered, regardless of the voltage. Therefore, that part of the interpole magnetomotive force which neutralizes that of the armature should also vary directly in proportion to the armature current. Also, the self induction of the commutated coils will vary in proportion to the armature current carried, and therefore the magnetic field under the interpole for neutralizing this self induction should also vary in proportion to the armature current. It is therefore obvious that if the main armature current be put through the interpole winding, the magnetomotive force of this winding will vary in the proper proportion to give correct commutating conditions as the armature current varies, regardless of the voltage of the machine. This is on the assumption that the entire magnetomotive force of the interpole winding is effective at the air gap and armature, which implies an absence of saturation in the interpole magnetic circuit. In the usual construction, the interpole winding always carries the main armature current as indicated above.

One consequence of the use of the interpole is that somewhat less regard need be paid to keeping the self induction of the commutating coil at its lowest value. In consequence, there is somewhat more freedom in proportioning the armature winding, slots, etc., than in a non-interpole machine, and advantage can be taken of this in bettering the proportions for other characteristics. The conditions of design are therefore not as rigid in the interpole as in the non-interpole type.

The above description of the interpole generator has been gone into rather fully, as many of the points mentioned will be referred to again in connection with interpoles on synchronous converters.

The synchronous converter differs from the direct current generator in one very important particular, namely, it may be considered as motor and generator combined. It receives current from a supply system the same as a motor and it delivers current to another system like a direct-current generator. The magnetomotive force of the armature winding as a motor acts in one direction, while the magnetomotive force of the armature winding as a generator acts in the opposite direction. As the input is practically equal to the output, it is evident that these two armature magnetomotive forces should practically neutralize each other, on the assumption that the armature magnetomotive force, due to the polyphase current supplied has practically the same distribution as that of the corresponding direct-current winding. Assuming that the two practically balance each other, then it is evident that one of the principal sources of commutation difficulty in direct current generators is absent in the converter and therefore the limits in commutation should be much higher than those of direct-current machines.

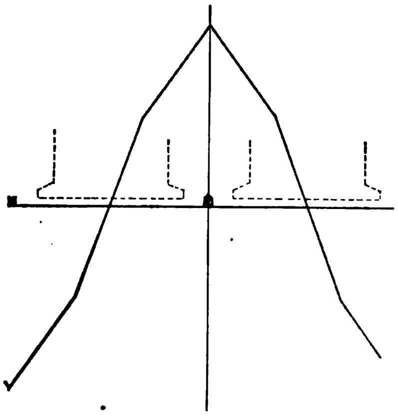


FIG. 2

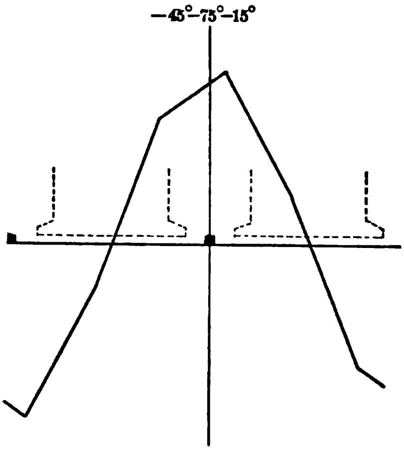


FIG. 3

The following diagram show the distribution of the alternating-current and direct-current magnetomotive forces on a six-phase rotary converter. The magnetomotive force distribution for the alternating-current input is plotted for several different positions of the armature. Three different positions are shown with the armatures displaced successively 15 electrical degrees. The general forms of these distributions repeat themselves for further similar displacements.

These distributions are illustrated in Figs. 2, 3 and 4. It is evident from these three figures that the peak value of the m netomotive force the armature varies as the armature is rotated, as indicated by the heights of the center line in the three figures.

In Fig. 5, the magnetomotive force distribution of Fig. 2 and the corresponding direct-current distribution of Fig. 1 are both shown, but in opposition to each other. In this figure both are shown in proper proportion to each other, taking into account the alternating current amperes and the direct-current amperes output. The resultant of these two distributions is also indicated in these figures.

In Fig. 6 the distributions correspond to Figs. 3 and 1 combined and the resultant is also shown.

Fig. 7 combines Figs. 4 and 1.

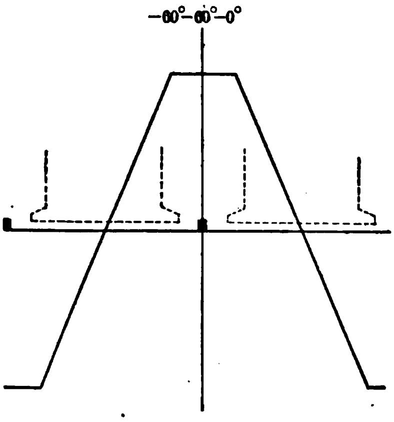


FIG. 4

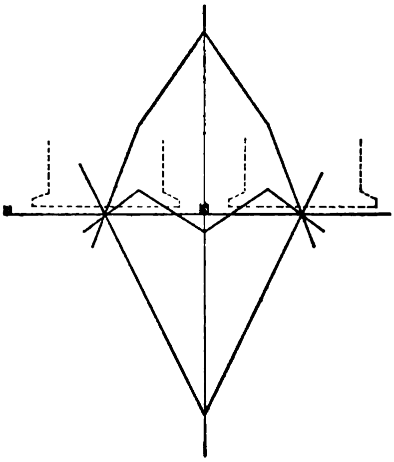


FIG. 5

It is the resultant magnetomotive force in these three figures which is important, as this is the effective magnetomotive force which tends to produce a flux or field over the commutated coil. It is evident from these figures, which are drawn to scale, that this resultant varies in height as the armature is rotated, but the maximum is only a relatively small per cent of the direct-current magnetomotive force. Therefore, it is obvious that one of the principal sources of difficulty in the commutation of the direct-current generator is practically absent in the converter, and it is also evident from this that the commutating conditions in the latter should be materially easier than in the former. This has proved to be true by wide experience in the construction and operation of converters.

In the above figures the magnetomotive forces have been plotted to scale on the following basis:

The six-phase converter winding is connected to three transformers with the so-called diametral arrangement; each of the three secondaries is connected across the diameter, or across 180 deg. points on the winding, the three diameters being displaced 60 deg. with respect to each other. Assuming the direct current in the winding as A, then the maximum value of the alternating current in any one phase of the alternating-current end will be equal to $\frac{2}{3}$ A, or 0.667 A, assuming 100 per cent efficiency. However, as the alternating-current input must be somewhat greater than the direct-current output, due to certain losses in the machine, it is evident that the maximum alternating current in any one phase must be somewhat greater than 0.667 A. The field copper losses may be considered as part of the output of the rotary. The armature copper losess may be considered as due to an ohmic drop between the counter e.m.f. of the armature and the transformer e.m.f., and simply a higher transformer e.m.f. must be supplied to overcome this drop and therefore it does not effect the true current input of the rotary. However, the losses due to rotation, such as iron loss and the friction and windage are excess losses which represent extra current which must be supplied to the alternating-current end of the rotary. These rotational losses will usually be relatively small in a 25-cycle converter, being possibly 4 per cent or 5 per

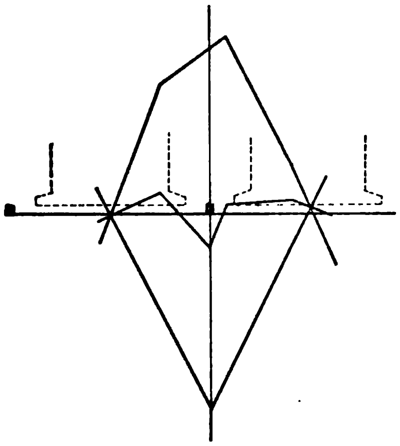


Fig. 6

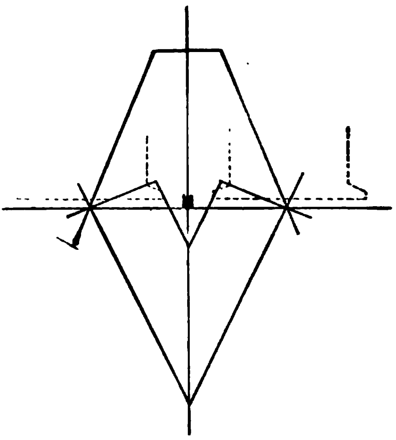


Fig. 7

cent in a small machine and 1½ per cent to 3 per cent in a large machine. In the 60-cycle converters, where the iron losses are relatively higher and the speeds are somewhat higher, giving greater friction and windage, the rotation losses may be considerably greater than on 25-cycle machines. Assuming these rotation losses will be 3 per cent, then the maximum alternating current per phase $= \dfrac{0.667\,A}{0.97} = 0.687\,A$. The foregoing Figs. 5, 6 and 7 are worked out on this assumption of 97 per cent rotational efficiency and on this basis of minimum value of the resultant magnetomotive force of the armature at the direct-current brush is about 7 per cent of the direct-current magnetomotive force of the same wording, while the maximum value is about 20 per cent. The lower the rotational efficiency the smaller would be these values, and with a rotational efficiency of about 89 per cent, the minimum resultant would fall to zero, while the maximum value would be about 13 per cent.

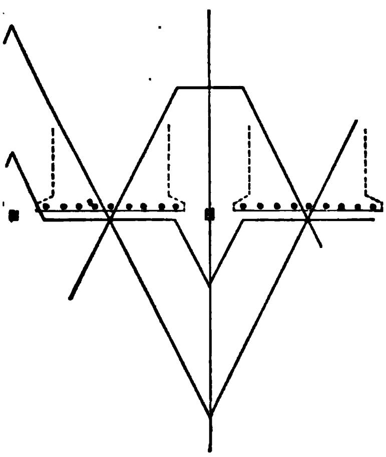


Fig. 8

The resultant magnetomotive force of a synchronous converter might be compared with that of a direct-current generator with compensating windings in the pole faces. It is generally known that such direct-current generators have much better commutating conditions than ordinary uncompensated machines. If such compensating winding on the field of a direct-current machine covered symmetrically the whole armature surface, then the armature reaction could be completely annulled, which is not the case in the converter. But with compensating windings located only in the pole faces, then the armature magnetomotive force midway between the poles could not be completely annulled, unless over-compensation is used, and the resultant would be as shown in Fig. 8, which is not quite as good as the average resultant in the converter. The commutating conditions in the converter can therefore be considered as at least as good as in a direct-current generator with a compensating winding of normal value located in the pole faces only.

In the application of interpoles to the synchronous converter the same principles should hold as in a direct-current generator, namely, the interpole magnetomotive force should be sufficient to neutralize that of the armature winding and, in addition, should set up a small magnetic flux sufficient to overcome the self induction of the commutated coil. As the magnetomotive force the armature varies between 7 per cent and 20 per cent shown in the above figures, it is evident that perfect compensation of this cannot be obtained and that therefore only some average value can be applied. Assuming that 15 per cent will be required on the average to compensate for this, then in addition the interpole winding must carry ampere turns sufficient to set up the small magnetic field for commutation. Thus the total ampere turns on the interpole will be equal to 15 per cent of the armature direct-current ampere turns plus a small addition for setting up the useful or commutating field. In the direct-current generator, the ampere turns on the interpoles must equal the total armature ampere turns plus a corresponding addition for the commutating field. It is therefore evident that an interpole winding on a converter will naturally be very much smaller than on a direct-current generator, and in general it is between 25 per cent and 40 per cent of the direct-current.

In the pulsating resultant magnetomotive force in the converter there lies one possible source of trouble with interpoles Assume, for example, the total ampere turns on the interpoles are equal to 30 per cent of the direct-current ampere turns on the rotary and that 15 per cent of this is for overcoming the average value of the resultant magnetomotive force, then an average of 15 per cent will be available for setting up a commutating field; but, according to the above diagrams, the resultant magnetomotive force of the armature varies from 7 per cent to 20 per cent. With a total interpole winding representing 30 per cent, then the effective or magnetizing part will vary from 30–7 to 30–20; that is, from 23 per cent to 10 per cent. The effective magnetomotive force therefore tends to vary over quite a wide range so that the commutating field would also tend to vary up or down over a very considerable range, which is an undesirable thing for commutation. However, as this pulsation is at a fairly high frequency it tends to damp itself out by setting up eddy currents in the structure of the magnetic circuit. If a good conducting damper or closed circuit were placed around the interpole, it is probable that this pulsation would be almost completely eliminated, but such a damper possesses certain disadvantages, as will be shown later.

In practice this pulsation of the armature reaction under the interpoles is apparently not noticeably harmful in most cases, as evidenced by the fact that well-proportioned interpole converters in commercial service show no undue trouble at the commutator or brushes.

Due to the relatively small number of ampere turns required on the interpole of a converter compared with those required on a direct-current generator, the design of the interpoles in the two cases presents quite different problems. In the direct-current generator the interpoles carry ampere turns, which in all cases are greater than the armature ampere turns, as explained before. As the field ampere turns on the main poles are, not infrequently, but little greater than the armature ampere turns, it is evident that the interpole winding may, in some cases, carry as many ampere turns as the main field windings. While but a small per cent of these interpole windings is effective in producing flux under the pole tip, yet they are all effective in producing leakage from the sides of the poles. As the interpoles are generally small in section compared with the main poles, and as they may carry ampere turns equal to the main poles, it is evident that the effect of leakage may be relatively great on the interpole.

For instance, if the leakage on the main poles is 15 per cent of the useful flux, then, with the same total leakage on the interpoles, this may represent a very high value compared with the useful flux, due to the small section of the interpole and the relatively low useful interpole flux. In consequence, it is considerable of a problem to proportion the interpoles of a direct current generator so that the leakage flux will not saturate the interpoles at some part of the circuit. If they saturate, then part of the ampere turns on the interpole are expended in such saturation and the part thus expended must be counted off from the extra or excess interpole ampere turns. If, for example, the interpole winding requires 100 per cent for overcoming the armature and there is 20 per cent extra ampere turns for setting up a useful flux, then any saturation in the interpole circuit must represent additional ampere turns on the field, as the above 120 per cent is necessary for useful flux and for neutralizing the armature. With reduced current, and consequent lower saturation, these additional interpole turns become effective in magnetizing the gap and thus the commutating flux is too strong. At greatly increased load, more ampere turns are required for saturation, and the commutating flux is altogether too weak. It is thus evident that a machine with highly saturated interpoles will not commutate equally well for all loads. Herein lies a problem in the design of interpole generators, as it is difficult to maintain a relatively low saturation in the interpoles due to their small section and high ampere turns which cause leakage. It is well known that in the main poles of the generator, a leakage flux which is higher than the useful flux is objectionable, from the designer's standpoint; and yet in the use of interpoles this is a normal condition rather than an exception.

In the synchronous converter the conditions are somewhat different due to the fact that the interpole ampere turns are usually only 25 per cent to 40 per cent as great as on a corresponding direct-current generator. The leakage at the sides of the poles becomes relatively much less, while the useful induction remains about the same as on the direct-current generator. In consequence, saturation of the poles is not so difficult to avoid. In some cases, due to the smaller ampere turns on the interpole winding, the interpole coils can be located nearer the pole tip and thus the leakage can be further reduced. However, the placing of the interpole coil over the whole length of the pole is not as objectionable in the converter interpole as it is on the direct-current generator as the ampere turns are less. It is those ampere turns which are located close to the yoke, or furthest away from the pole tip, which produce the highest leakage, while those close to the pole tip usually produce much less leakage, but in interpole generators with their high number of ampere turns on the interpoles it is often difficult to find space for the interpole winding, even if distributed over the whole pole length. In some cases, a direct-current machine may be larger than would otherwise be required, simply to obtain space for the interpole winding. This is not true to the same extent in the application of interpoles to converters.

In the above the leakage is referred to as a function of the interpole winding as if the main winding had little or nothing to do with it. The reason for this may be given as follows:

Fig. 9 represents two main poles and an interpole of a direct-current generator or converter, with their windings in place. The direction of current or polarity of each side of each coil is also indicated by + or −. It is evident that between the interpole and one main pole, the interpole winding and the main field winding are of the same polarity, while on the opposite side of the interpole, these two windings are in opposition. Let A equal the ampere turns of the interpole and B the ampere turns in the main coil. Then, $A+B$ will represent the leakage ampere turns at one side of the interpole and $A-B$ will represent the leakage ampere turns at the other side. Therefore, the leakage at the two sides of the poles is represented by $(A+B)+(A-B) = 2A$; that is, the leakage could be considered as due to the interpole winding entirely and may also be considered as due to double the interpole turns acting as one side of the interpole only. Another way of looking at this is to consider that the windings on the main pole produce leakage in the interpoles, but the leakage due to one main pole acts radially in one direction in the interpole, while that due to the other main pole is in the opposite direction.

Considering therefore the interpole leakage as being due to the interpole ampere turns only, it is evident that the synchronous converter will not be troubled with saturation of the interpoles to the same extent as a direct-current generator. With the same size of interpole it is evident that the converter should be able to carry heavier overloads than the direct-current generator before saturation of the interpoles is reached.

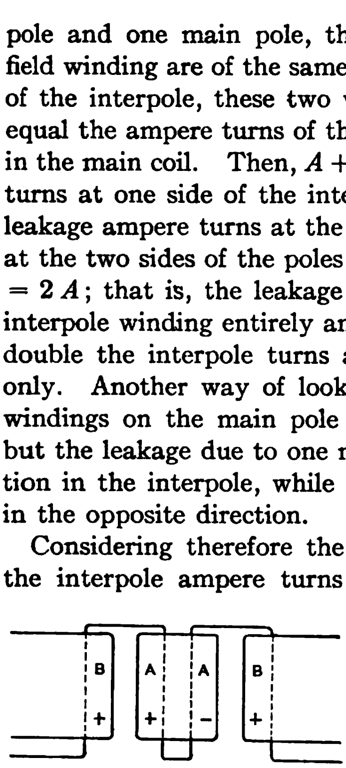


Fig. 9

It was mentioned before that a closed conducting circuit around the interpoles would be objectionable. This has been proved by experience with interpole generators. It is evident from the preceding analysis that the ampere turns on the interpole of a direct-current generator should always rise or fall in proportion to the armature ampere turns in order to give best commutation, assuming, of course, no saturation of the poles. If the interpole turns are directly in series with the armature winding, with no shunt across the interpole winding, it is evident that the interpole ampere turns must vary in direct proportion to the armature ampere turns. However, if a non-inductive shunt, for instance, were connected across the interpole winding in order to shunt part of the current, then in the event of a sudden change in load, the interpole winding being inductive due to its iron core and the shunt being non-inductive, the momentary division of current during a change in load would not be the same as under steady conditions. In other words, if the armature and interpole current were suddenly increased, then a large part of the increase would momentarily pass through the non-inductive interpole shunt until steady conditions were again attained. In consequence, the interpole ampere turns would not increase in proportion to the armature ampere turns just at the critical time when the proper commutating field should be obtained.

The same condition is approximated when a separate conducting circuit is closed around the interpole. A sudden change in the current in the interpole winding, causes a change in the flux, and secondary currents are set up in the closed circuit, which always act in such a way as to oppose any change in the flux, whereas, the flux in reality should change directly with the current. The above described non-inductive shunt across the interpole winding might be considered also as completing a closed circuit with the interpole winding, and therefore retarding secondary currents would be set up in this closed circuit with any change in the flux in the interpole.

In some cases it may be impracticable to get exactly the right number of turns on the interpole winding to give the correct interpole magnetomotive force. For example, on a heavy current machine, 1.8 turns carrying full current might be required on each interpole. If two turns were used, with the extra current shunted, the right interpole strength would be obtained. A non-inductive shunt, however, is bad, as shown above. However, if an inductive shunt is used, instead of non-inductive, and the reactance in this shunt circuit is properly adjusted, then it is possible to get the right interpole strength for normal conditions and still obtain satisfactory conditions with sudden changes in load. Also, by arranging the interpole winding so that a very considerable percentage of the current is shunted normally by an inductive shunt having a relatively high reactance compared with the interpole, it should be possible to force an excess current through the interpole winding in case of a sudden increase in load, in case a stronger commutating field were needed at this instant.

On the interpole synchronous converter a non-inductive shunt across the interpole winding should act very much as on an interpole generator and therefore non-inductive shunts are inadvisable. If any shunting is required it should be by means of an inductive shunt in those cases where the current from the converter is liable to sudden fluctuations, as in railway service. Where the service is practically steady, a non-inductive shunt should prove satisfactory for the interpoles of converters or direct-current generators.

Under extreme conditions of overload current, that is, in case of a short circuit across the terminals, it is questionable to what extent interpoles are effective. It is practicable to design interpoles on direct-current generators which will not unduly saturate up to possibly three or four times normal load. However, in case of a sudden short circuit the current delivered by the machine is liable momentarily to rise to a value anywhere from 15 to 30 times full load current. With this excessive current the interpoles of the direct-current generator must necessarily be more or less ineffective. On account of saturation, the commutating flux under the interpole cannot rise in proportion to the current. However, there should still be some commutating field present, which condition is probably considerably better than no field at all, or a strong field in the opposite direction as would be found without commutating poles. Therefore, in direct-current generators with well-proportioned interpoles, the conditions on short circuit are generally less severe than in non-interpole machines.

If the pole is highly saturated by the heavy current rush on short circuit, then it is evident that a highly inductive shunt, as described above, which would increase the interpole current in a greater proportion than the armature current, would simply mean higher saturation with little or no increase in the useful flux under the interpole.

In the synchronous converter at short circuit the conditions may be somewhat different. When the converter is short circuited it can also give extremely high currents, possibly much greater than the corresponding direct-current generator can give. Both the armature winding tied to an alternating-current supply system, and the presence of the low resistance dampers on the field magnetic circuit, tend to make the short circuit conditions more severe in the converter. The worst condition, however, would appear to be in the relation of the interpole ampere turns to the armature ampere turns on short circuit. As shown before, the normal ampere turns on the interpole winding will be only 25 per cent to 40 per cent of the direct-current ampere turns on the armature. In the case of a sudden short circuit the armature momentarily may deliver a very considerable current as a direct-current generator, and the armature reaction, or the resultant magnetomotive force, may approach that of a direct-current generator. In such case the ampere turns on the interpole will be very much smaller than the armature resultant magnetomotive force at this instant and thus there will be no commutating flux under the interpole, but, on the contrary, the armature being stronger, there will be a reverse flux which may be considerably higher than if no interpole were present, as the iron of the interpole represents an improved magnetic path for such flux. While the converter armature will probably never deliver all its energy as a direct-current generator at the instant of short circuit, yet it may be assumed that it will deliver some of its load thus, and it does not require a very large per cent to be generator action in order to neutralize, or even reverse the effect of the interpoles. In consequence, on a short circuit the converter may have a reverse field under the commutating pole, while the direct-current generator under the same condition will have a field of the proper direction but of insufficient strength which, however, is a much better condition than a field of the wrong polarity.

The inductive shunt mentioned before, which normally shunts a considerable portion of the interpole current, might be more effective in a converter than in a direct-current generator in the case of a short circuit. In a direct-current generator, the interpoles would be so highly saturated, as described before, that the increase in current in the interpole winding due to the inductive shunt would be relatively ineffective. In the converter, however, the saturation of the interpole can normally be very much lower than in the direct-current generator and it might be practicable to so proportion these interpoles that they do not saturate highly, even on short circuit. In consequence, a strong inductive shunt might force up the interpole ampere turns so that the negative field under the interpole would be much decreased, or might even be changed to a positive field and thus become useful in commutation. This would be helpful *only during the short circuit.* However, converters not infrequently flash over or "buck" when the circuit breaker is opened on a very heavy overload or a short circuit and not when the first rush of current occurs. If the flash tends to occur at the opening of the circuit, then the above mentioned inductive shunt might have just the opposite effect from what is desired, for it would tend to develop or maintain a stronger field under the interpole after the armature reaction is removed. In consequence, the heavy inductive shunt might prove harmful in such a case.

Another condition exists in a converter which does not exist in a generator. When a short circuit occurs on a direct-current generator, the armature reaction tends to distort the main field very greatly—so much so that the field of the machine is very greatly weakened. This decreases the terminal voltage and the resultant decrease in the shunt excitation will still further tend to weaken the field. In consequence, the machine tends to " kill " its magnetic field and the voltage tends to drop to a low value. Therefore, when the breaker opens on a short circuit the direct-current voltage may be falling rapidly. When the armature current is removed from the machine the voltage may rise slowly, depending upon the natural rate of building up the field. Consequently, after the breaker opens there is little or no tendency to flash, and practically all difficulties occur during the current rush, before the breaker opens. In a converter, however, the conditions are different. The armature of the converter is tied to an alternating-current supply system which tends to maintain the voltage on the converter. The machine cannot " kill " its field in the same way as the direct-current generator, for the alternating-current system tends to maintain the field by corrective currents which act in such a way as to tend to hold up the voltage. An enormous current may be drawn from the alternating-current system momentarily in case of a short circuit on the direct-current side of the converter. This heavy alternating current may cause a drop in the alternating-current lines, step-down transformers, etc., so that the supply voltage does fall very considerably and the direct-current voltage does drop materially in case of a short circuit. However, the instant the short circuit is removed by opening the breaker, then the converter at once tends to attain full voltage as the alternating-current supply system tends to bring the armature up quickly to normal voltage conditions. In consequence there may be a relatively heavy current flow in the alternating-current side of the machine, while there is no direct-current flow in the armature. Part of this alternating-current flow represents energy in bringing the machine back to a normal condition, and part is purely magnetizing or wattless current. The energy component tends to produce an armature magnetomotive force giving an active field at the point of commutation. This energy component alternating-current flow, however, cannot be corrected by interpoles, as there is no direct current flowing.

A further difference between the synchronous converter and the direct-current generator, in case of a short circuit, lies in the results of field distortion. The enormous short circut current from the converter with the armature acting partly as a direct-current generator, may very greatly shift or distort the field flux. The dampers on the field poles tend to delay this distortion. Also, after distortion has occurred they tend to maintain the distorted or shifted field so that momentarily after the circuit breaker opens the converter may be operating without direct-current load but with a very badly distorted or shifted field. This also tends to produce sparking or flashing after the direct-current breaker has opened.

Another condition which may affect the action of interpoles on converters, but which does not occur in direct-current generators, is hunting. When hunting occurs in a converter the energy current delivered to the alternating-current side of the converter pulsates, or varies up and down over a certain range, which may be either large or small. At the same time the direct-current flow is apparently varied but little. In consequence, the resultant magnetizing effects of the alternating current and direct current do not nearly neutralize each other at all times. When the alternating-current energy input is least the converter delivers part of its direct-current load as a generator, the stored energy in the rotating armature being partly given up to supplying the direct-current power. In this case the resultant magnetomotive force may be a very considerable per cent of the maximum direct-current magnetomotive force of the armature winding. Also, the magnetic field under the main poles is distorted or shifted toward one pole edge. The armature necessarily slows down during this operation, the field polarity of all the poles being shifted toward one pole edge. The position of maximum e.m.f. of the alternating-current end and also the position of maximum alternating-current flow may be shifted to a certain extent also. In consequence, the magnetomotive force due to the alternating-current flow will be shifted circumferentially a certain amount, while the direct-current magnetomotive force cannot be shifted, being fixed in position by the brushes. In consequence, the alternating-current magnetomotive force may not be in direct opposition to the direct-current at this instant, and the resultant magnetomotive force may be much higher than at normal condition. A moment later the swing may be in the opposite direction; that is, the alternating armature current may be greater than direct current and the energy being received from the alternating-current system is considerably greater than is given out by the direct current. Again, the two magnetomotive-forces will not nearly neutralize each other and there also will be field distortion, but in the opposite direction, and again, the two magnetomotive forces will not be in direct opposition to each other circumferentially. If hunting is very severe, the resultant magnetomotive force of the armature due to the inequality of the input and output, and to the circumferential shifting of the magnetomotive forces with respect to each other, may vary enormously and may pass from positive to negative values periodically. It is evident that under such condition the presence of an interpole may give much worse results than if no interpole were present; for, as mentioned before, if there is a magnetomotive force in the wrong direction at the interpole, the interpole magnetic circuit apparently makes conditions worse. In consequence, an interpole synchronous converter should be especially well designed to avoid hunting.

All of the above considerations have taken into account only the energy currents delivered to the alternating-current side of the converter. Some consideration should be given to the effect of wattless currents in connection with interpoles.

As is well known, when a synchronous converter has its field strength improperly adjusted for the required alternating-current counter e.m.f., alternating currents will flow in the armature in such a way as to correct the effect of the improper field strength; that is, if the field is too weak wattless currents will flow in the armature which tend to magnetize the field of the converter. These currents will be leading in the armature, but will be lagging with respect to the line. On the other hand, if the converter field is too strong, these wattless or corrective currents will tend to weaken the field and will lag with respect to the armature, but will lead with respect to the line. These corrective currents will have a lead or lag of 90 deg. with respect to the energy currents. Their magnetomotive forces also will have a lead or lag of 90 deg. from the magnetomotive force of the energy component of alternating-current input. As this latter practically coincides with the direct-current magnetomotive force, which is midway between the main poles, the corrective armature currents will have a maximum magnetomotive force practically under the middle of the main poles and therefore become purely magnetizing or demagnetizing due to such position. Also, being at right angles to the energy component, the magnetomotive forces of the corrective currents will have zero value where the energy component has maximum, and therefore should have no direct effect upon the resultant magnetomotive force midway between the main poles, or under the interpoles if such are used. It might be assumed therefore that the usual wattless or corrective currents, which the converter may carry on account of improper field strength, will have no direct harmful effect on the commutation. However, there are apparently some indirect effects due to this corrective current, for when a converter is operated at a bad power-factor, either leading or lagging, there is generally more trouble at the commutator and brushes than when a high power-factor is maintained.

Kw.	Volts	Poles	Rev. per min.	Cycles	Amperes per brush arm
3000	600	16	187	25	625
2000	250	18	167	25	889
1000	250	10	300	25	800
800	250	8	375	25	800
1000	250	14	514	60	570
500	250	10	720	60	400
1000	600	12	600	60	278
500	600	8	900	60	208
300	600	6	1200	60	167

It has been shown that the maximum possible benefit to be derived from interpoles in neutralizing armature reaction is much less in synchronous converters than in direct-current generators. In direct-current generators and motors interpoles have also been of great advantage, due to variable speed and variable voltage requirements. In synchronous converters, however, the requirement of variable speed is obviously absent and that of variable voltage very limited. The converter has constant voltage characteristics and variable voltage can only be obtained through the agency of such relatively expensive devices as induction regulators, synchronous boosters or split-pole constructions. The advantages of interpoles in synchronous converters are then to be looked for only in the direction of increased outputs and higher speeds.

It will be instructive, before considering the possibility of advance in this direction to take a brief survey of what has been accomplished without interpoles. The data of some machines of large output and high speed which have been built and placed in operation in the United States are given in the accompanying table:

The 3000-kw. converters mentioned above are the largest converters so far built. Eleven of these units have been installed or are being built for two of the traction companies of New York City. It is of interest to note that a number of these units are replacing 1500-kw. 250-rev. per min. units installed about ten years ago in the same substations, thereby doubling the capacity of the stations without increasing the real estate investment. The speed of these 3000-kw. units is the same as that of the 2000-kw. which, when designed four and a half years ago, represented the extreme in output and speed.

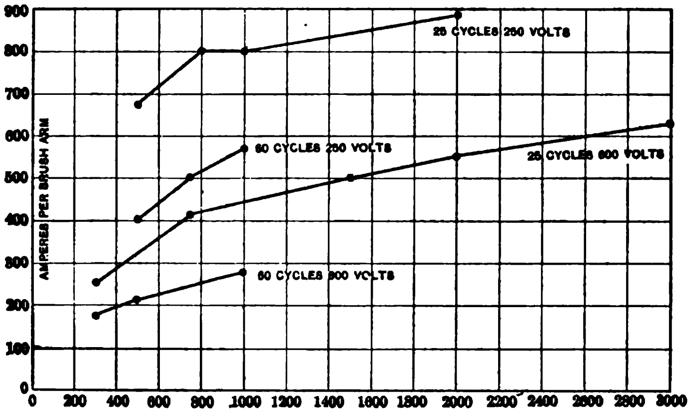


FIG. 10

The same ratings given in the table are plotted in the curve, Fig. 10, to which has been added other ratings which have been proposed and which can obviously be built in view of their relation to ratings which have been built. Fig. 10 represents concisely the situation to-day as far as the writers are familiar with it. The curves bring out very nicely the relation between permissible amperes per brush arm and frequency and voltage. It will be noted that the permissible current is greater in the 250-volt converters than in the 600-volt converters, and greater in the 25-cycle converters than in the 60-cycle converters of the same voltage. These differences call attention to the fact, important in connection with the study of interpoles, that there are limits to speed and output other than the limit affected by interpoles—the limit of sparking.

In any commutating machine the commutating conditions are dependent, to a large extent, on the number of poles. If, in a given design the commutation design constants are unduly large, the conditions can be improved by increasing the number of poles, since this, with the " parallel " windings invariably used in larger machines, increases the number of circuits in parallel and decreases the current to be commutated in a single circuit. In a direct-current generator the number of poles can be varied with in fairly wide limits with a given speed, since the alternations of the machine are not of controlling importance. In the synchronous converters, on the contrary, the number of poles and the speed are rigidly interconnected by the frequency of the supply circuit. This imposes a limitation in converter design which is not present in the design of direct-current generators. The least number of poles which a direct-current generator can have is determined largely by the total current to be handled and to a less extent by the speed. There is a maximum current which can be handled by each brush arm or for each pair of poles; this current is determined by the permissible length of commutator which, in turn, is determined by the stresses, the type of commutator construction employed, and the skill of the available manufacturing department. Due to the fixed relation between poles and speed in rotary converters, there is a fixed relation between the frequency and the commutator peripheral speed. The peripheral speed in feet per minute is equal to the alternations per minute of the supply circuit times the distance in feet between adjacent neutral points on the commutator. With the same distance between neutral points, the peripheral speed of commutators in 60-cycle converters is necessarily 2.4 times the peripheral speed of 25-cycle commutators. This does not mean that 25- and 60-cycle converters are actually built with this difference in peripheral speed, but that 60-cycle converters are pushed as high in peripheral speed as possible while 25-cycle converters are designed with a somewhat lower peripheral speed and with a proportionately greater distance between neutral points which, in turn, determine to a marked degree the sensitiveness of the machine in operation.

Another matter which has a bearing on the speed of converters is the fact that in any machine, whether an alternating-current generator, direct-current generator, or synchronous converter, there is a limit in the number of poles below which little or no reduction in cost results in spite of the increased speed. This is best shown by the relative costs of two-pole and four-pole alternating-current turbo-generators, but is also true of other machines although to a less degree where the number of poles is greater.

With these facts in mind, the difference in the high and low voltage and high and low frequency converters can be considered.

25 Cycles, 250 Volts. Due to the low frequency, low commutator peripheral speeds are possible without exceeding very conservative limits in distance between neutral points and voltage between adjacent commutator bars. This permits very long commutators, without exceeding safe mechanical limits. The large currents due to the low voltage require at best a large number of poles, which results in a low speed in revolutions, and which also simplifies the mechanical problem of the commutator design. The large currents to be handled, particularly in the larger outputs, make it desirable to push to the limit the current per brush arm. The permissible current per brush arm is high due to the favorable conditions mentioned above and the result is seen in the high values of amperes per brush arm used in converters of this class. It is evident that for converters of low voltage and low frequency the limit to further increase in speed —with consequent decrease in poles—is *length of commutator* rather than sparking.

25 Cycles, 600 Volts. As in the 250-volt converters, low frequency permits low commutator peripheral speed which, in turn, permits relatively long commutators. The smaller currents to be handled, however, permit fewer poles which results in higher speeds than in the corresponding 250-volt converters which necessitates somewhat shorter commutators. The result is that, due to the higher speeds, the limit in amperes per brush arm is lower than in the 250-volt converters. By comparing the curves for 25-cycle 600-volts, and 60-cycle 250 volts in Fig. 10 it is evident that somewhat higher values of amperes per brush arm could be used for the former, since for the same kilowatts and speed the amperes per brush arm are equal. Either the highest available speed has not been employed in existing designs, or higher speeds could be used if interpoles were added. With these converters the limits to further increase in speed is not the length of the commutator.

60 Cycles, 250 Volts. The maximum possible speed at the commutator is used in order to increase the space between neutral points, and the number of poles are chosen as small as possible without exceeding questionable operative speeds. This imposes very severe mechanical conditions in the commutator design. Going as far in this direction as is represented by the ratings mentioned above, the number of poles is still larger than would be selected in a direct-current generator of the same rating. The amperes per brush arm are smaller than in the 25-cycle converters of the same voltage due to the larger number of poles imposed by the frequency requirement.

We question, however, whether higher speeds and greater amperes per brush arm are possible without radically changing the present type of commutator construction. Here, then, as in the low-frequency, low-voltage converters, the barrier to higher speeds is found in the commutator mechanical design rather than in the electrical design.

60 Cycles, 600 Volts. As in the 250-volt, 60-cycle converters, the number of poles is made as small as possible, keeping within permissible speeds, but, with the small currents handled in 600-volt converters and the larger number of poles necessitated by the high frequency, the amperes per brush arm as shown by Fig. 10 are very low.

The limit to higher speed is obviously not amperes per brush arm. Interpoles would probably permit higher speeds due to more favorable sparking conditions, but higher speeds than those now used would certainly require changes in present commutator designs.

The higher speeds now used by the large American manufacturers of synchronous converters were introduced within a very recent date for units above 300 kw. With the relatively low commutator peripheral speeds previously used, the distance between brush arms was very small. This restricted the design to a comparatively small number of commutator bars between neutral points with a high voltage between bars, particularly in 600-volt converters. The use of a large number of poles resulted in very narrow neutral spaces between poles so that, with the combined effects of narrow neutral and high "volts per bar," 600-volt, 60-cycle converters had a bad reputation for sensitiveness to wrong brush position and to " bucking ", when compared with the substantial characteristics of low frequency converters. The later apparently radical increase in speeds has placed 60-cycle converters in the same class with the majority of 25-cycle machines now on the market in those features of design tending toward stability in operation. If this increase in speed which has been successfully accomplished without interpoles, had proven unsuccessful, due to commutation difficulties, then interpoles would without any question be justified for 60-cycle converters.

To summarize the above discussion of the various limits to increased speed: It would appear that 25-cycle, 600-volt converters offer the most promising field for the application of interpoles; that 60-cycle, 600-volt converters follow next and that 60-cycle and 25-cycle 250-volt converters show the least possibilities of improvement from the standpoint of design.

If the use of interpoles permits higher speeds and outputs than those possible without interpoles from the standpoint of commutation it will be necessary to raise our present limits imposed by the construction of commutators except possibly in 25-cycle railway converters, if advantage is to be taken of the higher speeds. These limits may be raised materially only by a change in the type of commutator construction used. In all of the converters referred to the usual *V*-ring commutator is employed. The shrink-ring construction developed for direct current turbo-generators might be used, especially for lower voltages, and the limits in peripheral speed and length of commutator be considerably extended. It may be found, however, that the use of this type would necessitate commutators of small diameter compared with those now used in synchronous converters, in order to obtain a construction of sufficient rigidity. This would in turn necessitate the use of the number of poles and speeds approaching those used in direct-current turbo-generators in order to obtain the necessary output. Such extreme proportions would apparently result in more expensive machines than those of the proportions now used without interpoles. A serious objection to the use of shrink-ring commutators is the difficulty of making repairs on them after installation. This, in general, limits the use of shrink-ring commutators to machines in which other constructions simply cannot be employed. Commutator dimensions and speeds comparable with turbo-generator practice would only be possible with 60-cycle apparatus. As a matter of fact it is not a long step from our present 60-cycle converter speeds to those usual in direct-current turbo-generators in this country. In the 300-kw., 600-volt, 60-cycle converter referred to, any further increase in speed would necessarily be from the present six poles to a four-pole converter operating at 1800 rev. per min. This is the same as the speed selected for a number of direct-current turbo-generators of 300-kw. capacity. Similarly, the 500-kw., eight-pole, 900-rev. per min. converter, if changed, would be a six-pole 1200-rev. per min. converter which is not very different from 1500 rev. per min. selected by several manufacturers for the direct-current turbo-generator of 500-kw. capacity.

The question of satisfactory commutator design for high speeds is a question that concerns the man who has to construct the commutator and the man who has to operate it, equally with the man who designs it. A large high-speed commutator is, whatever the design, a wonderful contrivance requiring constructive ability of the highest order and, when completed and put in operation, requiring careful attention on the part of the operator. Defects unnoticed at low speeds become disastrous at high speeds. The type of construction and the limits in size and speed are not to be changed without very careful consideration.

Granting that increased speeds are feasible through the use of interpoles, and that it is possible to build satisfactory commutators at the increased speeds and increased current outputs, the question still remains whether such a change results in a sufficient reduction in cost or improvement in performance to warrant the change. Considering 25-cycle, 600-volt converters, it is without question possible to build a 300-rev. per min. 1500-kw. converter without interpoles of a design in line with conservative practice. There is ample basis for the belief that still without interpoles, the speed could be increased to 375 rev. per min. without sacrificing good commutating limits, and that, with interpoles, and, assuming that a satisfactory commutator could be designed and built, the speed could be further increased to 500 rev. per min. But, comparing the material required in the eight-pole 375-rev. per min. converter and in the six-pole 500-rev. per min. converter, it will probably be found that the cost of the six-pole machine of such large capacity is as great as or greater than the eight-pole. It is also questionable whether the 750-kw. size which is now built with six poles for 500 rev. per min. could be changed to four poles and 750 rev. per min. with a decrease in cost sufficient to warrant the change.

As an illustration of what high speeds and long commutators will lead to, Fig. 11 is shown. This is a 25-cycle, eight-pole, 375-rev. per min. 800-kw. 250-volt, 3200-ampere synchronous converter. This machine carries a synchronous booster between the collector rings and the rear end of the armature, but this adds but little to the dimensions of the machine. The great length of the machine, compared with its diameter, should be noted. The use of interpoles would probably not allow any material change in the dimensions of this machine.

Considering 60-cycle converters, both 600- and 250-volt, any increase in speed would result in machines comparable with direct-current turbo-generators in type of construction and in cost. To state the matter conservatively, it is extremely doubtful whether any material increase in speeds above those now known to be possible without interpoles can be made with enough saving in cost to compensate for the expense of adding interpole windings, if such are required.

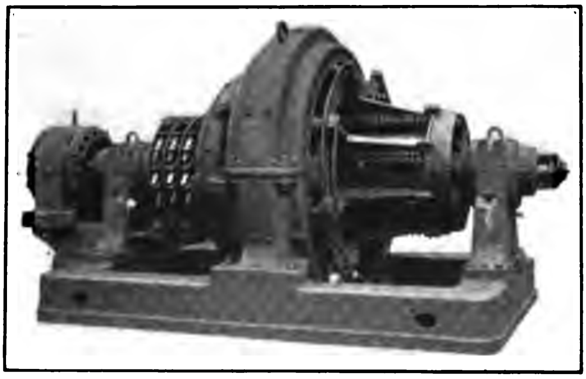


FIG. 11

The actual construction of converters with interpoles would be attended by some minor disadvantages. The field structure would be considerably complicated by the additional field winding, particularly in the case of converters for three-wire service in which both the series and interpole field windings would have to be connected in both the positive and negative circuits. In all cases the addition of the interpole would considerably crowd the field structure and increase the temperature rises in the converter unless it were designed with greater diameter to provide sufficient space for the interpoles without crowding. The efficiency of an interpole machine would in general be slightly lower than that of the corresponding machine without interpoles, due to the addition of the interpole losses. In the event of the use of higher speeds, the efficiencies will be considerably lowered by the increased friction loss due to the bearings, brushes and windage, unless the reduction in iron and copper losses is sufficient to compensate for the increased friction.

The advantages and disadvantages chargeable to interpoles may be summarized as follows:

1. Assuming that considerably higher speeds could be used:

Advantages.

- *a.* Possible reduction in cost.
- *b.* Less attention required in operation.
- *c.* Longer life of commutator and brushes.

The advantages *b* and *c* may be more than counterbalanced under the present assumption, by the greater difficulty of maintaining any commutator in proper condition with the higher speed assumed.

Disadvantages.

- *a.* Possibility of increased trouble from bucking on sudden changes in load or short circuits.
- *b.* Possible reduction in efficiencies, particularly in light load.
- *c.* Higher operating temperatures unless the same temperatures as now obtained in non-interpole machines are maintained by partly sacrificing the advantage of lower cost.

2. On the assumption that no higher speeds will be used with interpoles than have been found to be practicable without interpoles, but that the interpoles will be added simply as a refinement to machines that would operate satisfactorily without them.

Advantages.

- *a.* Less attention required during operation.
- *b.* Longer life of commutator and brushes.

Disadvantages.

- *a.* Possibility of increased trouble from bucking on sudden changes in load or short circuits.
- *b.* Slightly lower efficiencies.
- *c.* Higher operating temperatures.
- *d.* Greater cost due to the addition of interpoles.

This is true of course only with the stated assumption that the converter is designed to operate satisfactorily without interpoles. It would probably be possible to design a converter with interpoles without exceeding the cost of the non-interpole machine as has been done in other types of apparatus, but this would be done by making a machine which is unsatisfactory without interpoles and then improving the commutating conditions by interpoles. Such result, however, would hardly represent an improvement over present practice.

In conclusion, the authors have attempted to state the case for and against interpoles in all fairness. From the standpoint of design it seems difficult to make a sufficiently strong case for the interpole in synchronous converters to warrant the additional complication in construction. At best the addition of interpoles, properly applied, represents a refinement over present designs, and the fundamental question is whether such refinement is justified commercially. This question, however, must be decided, as all engineering problems are finally decided, not by the judgment of one man or any group of men, but by the results of experience in extended operation.

DISCUSSION ON "INTERPOLES IN SYNCHRONOUS CONVERTERS," NEW YORK, NOVEMBER 11, 1910.

Gano Dunn: This subject comes under the head of commutation, which Lord Kelvin used to lament was neglected in former years by the drawing away of the best minds in electrical engineering from direct current problems to the more interesting and complicated alternating current problems; although Lord Kelvin also said the problems of commutation were really more complicated than the problems in alternating current for which they were neglected.

To-night's paper, with the discussion expected, shows that the best minds are coming back again to the old subject of commutation, with a resolve to solve some of the difficulties that have been waiting so many years asleep, for the kinds of men that are now giving them attention.

There are two kinds of commutation; magnetic commutation, and what may be called resistance commutation, although the resistance referred to is that of the contact of the brush with the commutator and produces an effect similar to what would be produced by a counter electromotive force at this contact.

Resistance commutation depends upon this so-called counter electromotive force of contact under the heel of the brush for the reversal of the coil.

Magnetic commutation depends for the reversal of the coil, upon the direct electromotive force generated in it by either the magnetic fringe at the pole tip or by an auxiliary pole.

Under the action of the auxiliary or commutating pole the current in each coil of the arch of coils approaching the commutating region, is reversed at the same time that the coil is transferred from the approaching to the receding arch.

All commutating or interpole subjects belong under the head of magnetic commutation.

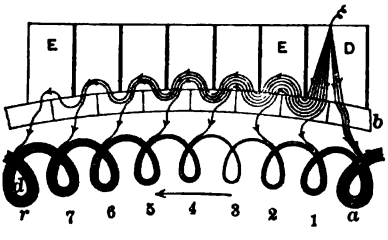
Interpoles have been known for many years, my first discussion of them being in a lecture delivered in 1893, but for many reasons, which this is not the occasion to mention, they were not taken up for constant speed machines until, when either through increased size or increased speed and after the number of turns had been decreased to one per bar, the volume of current loaded on the armature turns of dynamo electric machinery became larger than a carbon brush could, by resistance commutation, satisfactorily reverse.

A further reduction of turns per bar was impossible for the same reason that you cannot make a clock that will strike less than one, and there seemed at that time to be no known means of increasing the so-called counter electromotive force of contact of the brush. Interpoles were therefore resorted to, for the proper turning over of the heavy currents in the coil which had grown beyond the capacity of the brush to handle in the time allowed.

When taken up, interpoles were adopted very rapidly, becoming a fad and being used in many cases where they were not, as physicians say, " indicated," and I am glad to see in the paper a conservative tendency in regard to their use in rotary converters.

I wish to point out an improvement that has been made in resistance commutation, which may increase the range of applicability of that type of commutation into the field of interpoles. It is not yet satisfactorily developed commercially but may be of use as an alternative to the interpole, to those who are searching for means for improving the commutation of rotary converters.

I refer to what I have called fractional commutation, the principle involved in which was developed by Mr. F. W. Young and was mentioned at the Asheville Convention of the Institute. It applies particularly to machines whose voltage is, in a direct current sense, high. The improvement depends upon an increase in the counter electromotive force of the brush contact by putting a number of these contacts in series with the coil that is about to leave the brush.



If in the accompanying figure, *b* represents a commutator moving to the left and *D* represents the main brush connected to the line, and *E* and the brushes next to it represent brushes that are neither connected to the line nor to each other nor to the main brush *D*, but all dead and merely lying adjacent to each other in such a relation that each brush has the width of a commutator bar, then as the commutator moves to the left the last thread of current that is about to be sheared off from entering the coil *R*, it will be seen has had to travel successively from the main brush *D* against approximately one volt counter electromotive force into the commutator bar under it, then back upward out of the commutator bar against another one volt counter electromotive force into the first dead brush *E*, then down again through another counter electromotive force into the next commutator bar, then up again into the next dead brush, and so on, and in the case shown in the figure, assuming one volt counter electromotive force for each contact surface past, will have encountered thirteen volts counter electromotive force.

It is this last thread of current that makes the spark, and while the number of dead brushes used in the figure is large, merely to illustrate the principle, it is astonishing what excellent results are obtained with only two or even three dead brushes.

With three dead brushes there are seven volts counter electromotive force, which gives results comparable to the best that interpoles can do.

One dead brush alone increases the counter electromotive force at the heel of the main brush, from one volt to three volts, and roughly speaking extends to three times its former range, the powers of resistance commutation.

The reason for calling the method of commutation I have here described, fractional commutation, is that it secures the reversal of the current in the coil step by step, a little at a time as the coil passes each dead brush.

The fractional nature of the commutation can easily be seen by counting the number of threads of current running to each coil in the diagram. This illustrates quantitatively about how the current would actually change in the coil as it passed from a position on the extreme right of the figure to a position on the extreme left.

The net results are: The total time a coil is subjected to the influence of commutation is increased. In other words, the coil has warning of what is going to be expected of it in a way it does not have when there is only a single brush. And the electromotive force available for compelling the turn over of the coil is increased many times over that a single brush is capable of developing.

This system of fractional commutation does not seem applicable where currents are large and where commutator bars are wide, but with tendencies toward higher voltages with a corresponding diminution of current, and toward increase in the number and fineness of commutator bars, we can afford to give more commutator space to the purposes of commutation than formerly. I believe there is a principle in this method, that with some further development can be made extremely valuable and is well worthy of study. I have spent considerable time on it and conducted a great many experiments, with results, that while not yet commercial, indicate that the principle is sound. In certain cases fractional commutation of this kind would have many advantages over the magnetic commutation of interpoles.

H. F. T. Erben: The paper which has just been read is a clear exposition of the subject of commutation and general operation of synchronous converters with and without commutating poles.

While I agree with the general conclusions arrived at in the paper I do not think the authors dwell at sufficient length on one of the broadest fields of usefulness for converters with commutating poles, namely, for those operating on interurban service and for high voltage converters wound for 1000 to 1500 volts. The machines I refer to are those in which the general characteristics of design are determined solely by commutating conditions at heavy overloads and not by any consideration of heating. It seems to me that the conclusions which the authors of the paper have drawn regarding the advantages and disadvantages of commutating pole converters are pertinent principally to units used in connection with large central station systems in which the prime consideration of design is not commutation but heating, efficiency, and low maintenance. Synchronous converters installed in our large cities in connection with railway work have as a rule a very constant duty and are not subject to heavy overloads, the maximum as a rule not being greater than 50 per cent overload and in consequence I agree that for such service interpoles are unnecessary. On the other hand, converters used in connection with interurban service have a very low load factor but are subject to very heavy overloads, possibly two or three times normal and for such service I believe that commutating poles are a necessity.

During the past few years a number of 1200- and 1300-volt interurban systems have been put into successful operation and as a rule the generating apparatus has consisted of either two, 600-volt generators or converters in series. Single generator units wound for 1200 volts with commutating poles have been in successful operation for the past two or three years and at the present time some 1600-volt commutating pole generators are being built. I venture to predict that within two years we shall see 1200- or even 1500-volt single unit synchronous converters in operation on long interurban lines. I do not believe that any designer would be willing to build a 1200- or 1500-volt converter without providing commutating poles, as he is faced with the problem of producing a machine which is capable of withstanding momentarily overloads of two and three times normal without severe sparking or flashing, which is a condition very difficult of attainment on machines of the non-commutating pole type.

The experiments which we have carried on in connection with 1200-volt, 25-cycle converters show that if the commutating poles are properly proportioned, little is to be feared in the way of flashing within what one might consider the limits of daily service. We have repeatedly subjected a 750-kw. 1200-volt converter to four times normal load without any signs of flashing when the load was suddenly removed. In order to determine the damage, if any, resulting from flashing caused by a dead short circuit, we have repeatedly subjected the same converter to short circuits through a few feet of cable. Although the flash produced was of large volume we found that neither the commutator leads, brush-holders nor brushes were damaged to any appreciable extent. In fact, after the machine had been short-circuited six times it was immediately brought up to normal load and overloads without appreciable sparking.

I believe that the authors have laid too much stress on the effect of the various magnetomotive forces in connection with flashing. A long series of experiments made to obtain data on the flashing of various types of machines at time of short circuit has shown that there is little to choose, as far as flashing goes, between direct-current machines of the non-commutating pole and commutating pole type. Of course, commutating poles or compensating windings will help to a certain extent but if the short circuit causes the armature current to rise to say ten or fifteen times normal, the machine will surely flash over.

The authors call attention to the fact that when subjected to a dead short circuit a synchronous converter will behave differently from a generator, due to the fact that the commutating pole of the generator will become highly saturated, whereas the commutating pole of the converter will not have reached saturation. If one considers that at the time of a short circuit on either a rotary or generator the current may rise to fifteen to twenty times normal, such an increase in magnetomotive force will be sufficient to over-saturate the commutating pole, although in the case of the converter the value of the magnetomotive force will be less than on the generator.

The authors have stated that an inductive shunt used in connection with a generator or rotary may be of considerable value in helping commutation at the time a heavy load is thrown on but it might be a detriment when the load is thrown suddenly off. I hardly agree with their conclusions, as it has been shown in actual practice that a properly proportioned inductive shunt will cause the flux in the commutating pole to instantly drop to zero, in fact the inductive shunt may be so proportioned as to actually reverse the direction of flux in the commutating pole at the instant the breaker is opened. If the flux in the commutating field can be instantly brought to zero or reversed as has been shown possible by oscillograph records, there will be little or no chance of the machine flashing over except of course, in case of what is practically a dead short circuit.

C. P. Steinmetz: I agree with the conclusions in this paper in their general nature. They are that the commutating pole offers relatively little if any advantage in improving the design of the converter as at present built. There may be a slight advantage in 600-volt 25-cycle converters, which means that in 1200-volt, 25-cycle converters there would be a greater advantage and a still greater advantage in 2400-volt, 25-cycle converters; the former are with us now in operating 1200-volt railway service, and the others I believe will come at a not far distant future.

The paper is very interesting in showing that in electrical engineering investigations the conclusion which we arrive at depends very largely on the view point regarding conditions of operation and application of the apparatus. That is, they depend on the premises on which the study is based. In this paper a converter is considered with the design constants proportioned as they are today in large converters operated on steady service in our big lighting systems, at 250 volts, and on our big metropolitan railway systems, of very steady loads; and in this class of converters there is relatively little gain in the use of commutating poles. But let us take another view point, starting from different premises as regards the requirements of operation and see whether some different conclusions may not be derived. The overload capacity of the synchronous converter depends on the supply system, the heating limit, and the sparking limit. The supply system can be controlled by its design. If a converter in an interurban railway system has to stand overloads of 300 or 400 per cent, it means that the feeder or the transmission line must be sufficient to give that load without a drop of voltage such as would disturb the machine. If the load is steady and uniform the heating limit is a material limit. If the load is widely fluctuating with relatively low load factor, as in interurban railway service, where the load rapidly fluctuates between almost no-load and a load of short duration amounting to several hundred per cent overload, then the heating limit is eliminated, because the greatest length of time at which the converter may be overloaded is only the time that the train passes over that section, a few minutes, and during that interval the heating limit, even at three or four hundred per cent load, is not reached. That means that the only limit of overload capacity is the commutation limit. In the converter the armature reactions neutralize. Thus the sparking limit is determined by the self induction of commutation and this is controlled by the commutating poles.

It will be seen in that class of service, which is quite common and constantly increasing, where the load is very fluctuating, the load factor very low, and where, therefore, the only limit of overload capacity is the commutation limit, the commutating pole offers us a very material advantage in the design of the synchronous converter, by making it possible to greatly increase the overload which the machine will carry. In other words, for the same kind of service, we can build a converter whose rated load is much smaller and thus much nearer the average load. That is to say, we very greatly increase the load factor of the machine as based on its rated load, and therefore its efficiency of operation, and the efficiency of operation of the station and of the entire system.

When we come to an interurban railway system with infrequent heavy service, this feature may be and often is the difference between success and failure of the system; the nature of the load is so fluctuating, of such a low load factor, that we can get efficiency of operation only by a machine which can carry for a short time enormous overloads. Hence, as the heating limit is absent, the commutating pole gives us a very material advantage by making a smaller and a lighter machine. It is not only this advantage of better load factor, but coincident therewith is the advantage gained in the lesser liability to hunting, because the hunting of a synchronous machine is determined largely by its mechanical momentum, and if we can decrease the momentum of the machine by making it smaller it means that we will have greatly improved its stability.

As regards the danger of flashing due to unbalanced armature reaction, as illustrated in the paper, I will say that theoretically, the problem is there, but practically I do not believe it is material for the reason that I do not think that such unbalanced armature action can exist to any appreciable extent. If, as illustrated, the armature reaction should be unbalanced by a sudden heavy load thrown on the machine, without any corresponding or neutralizing alternating m.m.f., it means that the energy output will have to draw on the momentum of the converter by a decrease of speed. But we know that the converter cannot decrease in speed because it is locked synchronously. So it cannot gain any energy from the mechanical momentum except that insignificant amount corresponding to the drop in position—not in speed—from no-load position to the overload position, which, in a converter where the reaction is balanced, is extremely small. If we cannot draw on the mechanical momentum for energy, either the energy will not flow out and the machine will not take the load instantly, or it must at the same time flow in and then the reaction is balanced. The same thing happens again if you suddenly throw off the excessive overload. That means that the power input would accelerate the machine. But synchronism eliminates the chance of acceleration, so that we get only the momentum of the speed which shifts the machine from the relative position corresponding to one load to that of another load; that is, a momentum which involves a fraction of a cycle. But even this effect eliminates itself, because if the machine shifts from one position to another position by dropping back or running ahead, then it does not only drop into the new position, but it runs beyond it before it stops. That means it overreaches, and if there was an excess of the direct current it must be followed instantly by an excess of the alternating current and inversely, which reverses the former's effect.

Since the poles are solid iron, I do not see how you can get any appreciable effect in this direction, especially if the mechanical momentum of the machine is very small, due to its enormous overload capacity. So the momentum on which you can draw to give an output is very small. That possibly explains why converters designed with commutating poles even at very high voltages, 1200 or so, do not flash over under conditions of operation under an excess of overload, as it was expected theoretically that they would do.

Jens Bache-Wiig: In the paper by Messrs. Lamme and Newbury the probable effect of the interpoles in case of a sudden short circuit on the direct current side of the converter is brought out. It is reasonable to assume that the presence of the interpoles in case of a short circuit will tend, if anything, to increase the injurious effect on account of the unbalanced ratio between the armature and interpole ampere-turns, as pointed out in the paper. As is well-known, the effect of a short-circuit upon the converter often results in the voltage flashing over and, in consequence, the commutator and brush-holder parts are badly burned. The effect may be such that it is necessary to shut down the converter and clean it up before starting again. The large current flowing during the short-circuit will form an arc between the nearest points of different polarity and it will to a great extent depend upon the action of the alternating-current circuit breaker how bad the effect will be. Ordinarily, it is the alternating-current circuit or the power behind the rotary which determines the flow of short circuit current. Therefore, if this power behind the rotary could be eliminated at the moment of the short-circuit, the effect of the latter upon the rotary would be greatly reduced and would be determined only by the inherent characteristics of the rotary itself. The action of the rotary in case of a short circuit on the direct-current side would then be approximately the same as that of a direct-current generator of similar size. The injurious effect in this case would be small, as brought out in the paper.

It is customary to protect the converter on the alternating-current side by a circuit-breaker, having a maximum relay set for a certain current at which it is supposed to open the circuit and throw the converter off the line. Similarly, it is customary to have a maximum relay breaker on the direct-current side. In case now of a short-circuit on the direct-current side, a large momentary current will be drawn from the converter greatly exceeding the actual current required to open the direct-current breaker. As soon as the direct-current breaker lets go, this current which is rushing through the rotary will suddenly be brought to a stop and it is this sudden change in the flow of current which usually causes the flashing, in combination with the fact that the direct-current breaker lets go before the alternating-current breaker. This now can be overcome by arranging for an electric interlock between the direct-current and alternating-current breaker in such a manner that the alternating-current breaker lets go at the moment the direct-current breaker drops out. This can be arranged for by a tripping coil on the alternating current breaker operated by the direct-current breaker. In this manner the danger of flashing due to short circuits on the line can be greatly reduced if not wholly eliminated. This is of special importance in case of interpole converters.

As to the effect of such an arrangement from an operating point of view, there should in case of self-starting converters be no objection to it. It is true that the converter is altogether thrown off the circuit and may be thrown off oftener than would be the case if it was not arranged in this manner. However, if the attendance is present in case the breaker goes out, all he has to do is to throw it in again, and thus get it back in service at once. If he is not there, it is in most cases better to have the rotary stay out of service than it is to take any chances on flashing and its possible evil effects.

As regard the presence of the interpoles in case of hunting and their effect upon the operation of the rotary under such a condition, it may be said that while the interpoles may to an extent cause a less satisfactory operation than would be obtained without them, yet, with the present complete type of damper employed on many synchronous converters the liability of hunting in itself is practically eliminated. Barring the common causes for hunting which are excessive ohmic line drop and periodic impulses set up by the prime movers, as these can be guarded against in a well-designed power circuit, there remains as a source of hunting the possibility of short circuits on the system or the switching in and out of large units, causing heavy surges in the power circuit. However, in case effective dampers are employed, the hunting caused by these surges as quickly damped out and the effect will be of such short duration that it should not be harmful to the rotary. In case of a dead short circuit, the rotary will of course kick itself out and will have to be started over again. It seems evident, therefore, that the highest grade of dampers should be employed wherever interpoles are used on the rotary converters.

P. M. Lincoln: This term " interpole " has been somewhat loosely used. Interpoles in synchronous converters are used for more than one purpose. The kind discussed in this paper is used purely for commutation purposes. An interpole or split pole, has also been used for the purpose of varying the direct-current voltage, and I have noticed in some of the literature a confusion in the use of these two kinds of poles. In fact, in reading an abstract of an article in a foreign journal some time ago it was impossible for me to tell whether the author was discussing interpoles used for commutating purposes or interpoles used for the purpose of changing the direct-current voltage.

This paper is exceedingly clear in its presentation of the method by which the interpole works. The authors show very clearly that the inherent commutating characteristics of the rotary converter are very much better than they can possibly be in the case of the alternating-current generator. Any one can get this information for himself if he will endeavor to run a rotary converter as an alternating-current generator. Sparking at the commutator will begin at a point which will astonish the man who conducts the experiment unless he knows what to expect. One can take liberties with the commutation of a rotary converter for the reasons set forth in the paper, *viz.*, because the armature reaction due to the direct-current flowing, is practically all neutralized by the alternating-current.

It is also shown in the paper that a commutating pole on the rotary converters is necessary only in extreme conditions. It is only when the speed or the output reaches a high value that it is necessary to resort to the commutating poles in the rotary converter.

This brings out another point which might be mentioned, and that is that if conditions requiring commutating poles are approached in rotary converters it is impossible in such a condition to use the split-pole rotary converter because the latter does take considerable liberty with the commutating conditions

J. L. Burnham: The authors of this paper state that there is a limit to speed and reduction in number of poles, which cannot be exceeded with economy. For instance, for 25-cycle, 600-volt converters, it has been found that an output of about 150 kw. per pole is the maximum that can be handled economically without the use of interpoles where the usual specifications of 50 per cent overload for two hours and 100 per cent overload momentarily are to be fulfilled. This is on the assumption that commutation is to be good enough with ordinary carbon brushes for commutator and brushes to maintain good surfaces and require a small amount of attention. The output per pole may exceed this value by the use of very high grade and expensive brushes and greater maintenance, which may not be justified by the decrease in cost of the machine. With greater output per pole, the pole pitch must be increased to take care of the increase in size of conductor, slightly, but to a greater extent to decrease the reactance voltage to a value which will not cause excessive sparking. The limit in reactance voltage is really the factor which prevents the use of a less number of poles, since when we increase the pole arc to reduce the reactance factor in the slot portion, we increase the length of conductor outside of the slot portion, which adds to the reactance voltage and the gain in reduction of the total reactance voltage becomes less the longer the arc. In a 600-volt, 25-cycle machine, the reactance voltage generated in the conductor outside of the slot is about two-thirds of that generated in the conductor inside of the slot, when the output is 150 kw. per pole. If we attempt to increase the output, keeping the total reactance the same, the machine becomes very much larger than would be necessary with an economical proportioning of iron and copper. It is at this point that the introduction of commutating poles to increase the output per pole is of advantage.

Messrs. Lamme and Newbury have given a number of reasons why interpoles on synchronous converters may not work out as well as on direct-current generators or motors. In all of these cases the reason hinges on the fact that the ampere turns necessary for the interpole of a synchronous converter are much less than required for direct-current generator and very much smaller in proportion to the armature reaction ampere turns of the converter armature. This naturally leads to the suggestion that the required ampere turns of inter pole winding might be increased to advantage. Several months ago I conducted a number of tests, with various shapes of interpoles and lengths of air-gap, on 25-cycle, 1200-volt synchronous converters and found that with a narrow inter pole face and a very large gap, commutation comparable to that obtained with a compensated commutating pole generator could be secured. The load at which sparking would commence, without interpoles, was carefully determined. Interpoles were then fitted to the machine and adjusted so it would carry four times the load to cause the same sparking as without the interpoles. Four times full-load could be thrown on and off successfully but would always be accompanied by a slight spitting at the brushes. I attributed this to a shifting of the magnetic centres of the poles due to change in flux through the interpole and also to slight change in relative position of armature to poles, due to change in losses in the converter rather than to lag in change in commutating field. That is, the effect would be the same as produced by pulsation when the armature swings out of phase far enough to cause sparking, or when the machine is badly synchronized and thrown on to the power circuit slightly out of phase and spits at brushes several times.

Contrary to the statement of this paper, that a shunt to the commutating winding having greater inductance than the winding would be harmful, it was found in these tests that a shunt having about 50 per cent greater inductance than the winding of commutating pole gave the best results, particularly when the load was thrown off. The two circuits being in multiple, the higher inductance would reverse the current in the smaller, which reversed current would reduce the field flux more rapidly than would no current, as in the cases of equal inductance of field windings and shunt or with no shunt.

The effect of pulsating resultant armature reaction under the interpoles will be reduced in proportion to the increase of reluctance of the interpole magnetic circuit. Increasing the air-gap is the best means of increasing this reluctance since it introduces no effects of saturation.

As might be expected, the addition of interpoles causes more sparking at the commutator when starting from the alternating-current end than would be obtained without the interpoles, due to the decreased magnetic reluctance of the induced field at the point of commutation. This can be greatly improved by the large air gap and narrow commutating pole face previously mentioned.

Mr. Lincoln has pointed out the fact that commutating poles cannot be used with success on split pole converters. I would also like to add that this statement also applies to converters with direct-connected alternating-current boosters, but for somewhat different reasons. The synchronous booster when adding its voltage to the line is acting as a generator requiring corresponding motor action in the converter. When the booster is opposed to the alternating-current line voltage, it acts as a motor and drives the converter. This motor and generator action of the converter superimposed upon the converting action gives armature reactions the same as if the converter were acting only as a motor or generator. As the motor and generator reactions are in opposite directions, the total variation for ordinary conditions might easily equal the total excitation of the winding on the commutating pole adjusted for converter action only. For example, an average value of the commutating pole ampere turns would be about 30 per cent of the armature reaction. An ordinary voltage regulation would require 15 per cent boost or buck, or in other words, a motor and generator action of 15 per cent of the output. This would give a variation in armature reaction of 30 per cent, which is equal to the total full-load excitation of the commutating pole winding. Several arrangements for varying the commutating pole excitation with variations in the amount of buck or boost, as well as with variations in load, have been worked out, but they are at best rather complicated and undesirable.

C. W. Stone: Dr. Steinmetz has said practically all that I wanted to say, but I am going to try to express it in a little different way. There is one clause in the paper which is not quite clear, possibly I misinterpret what the authors mean. However, I think it is well to bring the point out more clearly. The authors say:

" Assuming the direct current in the winding as A, then the maximum value of the alternating current in any one phase of the alternating current end will be equal to $\frac{2}{3}$ A or 0.667."

I think that the authors should have said the current in the direct current leads instead of the winding, otherwise, the value would be double that stated in the paper.

I think the principal point in connection with the interpole and its use on synchronous converters, is the point raised by Dr. Steinmetz, and that is, the greater capacity that can be obtained for momentary overloads. If, as Mr. Burnham pointed out in his remarks, the momentary overload on a machine without injurious sparking can be increased to four times as much on the machine without interpoles, it is possible to use small machines in interurban railway substations. In other words, we could, in many cases, put in 200-kw. machines where 400-kw. machines are now used, which would mean economy.

The principal reason, I think, why this has not been done, has not been because the manufacturer did not want to do it, but because the operating engineers did not like to try the experiment.

I hope that this paper will cause the operating people to try this experiment in some place, and I think that the result will astonish them, and it may result in a total revision in the practice of synchronous converter substation design on interurban roads.

The authors of the paper state that the principal application would appear to be in that of 25-cycle, 600-volt converters. This, to my mind, is the smallest application. The broadest application would be that of high-voltage rotary converters, and high frequency rotary converters, and also, as stated above, for rotary converters when installed on loads which are greatly fluctuating.

It would seem to me that the conclusions which the authors reach relate more to the synchronous converter substations installed on city loads rather than on loads such as are usually found in interurban service.

One point which Mr. Lincoln spoke about in his discussion is, that with synchronous converters the alternating-current circuit-breaker opens and thus limits the damage in case of a short circuit. This is, of course, true. With the ordinary direct-current generator, driven by some form of alternating-current motor, the action of the circuit-breaker is not so quick, that is, the alternating-current circuit-breaker does not open as quickly, and the flash-over which is the cause of the short circuit will cause greater damage than on the rotary converter.

Mr. Lincoln speaks of the flashover as being caused by the sudden change in the current flow due to the circuit-breaker opening. I do not think this is usually the cause. My conception of the flash-over is that it is caused more by the sudden increase in current, which necessarily forms more or less gas at the point of contact of the brush and commutator. This gas is of low conducting value, and it is not only immediately beneath the brush but surrounding the brush, and on account of the low resistance of this gas a large arc is formed by the current passing through the gas, which creates more gas, and due to the fact that the commutator is revolving away from the brushes a part of this gas and the arc are carried over to the next brush holder and cause the flash-over.

To sum up, I think the principal advantages in the use of the interpole on synchronous converters is the possibility of using small machines to do the same work that larger machines are used for; the possibility of building successful high voltage machines, and the possibility of building high frequency machines of large capacity.

C. A. Adams: At the last meeting Professor Franklin prefaced his remarks by the statement that he found it difficult to divorce himself from the attitude of the teacher. I find myself in that same state of mind to-night. The first thought that came to me when reading this paper was that it would be an excellent one for purposes of instruction.

The greatest difficulty in teaching a subject of this kind is to bring about a thorough understanding of the phenomena involved. This cannot be done for the average student by a mathematical analysis of the problem in hand; but, since a mathematical analysis is much easier to prepare than a clear verbal exposition, and since some algebraic formulation is generally necessary for purposes of computation, the average author feels that he has covered the ground if he adds a few words of explanation to his mathematical solution. There results an abuse of formulae by those who do not understand their true inwardness and a general lack of appreciation of mathematical analysis on the part of others.

It is therefore a great pleasure to read such an admirably clear verbal presentation as that which appears in the paper under discussion. It is sure to be a great help to students of this subject. I congratulate the authors most heartily.

I had hoped to present a simple algebraic analysis showing the quantitative relations between the kilowatts per pole of a synchronous converter and some of its fundamental design constants, but it is not yet finished and in any case would better appear in print as a communication.

B. G. Lamme: I will take up a little time in answering some of the points brought out in this evening's discussion, but will not attempt to answer them in full. I also have a few additional points which I would like to bring out, which were not included in the paper of the evening, because it would have made it of undue length.

Reference has been made to the use of converters with very large overload capacities for interurban practice, and it was stated that for such a service interpoles would be advantageous. While not contending that interpoles would not be advantageous, I will call attention to the fact that for interurban service as now carried on, most of the converters furnished have been of 200 to 500 kw. capacity. Such machines, as now built, have a relatively small capacity per pole and therefore their commutating conditions as regards overload, etc., can be very much better than in very large capacity converters with large outputs per pole. Consequently, a modern design of a 300-kw., 600-volt converter, for instance, should allow commutation up to three or four times full load without excessive sparking, and even much higher than this without flashing. I have seen such machines loaded until the limit was found in the current-carrying capacity of the brushes and not in the sparking. However when machines of greater capacity are taken into account, with much larger outputs per pole, then with excessive overloads the advantages of interpoles will become much more pronounced.

Reference has also been made this evening to the use of interpole converters on 1200- and 1500-volt circuits and it has been intimated that interpoles bring up the possibility of making 2400-volt converters for 25 cycles, and also high-voltage, high-frequency converters, 1200 volts presumably being meant by this latter. Some reference was also made to the use of interpoles for helping the commutation of high-voltage converters which, it was intimated, suffered somewhat in comparison with 600-volt machines due to poorer proportioning of slots, etc., on account of the high-voltage winding.

I have gone into this problem of high voltage direct current generators and converters to a very considerable extent and, according to my figures, I find that the real limit in such machines is not in the commutation as much as in the mechanical conditions, such as peripheral speed of the commutator, thickness of commutator bars, etc., and also in the permissible voltage between bars. To illustrate this, let us assume a 25-cycle, 1500-volt converter. To begin with, the peripheral speed of the commutator, as mentioned in the paper, is equal to the ***alternations per minute multiplied by the distance between adjacent neutral points on the commutator.*** This is a general law and applies in all cases regardless of frequency, number of poles or revolutions per minute. Let us assume, on our 25-cycle machine, a commutator peripheral speed of 5,000 ft. per minute, which is pretty high. This gives a distance of 20 in. between adjacent neutral points and this is the maximum distance which can be obtained with this peripheral speed and frequency, regardless of the number of poles and revolutions per minute, or any other conditions. Assuming a thickness of a single commutator bar plus its mica as $\frac{3}{16}$ in. which every body will admit to be very thin, then the total number of bars which can be placed in this 20-in. space will be 107. With 2400 volts this gives about 22½ volts per bar as the average. This is much higher than is considered good practice in 600 volt machines, and naturally one would not expect to do better with 2400 volts than with 600 volts. In fact, for the same margin of safety, as a whole, we should have somewhat better conditions with 2400, or even 1200 volts, than is required with 600. However, with 107 commutator bars, which was given as possible, it may be practicable to operate at 15 volts per bar average, which will give, roughly, a 1600-volt machine as a possibility on 25 cycles. It should be remembered, however, that this is on the assumption of 5,000 ft. per minute speed of the commutator and $\frac{3}{16}$ in. thickness of commutator bar plus mica. Any reduction in the peripheral speed, or increase in the thickness of the bar, will at once lead to a smaller number of bars with a correspondingly higher voltage between bars. As an example of the approximate limit to the average voltage per bar, the company which I represent has in the past, furnished a large number of converters for 600 volts with 36 commutator bars per pole, giving 16⅔ volts per bar average. From long experience, this appears to be rather close to the limit and on later designs of 600 volt machines this voltage per bar has been reduced about 20 per cent.

Next, considering a high-frequency, high-voltage converter, and again, assuming 5,000 ft. commutator peripheral speed for a 60-cycle machine, then the distance between adjacent neutral points on the commutator becomes 8.4 in. With $\frac{3}{16}$ in. of bar plus mica, this gives 45 bars as the maximum number. For 1200 volts this means almost 27 volts per bar average, which I would consider as entirely too high for low-voltage machines. It should be noted that in neither of these cases has the question of interpoles been brought in, and the use of interpoles cannot in any way affect these conditions. The use of two windings and commutators in series on the same armature might be considered, but the arrangement is awkward and complicated.

As to the commutation of a high-voltage machine being inferior to a low voltage, this would not necessarily be true. On the contrary, the commutation should be better in some instances. Assume, for example, that the commutator has a certain number of commutator bars for 600 volts with one armature turn per bar. If the number of commutator bars is doubled for the 1200 volts, then the number of armature turns per commutator bar would remain the same. If the same number of poles were used at 1200 volts as at 600, then the current per conductor would be halved and the commutating conditions would be about twice as good as on the 600 volt machine. However, in practice this result will not always be obtained, for the number of poles may be reduced somewhat in the high voltage machines, except in the smaller capacities, such as 300 to 500 kw. where a small number of poles is already used for 600 volts. However, taking everything into account it would appear that in general the commutating characteristics of 1200-volt machines of the usual capacities ought to be as good as, or better than, those of 600 volts regardless of the question of interpoles.

The statement was made this evening, that it was found in general that 150-kw. per pole was about the limit of output which would be obtained with ordinary non-interpole converters. This figure agrees fairly well with those given in our paper, but attention should also be called to the fact that this rating per pole is also approaching close to the limit of cost, that is, when the output per pole goes much above this a larger number of poles can be used with practically the same cost per machine.

The point has been brought out this evening that the real field for the interpole commutator is where the loads are very intermittent and where the peaks are very high and of comparatively short duration, such as in certain classes of railway service, etc. In general I agree that it is wrong to put in a larger machine to do a certain service, simply to obtain momentary overload capacity. If a 200-kw. machine, for instance, can handle a certain average service, while a 400-kw. machine is installed simply to take the swings or peaks, then if the smaller machines can be made to take these swings by the use of interpoles, and cannot be made to do it without the interpoles, the interpoles will certainly represent an improvement in such cases. On the other hand, it must be borne in mind that in small units, such as from 200 to 400 kw., the machines would be made normally with four poles and, such being the case, then with well proportioned windings the commutating characteristics of a 200-kw. machine can be made considerably better than those of a 400-kw. relative to its normal rating; that is, the 200-kw. machine could be made to commutate almost as much total overload as the 400, while its average losses are considerably lower.

Such a 200-kw. machine could possibly be made of a somewhat cheaper construction, if its inherent commutating characteristics were sacrificed somewhat and then again improved by the use of interpoles. However, part of the gain from the reduction in the size of the machine is lost in the addition of interpoles. On the whole, however, such a machine with interpoles may be somewhat more suitable for very intermittent service than the equivalent non-interpole machine. But, when it comes to large capacity units for very intermittent service, then the use of a smaller rating machine, corresponding to the average load, would naturally tend toward the choice of a higher speed when such is possible, and the conditions result in those mentioned in the paper as being advantageous for interpoles. For instance, if a 1500-kw. machine is required for very intermittent service, in which the average load is 750 kw., then we might take a machine with a smaller number of poles than required for the 1500-kw. rating. With this smaller number of poles and higher speed, the extreme limit of commutation would naturally be lower than on the 1500-kw. slower speed size, and therefore by the addition of interpoles the commutating limit may be raised so that this smaller machine would handle the same peak service as the larger machine. In such a machine the real limit is not in the mechanical conditions, such as the commutator construction, but in the commutating characteristics, and therefore it could advantageously be made of the interpole type consistently with the conclusions drawn in the paper.

In the discussion this evening, the assertion has been made several times that the interpole type of converters will not flash any more readily on short circuit than the non-interpole type. In reply to this I will say that this is a very difficult question to determine definitely in commercial service, as it is difficult to find exactly comparable conditions. Reports which I have received from time to time in regard to 600-volt interpole converters in actual service are to the effect that the operators of the machines considered them somewhat more sensitive on short circuit than the non-interpole type, although under normal operation, and especially under heavy overloads, the comparison is slightly in favor of the interpole type. However, as stated before, it is difficult to make an exact comparison, for two different size converters, built along the same designs, will not always operate exactly alike. It seems to me in regard to this question of flashing on short circuit, that the real remedy is to eliminate, as far as possible, the cause of the short circuits. Violent short circuits on large railway systems are liable to cause troubles other than in the converters themselves and every endeavor should be made to reduce the short circuits to a negligible number. If the short circuits can be made infrequent enough, then any possible difference which there may be between the interpole type and the non-interpole type as regards flashing would be of no moment. It should be noted also, that such short circuits are confined almost entirely to railway service, while in industrial power service and in lighting they may be considered as extremely rare.

Some question has been raised this evening regarding the statements in the paper that in case of sudden overload or short circuit the alternating-current and direct-current magnetomotive forces will not balance each other and that the machine will operate momentarily as a direct-current generator, with a correspondingly high armature reaction. The basis of the criticism is that the converter, being a synchronous machine, cannot change its speed except for a very short period, namely, that occurring within a small fraction of one cycle, otherwise the machine would fall out of step. For such a small change in speed, it was argued, very little energy could be given up as a direct-current generator as there is not enough stored energy in the converter armature to give up much energy as a direct-current generator without falling out of step.

At first thought, such an argument seemed reasonable, but one answer to it is found in the operation of a synchronous converter on a single phase circuit. In such operation the energy supplied to the alternating current end *falls to zero twice in each cycle, while the direct-current output remains practically constant.* The alternating-current input must therefore vary from zero to far above the direct-current output of the machine. The converter must therefore act as a direct-current generator, for a brief period, twice during each cycle. When it is considered that such a converter can operate with more or less sparking up to three or four times full-load current, or even much more, depending upon the design of the machine, it is obvious that the converter can deliver very heavy outputs momentarily as a direct-current machine without falling out of step.

Also, a little calculation will show that with an ordinary design of synchronous converter the stored energy in the armature is such that, in dropping back as much as 45 electrical degrees in position, the armature could give up an enormous energy compared with its normal rated capacity. If it were not for this it would not be possible to run the machine on heavy load on a single phase circuit.

That is all I will say in regard to the points brought up in the discussion. However, there are several points I want to bring out in connection with the paper itself. In the first part of the paper it is stated that the ampere turns on the interpoles of a direct-current generator are always greater than the ampere turns of the armature winding. This statement is not correct in all cases but in those arrangements which depart from this rule, direct-current generators and converters would be affected in the same way so that for comparative purposes the statement in the paper may be considered as correct.

When there are as many interpoles as there are main poles it is correct to say that the ampere turns on the interpoles should always be greater than on the armature. However, in some cases, especially on small machines, the number of interpoles on direct current machines is made only half as great as the number of main poles. There are several advantages in this arrangement and they apply equally well to generators and synchronous converters. Obviously where only half as many interpoles are used the commutating flux or field of each interpole must be at least twice as strong as when the full number of interpoles is used, as the opposing e.m.f. set up by the interpoles must be sufficient to overcome the e.m.f. of self-induction, regardless of the number of interpoles. This opposing e.m.f. need not be distributed over the whole armature coil, but could be located over either side of the commutated coils or even along a short portion of its length. It is only necessary that this opposing e.m.f. should have the proper value, while the distribution of it seems to be of relatively less importance. It should be understood, however, that the use of half the interpoles is permissible only with drum-wound armature windings, where each armature coil spans approximately one pole pitch. Ring-wound armatures require the full number of interpoles.

Experience shows that when but half the number of interpoles is used the demagnetizing ampere turns, or those which directly oppose the armature magnetomotive force, should have about the same value *per interpole* as when the full number is used. However, the effective ampere turns which set up the commutating flux must be doubled in value, as just stated. Therefore the total ampere turns *per interpole* would be greater than when the full number of interpoles is used, but the total number of ampere turns on all the interpoles is much less than with the full number of interpoles. In consequence, there is a very considerable saving in the amount of copper required.

On account of the increased number of ampere turns per interpole when half the number of poles is used, the interpole leakage will be increased in proportion. This is particularly objectionable on large machines where the design of the interpole becomes difficult on account of magnetic leakage. Therefore this arrangement is usually confined to small machines.

A very considerable advantage in this arrangement is that the ventilating conditions are improved due to the fact that the interpoles and main poles do not so completely enclose the armature, for, with alternate interpoles omitted, the circulation of air between the armature and the field poles can be materially improved.

With interpole converters, with their smaller ampere turns per interpole, the omission of alternate interpoles will not have as much influence on the general design as in the case of direct-current generators. As the interpole ampere turns are only about 35 per cent as great as on a direct-current machine, and as about half is useful and half demagnetizing, it is evident that the useful component would readily be doubled, thus doubling the useful flux, while the total leakage would still be far less on a direct-current machine. Therefore the smaller number of interpoles is much better adapted to the synchronous converter than to the direct-current generator.

In the converter the use of the small number of interpoles also possesses a further advantage. In the case of a short circuit, and assuming a negative field to be set up by the armature reaction, as described in the paper, the use of half the number of interpoles would cut this reverse field to half value. In consequence, any flashing tendency would be proportionately reduced. Half the neutral spaces being without interpoles, and the other half having interpoles, it is evident that such an arrangement should be practically midway between a non-interpole and a full interpole converter as regards any flashing tendencies.

It is also evident that with half the number of interpoles the ventilating conditions will be improved just as on the direct-current generator.

The lower leakage in the interpoles of the converter allows another material difference between the design of the converter interpoles and those of the direct-current generator. In ordinary direct-current generators, especially those of large capacity, the interpoles, as a rule, are made almost the full width of the armature core, principally in order to maintain a lower saturation of the interpole core. As the width of the interpoles is varied the leakage flux varies practically in proportion to the width, but the total useful flux remains practically constant. Therefore, with wider interpoles the flux density due to the combined leakage and useful fluxes will be lower than if a narrower pole were used, and the saturation will be correspondingly reduced. In the interpole converter, however, the leakage flux being so much lower than in a direct-current generator, it is evident that the useful flux could be correspondingly increased while maintaining no higher saturation than on a direct-current machine. This, therefore, permits a much narrower interpole on the converter than on a direct-current machine. As the interpole becomes narrower than the armature the reverse field which may be set up on short circuit also should be proportionately reduced, so that with interpoles of practically half the width of the armature, the conditions should be practically equivalent to those where half the number of poles is used, as far as flashing conditions are concerned. The use of narrow interpoles should also allow better ventilation than when the full width is used. Narrower interpoles, of course, allow considerably less copper for the same total number of ampere turns. However, unless the interpoles can be made less than half the width of the armature, the amount of copper required for this arrangement would be still greater than would be required with only half the number of interpoles, each of full width of the armature.

There are many other points in connection with the use of interpoles on converters which were not mentioned in this paper. I will describe briefly a few interesting features which are encountered in the design of such machines, but which are not found in direct-current machines.

One of these concerns the application of dampers to interpole converters. It is found that the usual distributed cage type of damper supplied with self-starting converters is not directly applicable to the interpole converter. Dampers are supplied to synchronous converters for two purposes, namely, to prevent hunting and to obtain good self-starting conditions. To prevent hunting the damper should be thoroughly distributed through and around the pole face in the form of numerous low resistance bars or rods which are joined together at each end by low resistance connectors. There may or may not be any connection between the dampers on adjacent poles. In practice, with well proportioned dampers, such connection between the poles may be of some benefit, but this is difficult to determine as far as hunting is concerned. Those conductors embedded in the pole and immediately surrounding it appear to give all the damping action which is necessary if the damper is well proportioned.

However, when it comes to self-starting converters, that is, those which are started and brought up to speed by direct application of alternating-current to the collector rings, it is claimed by some designers that the interconnection between the adjacent dampers is of benefit at the moment of starting, by reducing the tendency toward dead points or points of very low starting torque. When started in this manner the armature of the converter becomes the primary of an induction motor, while the cage damper in the field poles becomes the equivalent of a cage winding on the secondary of an induction motor. It is claimed that the interconnection between the dampers to form a complete cage allows better polyphase action in the secondary winding. Any beneficial result of this should show in more uniform torque at start, but not to any pronounced extent in the apparent input required to start the converter and bring it up to speed.

When hunting occurs the magnetic field in the main poles is alternately shifted or crowded toward one pole edge or the other and the parts of the damper embedded in and immediately surrounding the pole face are particularly effective in preventing such shifting. Also, the lower the resistance and the better distributed this damper, the more effective it appears to be in general as regards damping.

On the other hand, for self starting, the damper, acting as a cage secondary of an induction motor, will have the characteristics of such secondary and therefore for best and most uniform starting torque conditions, a relatively high resistance is desirable and a continuous cage is usually preferred. In consequence, the two conditions of best damping and best starting are, to a certain extent, opposed to each other.

In the use of a continuous cage damper is found a difficulty in the application of interpoles to the synchronous converter. If adjacent dampers are connected together, as shown in Fig. 1 then the interpole between the two main poles is actually surrounded by the low resistance damper circuit, a condition which is very objectionable, as explained in the paper. Consequently, the usual arrangement of the cage damper for self starting is not advisable on an interpole converter which is subject to sudden fluctuations in load. In other words, the continuous cage damper should not be used, or its design should be modified very considerably, in the case of self-starting converters, which are subject to considerable fluctuations in load in service. If the continuous cage construction is desired, the individual dampers might be connected together by high resistance connectors.

A second interesting point in the design of interpole converters, but not found in direct-current generators, comes up in connection with the copper loss in the tap coils, that is, those armature coils which are tapped directly to the collector rings. As is well known to those familiar with synchronous converter design, the copper loss in the tap coils of a rotary is relatively high compared with the average loss in all the coils, the loss per coil falling off to a minimum value between the taps. The real limit in carrying capacity of the armature is fixed by the heating of the tap coils and not by the armature copper as a whole. It is possible to overload an armature so that the tap coils will roast out while the remaining coils will show very much less signs of heating. The heating in these tap coils also increases rapidly as the power-factor of the alternating-current input is decreased, the output remaining constant. Therefore by reducing the power-factor of a converter while keeping the direct-current output constant it is possible to roast out the tap coils. The true limit of heating in a converter armature therefore is found in these coils. Herein is found a difference bewteen the interpole and the usual non-interpole converter. In the non-interpole type, as usually constructed, the armature coils are of the fractional pitch or " chorded " type in which the " throw " or " span " of a coil is one or more slots less than the pole pitch. The primary object of this is to improve commutation. In the ordinary direct-current winding there are two coils in each slot, one above the other. With a full pitch winding, when the upper coil is being commutated or reversed the lower coil in the same slot is also being reversed so that the e.m.f. of self- and mutual-induction of the commutated coils is due to the reversal of the local field of both upper and lower commutated

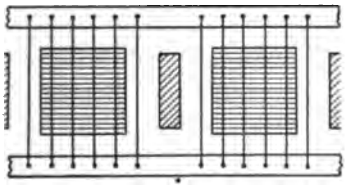


FIG. 1

coils in the slot. With a fractional pitch winding, the upper coil which is being commutated lies in a different slot from the lower one which is being commutated at the same instant.

This same arrangement of fractional pitch winding puts the upper tap coil in a different slot from the lower one so that the maximum heating does not occur in the upper and lower coils in the same slot, as would be the case if a full pitch winding were used. Therefore, with a fractional pitch winding the heating is somewhat better distributed than in the full pitch winding. However, with interpoles, a full pitch winding would naturally be used, as a fractional pitch winding would mean a relatively wide interpole with a corresponding increase in distance between the main poles. Therefore with the full pitch winding used with interpole converters the heating due to the tap coils will be more concentrated than in the non-interpole type. In other words, the machine will have less maximum capacity unless more copper is used in the armature coils, or an inferior type of interpole construction is used in order to allow a fractional pitch winding. This looks like a minor point, but when it is borne in mind that in modern converter designs the starting point in the design of the armature winding is the permissible copper loss in the tap coils, and not the armature copper loss as a whole, the importance of this point may be seen.

A third point, not mentioned in the paper but which concerns design as well as operation, is found in self-starting converters. In such machines the alternating current is applied directly to the alternating-current end of the converter and a rotating magnetic field is set up, just as in the primary of an induction motor. This field travels around the armature at a speed corresponding to the frequency of the supply circuit and the number of field poles and all the armature coils in turn are cut by this traveling field. Those coils which are short circuited at the commutator by the brushes form closed secondary circuits and secondary currents are set up by the alternating field just as in commutating type alternating-current motors at start. As soon as the converter gets in motion the short circuit is transferred from coil to coil but the short circuit current must be broken as each coil passes out from under the brushes and this results in more or less sparking, depending on the size and general proportions of the machine. It is a question to what extent this sparking is dependent upon the normal commutating characteristics of the armature winding. Other things being equal, presumably the better these characteristics the less should be the sparking and burning at the brushes when the converter is self started from the alternating-current end. On this basis then, a converter armature designed with poor commutating characteristics and in which the commutation at synchronous speed is accomplished by interpoles, should spark considerably more when starting than a converter which has inherently very much better commutating characteristics. The presence of commutating poles should in no way help commutation at start as there is no current in the interpole winding. However, as converters are started very infrequently, such increased sparking at start would probably do but little real injury. This is simply mentioned as one of the points in which the designer is concerned.

Some reference has been made this evening to the split pole converter in connection with interpoles. Some distinction should be made between the true interpole or commutating pole arrangement referred to in this paper and what is sometimes referred to as the interpole in the so-called " split-pole " converter. In the split pole converter, as usually built, there is a series of wide poles alternating with narrow poles, the field construction therefore resembling somewhat the ordinary interpole machine. In the split pole converter, however, the small pole is used primarily for the purpose of obtaining variations in the direct current voltage and not for the purpose of obtaining a true commutating field. The winding on this small pole on the split pole machine is usually in shunt with the armature instead of in series, and its circuit is so arranged that the polarity can be varied from maximum down to zero and to maximum in the opposite direction regardless of the armature current carried. In certain combinations this arrangement can be made to have the effect of commutating poles, but under other conditions it may have just the opposite effect.

The small pole is usually placed close to one of the main poles, thus allowing a fairly wide interpolar space between itself and one of the adjacent large poles and a very narrow space to the other large pole. Commutation occurs usually in the wider interpolar space and not under the small pole itself as is the case in the true interpole machine. The direct-current e.m.f. is generated by the resultant field due to one large pole and the small pole which is closest to it. When these two have the same polarity the direct-current e.m.f. is highest and when they are of opposite polarity it is lowest. However, the alternating-current e.m.f. is due to the flux of two adjacent poles, a large and a small one, of like polarity. It is evident therefore that the maximum alternating-current e.m.f. will coincide in position with the direct-current only at the highest direct-current e.m.f.; that is, when both fluxes included in one direct-current circuit are of the same polarity. At lowest direct-current e.m.f. when one direct-current circuit includes two fluxes of opposite polarity, it is obvious that the maximum alternating-current e.m.f. must be shifted circumferentially with respect to the direct-current. The alternating-current magnetomotive force will also be shifted in like manner with respect to the direct-current and the resultant of the two will vary both in height and position with variations in the strength and direction of the flux of the small pole.

At highest direct-current e.m.f. a coil which is being commutated lies midway between poles of opposite polarity and the conditions resemble those in an ordinary converter as regards commutation. At the lowest direct-current e.m.f. the commutated coil lies midway between two poles of like polarity and there will be a field flux in the interpolar space in which the armature coil must commutate. The direction of this field may be such that it will assist in commutation; that is, it will tend to overcome the higher magnetomotive force of the armature currents resulting from the alternating-current and direct-current magnetomotive forces being shifted with respect to each other, as just mentioned. Therefore this interpolar field flux may act in a very beneficial manner under certain conditions. However, if this flux is in the right direction for assisting commutation when transforming from alternating-current to direct-current, it will evidently be in the wrong direction when operating from direct-current to alternating-current. Also, this field flux in the interpolar space will vary with any variations in the strength of the small pole; that is, with any change in the direct-current voltage, although the currents in the armature may be unchanged. Also, this interpolar field may remain of constant strength, while wide changes may occur in the armature currents, and thus in their resultant magnetomotive forces. It is obvious therefore that this interpolar flux can be equivalent to a true interpole of proper strength and polarity, only under a very limited range of operation.

In conclusion I may say that, as brought out in the paper, the real field for interpoles in synchronous converters is found in connection with higher speeds and large outputs per pole. I am an advocate of the highest speeds which the public will stand, up to the point where no further real gain in cost and performance is obtained. If this highest speed in converters is such that interpoles are of material benefit, then in such machines we may look forward to the use of interpoles. However, for the relatively low speeds represented by much of our present practice the use of interpoles can be considered as only a relatively small improvement, concerning which there may be honest differences of opinion regarding the commercial value.

DISCUSSION ON " TESTING STEAM TURBINES AND STEAM TURBO-GENERATORS ", NEW YORK, DECEMBER 9, 1910.

Gano Dunn: Although it recognizes in full the necessity of manufacturing tests, the paper deals principally with over-all efficiency tests largely as acceptance tests. Before acceptance tests come to be necessary—in fact before the manufacturer can know what he may guarantee—there must be an enormous amount of detail testing and of research testing, both of the generator and of the turbine.

The latter tests, from an engineering and certainly from a scientific point of view, are more important than acceptance tests, and I had hoped to see in the paper more data on the segregated tests of the generator itself and of the turbine itself.

In respect to innumerable details, the design of the generator is essentially a result of what previous designs have done and in a piece of machinery of high speed and difficult arrangement of parts such as a turbo-generator, tests are more necessary than in any other kind of similar electrical apparatus, because so large a part of the design is empirical.

This is also true of the steam end of the combined unit and as I see Mr. Emmet here and remember conversations with him on steam tests, I feel that as the American Institute of Electrical Engineers, we are more interested in the research portions of the tests on steam turbines and on turbo-generators, than in the commercial portions.

When speeds are pushed beyond limits with which we are familiar, we reach a point where a further increased speed is no longer merely quantitatively different from the speed we have been using; a qualitative change takes place in our conditions and it is no longer safe to exterpolate.

It is found, for instance, when retardation tests are made on turbo-generators, that the losses from vibration, windage and eddies after certain critical values, do not follow the laws of variation that they follow below these critical values and some of them are quite erratic in the way their rate of variation is related to the variation of speed.

Since in turbo generators these losses are proportionately much larger than in ordinary generators, and since in dealing with them we are, so to speak, in a strange country, we are particularly in need of research tests.

To cite an instance, the designer of an ordinary generator provides for windage to cool the parts of his machine and he busies himself with considering only how much air will be thrown.

The designer of a turbo-generator finds such an enormous increase in the power consumed by windage that the air itself is increased in temperature, so he has to consider, not only how much will be thrown, but how much it will be heated in the course of throwing.

The increase of its temperature is so dependent upon the shapes of passages and the volume of chambers in the interior of the machine, that prediction of this increase is practically impossible at present.

In respect to balance, it is well known that below the first critical speed, if a turbo-generator is run in flexible bearings and a piece of chalk is made to approach the revolving periphery, it will first hit and make a mark on that side of the revolving mass which is the heavier, and to secure a proper balance a balancing weight must be put opposite the chalk mark.

It is also well known that above the first critical speed when the apparatus may be regarded as ceasing to revolve around its axis of figure and is gyrating around its axis of gravity, the place where the piece of chalk will hit will theoretically be rotated 180 degrees from the first place.

Under these conditions the balancing weight must be put at the chalk mark.

In the range of speeds between the limits I have mentioned the balancing weight must be put somewhere between a point 180 degrees removed from the chalk mark and the chalk mark itself.

It looks as if the working out of a law of these mass vibrations, was simple, but the flexible bearings in which the rotation must occur, impose complicated conditions, and the beautiful formulas of the ordinary laws of forced vibrations do not seem to hold.

In the works of a celebrated European company, distinguished for the success of, among other things, its turbo generators, the study of balance has been thoroughly pursued, and incidentally I might mention every turbo-generator, is balanced by a member of the Board of Directors.

This member of the Board said to me that he had worked out a formula which indicated that the position of the chalk mark lagged behind the position of the heaviest region somewhat in the way current lags behind electromotive force in an alternating circuit. This formula guided him in the calculation of the amount of this lag and the position of balancing weights and enabled him to secure the beautiful balances which characterize the apparatus of his company.

Tests and research work on questions like these are greatly needed.

Where a manufacturing company builds both the steam turbine and the turbo-generator its responsibility is of course, based upon the ratio of the electrical energy developed to the steam consumed and segregated tests of the generator and of the turbine are not essential for acceptance tests, but a number of companies make steam turbines only and other companies make turbo-generators only.

Here segregated tests are necessary to determine each manufacturer's share of the over-all responsibility.

The principal value of the segregated tests are in the reaction upon design of the laws and constants the testing discovers, and when we realize how qualitatively different many of the phenomena in turbo-generators are from similar phenomena in ordinary generators, we realize the particular need of research tests in the turbo class of dynamo electric machinery.

I hope much will be brought out in the discussion on the subjects of eddy current losses, windage losses, mechanical losses due to vibration, and the practise of balancing, all of which are so different under the high speeds of turbo-generators that they fall outside of ordinary experience and the mass of data that has been collected from it.

W. L. R. Emmet: One matter which Mr. Dunn has brought out relates to the relative value of the test of the part and of the whole—that is, he suggests, as I understand, a separate study of the generator and of the turbine.

This is very desirable, but in the case of turbine and turbo-generator units it is extremely difficult; and the only thing which can be really thoroughly investigated as a rule, is the net result.

The turbines should be sold on a basis of net result, and the net results should be really the test of the ability of the engineer who has made them, and the value of the apparatus. The reason for this difficulty is that the generator is a very high-speed piece of apparatus requiring a large amount of power, and cannot well be run by anything but the turbine which drives it. If this generator could be thoroughly investigated and evaluated on its own merits, it would be highly desirable; because there are many unknown and obscure conditions in these generators which pass muster as parts of a satisfactory general result.

We have tried very hard to investigate the generator alone, and there is one method of so doing which I believe was first carried out in our works, and which has a good deal of value. It is what I call the " deceleration "* method of testing. This consists in bringing the generator—by any means, as a motor or otherwise—to a speed in excess of that at which it is to be operated, and then allowing it to decelerate, noting the rates of deceleration and from these rates, with a carefully calculated moment of inertia, determining the amount of power exerted at any particular instant.

By so operating a generator, the power required to drive the machine at any instant in the process can be determined, and the process may be repeated with different degrees of excitation and other possible variations.

I use the word " deceleration " as it is part of the language spoken in Schenectady. I do not think there is such a word in the dictionary, in reality, but you will probably all understand what I mean.

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*For a criticism of the word "deceleration" see communication by C. O. Mailloux on page 44 of these PROCEEDINGS.

It is extremely important, no matter what methods of investigation are used on the generator, to take nothing for granted in the matter of generator efficiency in a high speed unit. That is, if somebody guarantees a certain result on a turbine generator shaft, and gives a list of losses, such statement should be accepted with great caution. The losses in high speed generators are very much greater in many cases than are generally supposed.

The windage losses are extremely large and very variable, and they vary greatly owing to the way the air passes through the machine, much power is concentrated in a small space, and there are various losses incident to leakage fluxes, and eddy currents, which often do not occur in other kinds of apparatus. There are also very large load losses; that is, I mean losses caused by the existence of large currents in the conductors which cause unequal distribution of flux in the neighborhood of the slots, and consequent eddy currents in the iron and sometimes in the field windings.

All of these conditions make it desirable to test the unit as a whole, and in fairness to manufacturers this testing the unit as a whole should be made justly and carefully, and I think Mr. Dickinson's and Mr. Robinson's paper gives a fairly complete list of the precautions to be observed.

There is one matter I want to mention which is only slightly alluded to in this paper and which I think is of a great deal of interest, and that is the steam meter. We have been using steam meters in all of our turbine tests for a long time past, and at the same time have been weighing the condensed water. We have checked results within two per cent in practically every case, and in all cases where the conditions were accurate and uniform and well understood, it was generally within one-half of one per cent.

A steam meter is a very valuable piece of apparatus and those who have used it will depend upon it and use it more. In any test it may give valuable indication which will prevent error; for if not trusted as a source of information, it will at least give a gauge on relative proportion of values.

Very often in steam tests there are obscure sources of error. In one case in the testing of a turbine near Boston, a radically wrong result was obtained—or it seemed entirely wrong, and I observed that the slope of the load curve was such as to indicate leakage. They tested the condenser and found no leakage; with a high degree of vacuum on the condenser, it was found, however, that when the steam blew into the condenser in considerable quantities it leaked badly as the pressure and the heat of the steam caused certain tubes which were split to open, so that circulating water came out and was added to the condensation which was being measured.

Francis Hodgkinson: In reading the portion of this paper covering tests on the steam ends of turbine units, I fail to see anything brought out in the way of necessary precautions to be taken, which are not well known, and are practiced by any self-respecting station engineer, undertaking the work of conducting a test. Doubtlessly, no precaution that leads to accuracy is too trivial to be neglected.

In the case of tests where the condensate is weighed, it is not difficult to obtain dependable results. The leakage of the condenser must be carefully watched, however, and sometimes as Mr. Emmet has remarked, peculiar leakages from split tubes may develop, which exist when the plant is in operation, but curiously sometimes, do not show themselves during an ordinary condenser leakage test.

In the case of tests where a jet condenser is used, or a non-condensing turbine is installed the only means available, of determining the steam consumption, is to measure the feed water. The difficulties are much greater, rendering it necessary to tear down feed pipes, steam lines, blow-offs, etc., to insert blank flanges. This frequently causes a disorganization of the whole plant, but it is nevertheless a necessity if the test is to be dependable. Nothing should be taken for granted. Every connection should be investigated. In the event of contemplated tests, the builder who demands these precautions for the sake of accuracy, is likely to find himself rather unpopular.

One point which we think might have added considerably to this paper, would have been to set forth an opinion as to the proper duration of tests. In the case of weighing the condensate true results may be obtained with a test of one hour after conditions have settled down. Nevertheless, in the case of a formal acceptance test, two or three hours at least, would generally be employed, and it will usually be found that one hour closely agrees with another. In the case of weighing the feed water, the test should certainly be for not less than eight or ten hours, at any one load. This, of course, is made necessary by the difficulty in determining the height of the water in the boiler. We all know that on blowing down the gauge before making an observation as to the height of the water, you will find the level will go up, due to the difference in temperature between the water in the glass, and that in the boiler, and there are other things which will vary the height of water in the boiler, by changing the rate of firing.

Some reference is made in the paper to what is called a heat balance test, measuring the quantity of cooling water supplied to the condenser, and noting the rise in temperature of the same. I do not think anybody would look upon this as a reliable means of determining the steam consumption of a unit, because such a small error in the temperature of the water would influence, so greatly, the amounts of steam calculated therefrom. There is, however, a possibility, with extreme precaution and using condensers which cause a high thermal rise of the condensing water, to derive fairly satisfactory results in a test of this nature.

One of the most important things which I find in the conducting of turbine tests, is the proper reading of the vacuum. One not infrequently finds mercury columns located some distance from the chamber where the vacua is being observed. These are sometimes connected by a small pipe, perhaps containing loops, which together with capillary action, will seriously interfere with the reading of the mercury column. The mercury column should be connected with as short a pipe as possible, and of sufficient size to absolutely preclude any capillarity. These same precautions, of course, apply also, to reading the lower steam pressures within the turbine, which approximate atmospheric pressure, or less, but do not necessarily hold for the high pressures. In the case of the mercury column, the barometer should preferably located alongside of it, so that the temperature correction will only apply to the inch or so difference between the barometer reading and the column reading, which may then be ignored. When great accuracy is demanded, it is as well to have a quantity of the mercury weighed in a chemists laboratory, as I have known a higher vacuum reading to have been obtained by the amalgamation of the mercury with some tin, somewhat to the enhancement of the condenser performance.

I do not feel competent to discuss that portion of the paper referring to the electrical instruments. In my experience in testing turbines in the builder's works, I was very glad when I succeeded in devising a hydraulic brake, by means of which, the question of the electrical instruments was eliminated, together with the delays required for the water rheostats and the like to become settled. By means of the brake, the load may be applied as quickly as desired, and all the refinements of observation are to know the radius of the brake arm, measure the speed of the turbine, and the reaction of the brake arm on an ordinary weighing scale, none of which call for any particular skill.

In all acceptance tests which are carried out in the purchaser's plant, it is necessary beforehand, for the builder to come to some agreement with the purchaser, as to what corrections shall be made for deviations from the contract conditions. The introduction of corrections is as objectionable to the builder, as to the purchaser, and is the more embarrassing because the purchaser is more or less compelled to accept whatever corrections the builder insists are proper. Protest on the part of the purchaser may be met with the contention that the matter of corrections is entirely in his hands, and may be entirely eliminated if he will but conduct the tests under the conditions recited in the contract. However, this is not as serious as might seem.

There should, generally speaking, be no necessity for making corrections on account of pressure. It should be easy for the purchaser to maintain the contract steam pressure, within five pounds either way, the effect of which deviation should prove negligible.

Superheat and steam quality cannot be controlled, but this is the only correction which need be determined beforehand, and there is but little diversity of opinion as to what the superheat correction should be. In steam quality, it is usual to allow 2 per cent for each 1 per cent of moisture, because of the friction caused by the presence of the water.

In the case of the vacuum correction, however, this is a variable factor, depending entirely upon the inherent design of the turbine. Where the purchaser is unable to maintain the vacuum called for by the contract, I have always arranged to determine the vacuum corrections directly from the tests themselves, by running a series of tests at different loads with the highest vacuum obtainable, and a set of similar tests at like loads with 1-in. or 2-in. lower vacuum. From these results, the proper vacuum corrections may be determined—these corrections, of course, being greater at the fractional loads. In all cases, a series of not less than three tests at different loads should be run under the same operating conditions, in order that the results may be plotted on cross-section paper, when any discrepancy or disagreement will immediately become obvious, bearing in mind that the total steam consumption of any turbine, no matter what its design may be, follows a right-line law up to the point where any by-passing or changing of areas in the turbine is resorted to. The plotting of pressures to load, and to total steam, may be a means of discovering the cause of a discrepancy.

W. L. Robb: In general I agree with the methods of testing recommended in the paper. On a few points, however, my opinion is somewhat at variance with the authors'. I agree with them that the steam conditions during test should be as near as possible the conditions under which the turbine is normally to operate in service; but I would go one step further and have the generator loaded during test with a load of approximately the same power factor that will be met with in the normal operation of the plant. Such a load will be the one most easily obtained for the test under ordinary circumstances. A test with a load of unity power factor, when under ordinary operating conditions the power factor will be much less, does not give a purchaser the desired information.

All instruments on whose readings the calculation of efficiency are finally based, should be calibrated before and after the test. My experience has not given me such confidence in series transformers that I would be willing to make any exception in their favor as recommended in the paper.

Neither steam flow meters or watt-hour meters should be used as a basis for the final calculation of the efficiency of the set. It will be found convenient, however to have both instruments in service at the time of the test. Frequently some irregularity in operation or in conditions of test, will be indicated more promptly by these instruments than from the periodic readings of the indicating wattmeters and the weights of steam. Much time may be saved in the test, from the prompt correction of troubles. At the completion of test, data will be available for determining the accuracy of the steam flow and watt-hour meters.

There are a few points that have been impressed on me by my own experiences in testing steam turbines that may possibly be worth mentioning.

The time to prepare for a test is before the turbo-generator and its auxiliary apparatus, including steam piping and switchboard are installed.

A few extra valves of relatively small cost will greatly facilitate blanking off the apparatus under test from the rest of the power house equipment, and no test is worthy of the name if reliance is placed on all valves being tight.

Little if any attention is usually given in switchboard design, to making provision for the introduction in the circuits of standard series transformers or instruments, either for use in efficiency tests or in calibration of switchboard instruments. A slight and inexpensive change in the design of the disconnecting switches now commonly installed, would greatly facilitate the use of standard instruments at times when their use is desirable.

Measurements of feed-water are unreliable as the quantity of water in the boiler is usually determined by the height of water in the gauge. The height of water in the gauge is not only a function of the quantity or weight of water in the boiler, but also of the temperature of the water and the rate and point from which the steam is taken from the drum.

A turbo-generator should of course be tested at fractional and overloads, as well as at full load. A study of the efficiency at various loads will indicate whether the capacity of the turbine and generator have been properly proportioned.

I have always found it convenient during test to work up data as rapidly as possible, to enable one to plot the steam flow as a function of the kilowatt output, selecting scales that would give approximately a forty-five degree slope to the line. Any irregularities occurring during test, such as abnormal leakage in the condenser, will be apparent in irregularities in the points on this line, and much time will be saved in removing the causes of these irregularities.

I have always made it a practice to work out the results to be obtained from observations every fifteen minutes and to eliminate in the final calculation all observations taken before the results obtained for successive intervals became uniform. This has usually meant the elimination of the observations taken during the first hour, and sometimes during the first two hours. A run of one hour after the conditions have become constant, will give sufficient data for a calculation of the efficiency, provided a surface condenser is used. A much longer test would be required if the steam consumption was obtained from a measurement of the feed-water.

When all possible precautions are taken, all instruments, both mechanical and electrical are calibrated, the steam supplied under approximately normal conditions, and the load on the generator has approximately the normal power factor, I believe that results can be obtained that are correct to within one per cent.

Edwin D. Dreyfus: The subject of the evening's paper is not only an interesting but a timely one. It is a phase of engineering work on which a great deal may be said regarding actual experience obtained and expedients and methods employed to vouchsafe very accurate and reliable results.

It is to be remembered that there are now over 2000 steam turbines in operation in this country, which has permitted us to have acquired close and quite intimate familiarity with this type of prime mover, as well as to learn the best methods of examing its characteristics. Consequently, I cannot accept the same pessimistic view as the authors, placing somewhat in question the ability of engineers in general to definitely and positively determine within very small limits of error the true performance of a turbine and its component generator.

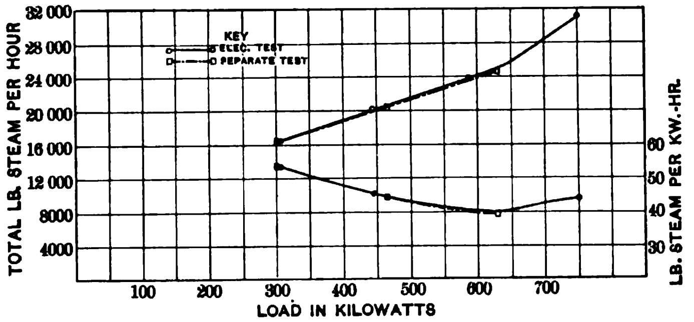

FIG. 1.—Efficiency test, 600-kw. turbine—120 lb. steam pressure, 7 lb. back pressure, 3 to 6 deg. fahr. superheat

While I fully subscribe to the precautionary measures laid down by them, it seems to me their definitions have to the casual observer the complexion of being unduly apprehensive and are unsupported by any reassuring statements in this direction.

I am able to present some evidence that I believe shows that tests should be no matter of uncertainty and that by exercising the usual care, remarkably consistent results may be obtained.

First of all, proper development in the turbine art requires that the designers and manufacturers of turbines carry out very complete tests in their own shops. For this purpose, special test floors are provided and the surface condenser and hydraulic dynamometer, involving simple formulae, are used. Obviously, some of the large turbines may be tested to only about one-half load on account of the heavy draft on the boiler plant of the works.

Fig. 1 includes tests on a 600 kw. non-condensing turbine made independently on both the turbine and the generator by brake and separate loss methods respectively, and the results combined, and then assembled and tested as a unit. The first series was conducted in conformity with the usual practice at the builder's works, and the second set were the over-all witness tests which had been specified by the purchaser. The check between the two is, of course, very gratifying, but it is just as should be expected with the necessary care and experience.

Witness tests for the U. S. Government on the two different machines of 1000 kw. capacity and of the same design, are shown in Fig. 2, for identical operating conditions. These results are, in every measure satisfactory (the normal variation being 2½ per cent) as it is to be remembered that they were run individually, and the small variation is only such as one would expect, for the dual reason—the probable slight difference in the construction of the two machines built from the same pattern, and small personal errors in observations. The foregoing tests were made with all special facilities at hand in the shops.

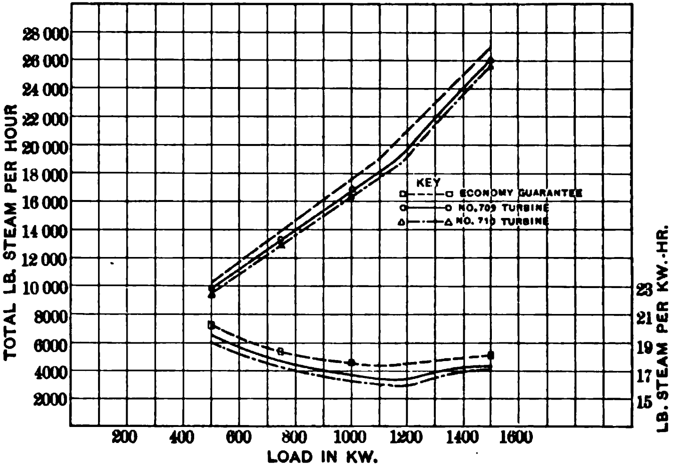

FIG. 2.—Test of 1000-kw. turbine, 3600 rev. per min.—150 steam pressure, 100 deg. fahr. superheat, 28-in. vacuum. (30-in. barometer)

Coming to Fig. 3, we have an example of three 10,000-kw. turbines at the Brooklyn Rapid Transit Company, tested after erection by the owners. At full load, the maximum variation from the mean is somewhat less than 1 per cent, which shows forcibly the degree of accuracy obtainable, bearing in mind that these three tests pertain to different machines. It also exhibits the uniformity of construction according to a given design that has been secured, which is undoubtedly more noteworthy than it would be for the reciprocating engine. One point in the test of Unit No. 7 (150 per cent load) departs appreciably from the values established in the other two machines. There is no plausible explanation for this discrepancy, but as it is the only appreciable deviation out of fifteen load tests, it should not be taken seriously. Moreover, these turbines naturally have quite a flat over-load characteristic, as the heavier loads are obtained by opening more nozzles on the high pressure wheel by means of a secondary valve, (by passing no active part of the turbine.) Mr. C. E. Roehl, the Company's electrical engineer, under whose supervision the tests were made, would I believe, be willing to make these data available to the Institute if requested. These particular 10,000-kw. turbines were the first of the double-flow design built in such capacities and are, therefore, operating at lower speeds than used in the latest practice. Higher speeds are, of course, beneficial to economy.

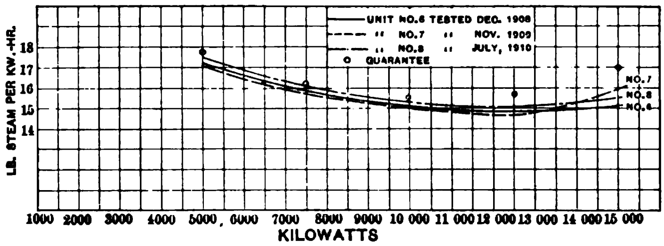

FIG. 3.—Test of 10,000-kw. turbines—corrected to 170 lb. steam pressure, 100 deg. fahr. superheat, 28-in. vacuum. (30-in. barometer)

The value of the Willans right line law applying to turbines, has already been noted by a previous speaker, as well as the characteristic line of the throttling turbine in which the inlet pressure varies directly with the load. These features prove very important in the absence of an "exploring device" like the steam indicator for the reciprocating engine. By means of these virtues, the results for any given load which may not be satisfactorily maintained for operating reasons, may be conveniently and accurately interpolated or extrapolated from the other available tests.

It has been found in most of the throttling governed turbines that the total steam line continues rectilinear until the first stage inlet pressure reaches within 10 lb. of the throttle pressure, when the curve deflects slightly upward, on account of the secondary admission valve opening at this time.

In the case of the Brooklyn Rapid Transit turbines above referred to, this occurred between 5 and 10 lb. It is to be understood, of course, that the same pressures, superheat and vacuum are maintained over the entire range of load. The value of the pressure characteristic is very well exemplified in one instance where the horse power of a turbine was calibrated against the first stage inlet pressure. This furnished a measurement of the power applied to marine reduction gear, and its efficiency was then obtained by determining the delivered work with a hydraulic brake.

Through some misunderstanding or oversight, a set of observations may show fallacious results and this important right line law immediately disproves them by their failure to rationalize with respect to others that prove themselves to be regular. Hence, there must be an element of doubt in regard to a single load test, and it is consequently entitled to no especial claims unless verified conclusively by several parallel tests in nowise connected with one another. Unfortunately such commendable practice is so frequently violated that we often find our engineering proceedings inflated with more or less doubtful information.

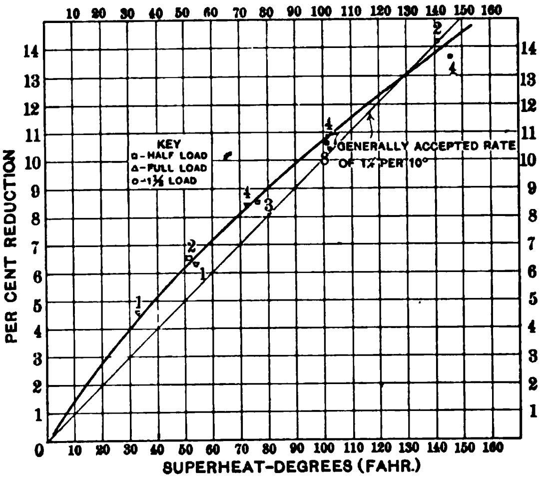

FIG. 4.—Approximate reduction in average steam consumption with varying degrees of superheat (average of 32 tests at practically the same vacuum—number of superheated steam tests indicated by figures on curve).

A word may be said for the graphical recording instruments. While they are not very sensitive from a scientific standpoint, they establish a very valuable index of any change of events during a test. And it might be possible, by their use, to discover the reason for any discrepancy that may appear in the final plot.

An understanding must be had in regard to correction factors for reducing the observed values to contract or designed conditions as has already been discussed. Different constants for pressure correction are employed, but ordinarily this is a very small factor. One company uses about one-half of the theoretical change, that is, one-half per cent for every 10 lb. For determining the variation due to changes in superheat, I recently went over the tests of a great many turbines of 500-kw. size selecting those which had been made under practically the same conditions, and found the curve of the nature shown in Fig. 4. Size should not influence the factor materially and the accepted correction of 1 per cent for 10 per cent variation is thus substantiated for ranges of superheat which are now found warranted. Similar superheat determinations were published in the September 30, 1910 issue of the ***London Engineer***, applying to a Brown-Curtis marine turbine and having the same drooping tendency. This characteristic is evidently natural as the delay of the " dew point " in the turbine occurs in a less degree for equal increments of superheat in the higher than in the lower ranges, and consequently a point is eventually reached where the ultimate improvement ceases because the quality of the steam going into the exhaust represents a greater loss than the saving due to the reduction in internal friction.

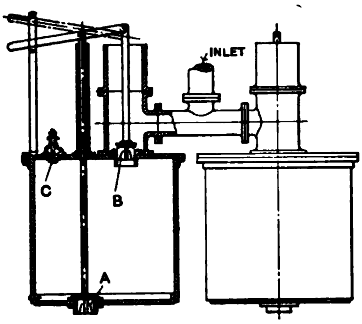

FIG. 5.—Weighing tanks

The authors rather broadly discount any value which may be given the indirect measurement; that is, appropriating the condenser as a large calorimeter. I have one test in mind particularly, where this method had to be resorted to, and by executing the work with every possible degree of precision, it served the occasion admirably. There were several different interests concerned, and efforts were combined to ensure reasonably close results. The Venturi meter installed was accurately calibrated over the range required by discharging into rectangular tanks which were accessible for the purpose. The meter coefficient determined by the builders was completely verified. To avoid liability of error in observing temperature of the discharge water, two calibrated laboratory thermometers were placed at virtually opposite points of the pipe and simultaneously read. Any variation throughout the body of water due to stratifying of the temperature, would have been noticed. These thermometers agreed as they were placed at the foot of a barometric tube which allowed time enough for the temperature to become evenly diffused. Furthermore, a recording thermometer was moved back and forth across the hot well discharge. The entire results were well within 1½ per cent correct.

In surface condenser work weighing tanks and standard scales are the rule in official testing. At some plants large weighing scales may not be readily obtainable, and arrangements of tanks shown similar to those in Fig. 5 has been used with success. A snifting valve is provided at " C " allowing the ingress and egress of air to and from the tank and which automatically closes when the tank is full, furnishing one signal to the operator to shift the levers. This, of course, represents only one of the tank arrangements that has proved a successful expedient.

Wm. C. L. Eglin: There are two phases of this discussion to-night, namely, the acceptance test and the manufacturers test. I hold some difference of opinion from the views expressed in the early part of the evening regarding the acceptance test. I do not believe the acceptance test is of any value unless it is made in the manufacturer's plant. I think Mr. Hodgkinson brought that out when he said the agreement was between the purchaser's engineers and the manufacturers' engineers.

It is very difficult to make corrections in such a way as to be satisfactory to both sides; so a test should be made under the conditions which can be reliably obtained in the manufacturer's plant; and that limits the test to very small turbines. One of the greatest difficulties is obtaining unity power factor in plants. When the turbine gets above 10,000 kw., then running a test under full rated load becomes expensive and practically precludes that class of testing.

There is another difficulty the owner is confronted with, and that is the difficulty of having trained observers. In the manufacturing plant there are a number of trained observers, and that is an advantage that is not touched upon in this paper.

This paper seems to indicate that the most necessary thing is to have reliable instruments. In a large equipment it would be almost impracticable to install additional instruments to the extent indicated by this paper; and from our standpoint, we would turn over the instruments and have them checked in place before the test was made. We have found that accurate results could be obtained from the steam flow meter and it is of great value in checking the operation.

For several reasons turbines have fallen off in efficiency, and by the use of the steam flow meter, we can determine that within a day or two of the changes in conditions.

The paper covers practically all the standard conditions of making a test; but from our standpoint we prefer a test covering a large period of time—of several days or a month—with our instruments checked by the regular operating force.

C. O. Mailloux: I have designed plants where turbines have been used. I want to emphasize the point made by Mr. Dunn in regard to the advisability of segregation tests. I have had at least two experiences which indicated the desirability of it.

In 1906 I was a member of an expert Commission, consisting of three men, sent to Europe, for the purpose of making a general investigation of the entire subject of steam turbines and turbo-generators. In the course of our peregrinations through the various countries of Europe and through the various shops where turbines were made—that is, at least so far as we were admitted into them—we found a remarkable diversity of opinion as to the relative merits of the turbo and the dynamo part. It made a great deal of difference as to whether we were speaking to the designer of the turbine or the designer of the dynamo. If we were speaking to the man who designed the turbine, the dynamo was blamed for all the trouble; and if we were speaking to the man who designed the dynamo, the turbine was blamed for all the trouble. The other instance where it was desirable to separate the losses in the turbine and the dynamo, was a case where I purchased a turbine in Europe to be used in this country by a client. The turbine was bought, subject to tests in Europe; and when it came here we repeated the tests. We found a wonderful discrepancy. It was hard to believe that the machine could have deteriorated so much in merely coming across the ocean. Yet it was difficult to put our finger on the leak, owing to the difficulty of making a test of such part of the machine by itself.

I agree with Professor Robb in regard to the length of time necessary to make a test after steady conditions have been obtained. I have oft-times taken the results of a test running from four to eight hours, and cut it into portions of one, two and three hours, in order to see whether the result as calculated from a portion of the time would differ from the result calculated for the whole time under uniform conditions; and I think, as Professor Robb does, that a period of one hour under steady conditions might be sufficient, particularly if you have proper means, as with a flow meter that is not open to various errors, and with them I think we could make tests in shorter time. In other words, we could make them by comparing instruments—input and output.

A. Henry Pikler: The authors in their paper say: " The use of watt-hour meters for this class of testing should be avoided wherever possible."

The adoption of such a principle I am afraid would introduce grave errors in the results. The efficiency test of a turbo-generator unit is a duration test, therefore the time-integral of the output should be measured and not the rate of output. This is especially important because, as known from experience, no matter how careful arrangements are made, the load will fluctuate. It is true that the watt-hour meter is not as accurate an instrument as an indicating wattmeter, yet its error can be ascertained accurately. Furthermore, the errors due to fluctuations in the load are far greater than the error in the watt-hour meter. Both instruments, the indicating watt-meter and the watt-hour meter should be in the circuit simultaneously, the indicating instrument serving as a check on the integrating instrument under the conditions given.

E. W. Yearsley: The steam flow meter is such a convenient means of measuring steam consumption, that it is important to know its approximate accuracy under various conditions. This paper refers to these meters in a general way. I should like to hear further expressions of experience regarding suitable circumstances and necessary precautions in the use of such meters. Within what percentage are they correct for measuring turbine consumption? Are they satisfactory if connected in a turbine branch, which is taken from a main steam line carrying reciprocating units in the immediate vicinity? How are they affected by the varying pressure of an exhaust steam line in a mixed flow turbine? Is it necessary to calibrate such meters when used to measure reciprocating engine consumption? What is the comparative accuracy of the Venturi and nozzle plug types for continuous and intermittent flow? Are the recording meters as accurate as the indicating meters? Do these meters retain their accuracy after operating for some time subject to considerable vibration?

E. B. Rosa: I have had no experience in testing turbo-generators, but we have had some experience at the Bureau of Standards in testing the instruments used in the electrical measurements made in such tests. We are very much pleased with the instruments that are being furnished by the best manufacturers for such purposes. If they are properly tested and calibrated, they are frequently more accurate and reliable than one would anticipate. Particularly is that true of potential transformers and current transformers. If they are properly calibrated, they are very reliable, and are indeed instruments of precision. The transformers are, perhaps, more reliable than the instruments used in connection with them, but the instruments used in connection with them may be trusted to give very good results, indeed.

If the results of a test are to be reliable to 2 per cent, each one of the many separate errors must be kept as small as possible, and that makes it necessary to use accurate and reliable instruments.

I did not see the paper before this evening, and have had no opportunity to read it carefully. I heard the greater portion of it read, however, and I must commend the discussion which is given in it of the electrical measurements to be made in such tests.

I would particularly like to speak about the shunts. There are more errors in shunts than many people using them imagine. I have known of instruments and shunts being sent for careful standardization after tests were over, whereas if they had been tested before they would not have been used. They should be tested both before and after, as Professor Robb has said. But if they are tested only once, it is rather better before the efficiency test than after, as it gives one opportunity to know their conditions and to discard unsuitable instruments.

The distribution of the current in the shunt is important, and the heating of the shunt is also important. If they are to remain in circuit during the run, carrying heavy load, they become heated, and obviously the effect of such heating should be definitely known.

L. T. Robinson: There are a few things I would like to refer to. The principal point in writing about measuring the electrical output was to emphasize the advantage of relying upon indicating instruments rather than watt-hour meters, when the most accurate results are demanded. Referring to some remarks that Mr. Hodgkinson made, I think he seemed to feel that the listing of so many precautions was rather a reflection on the intelligence of engineers in general but I would say that considerable experience with what actually does happen makes more careful attention to details desirable in many cases.

It has been my experience that tests are either left to a steam engineer or to an electrical engineer, and in some cases " the other end " suffers. That is, if he is a good steam engineer he gets the steam end all right and takes whatever is handy, and makes the electrical test with it.

With reference to Professor Robb's remarks, I think that the endorsement of the instrument transformers given by Dr. Rosa needs no further comment from me.

With reference to the provision for inserting portable standards for tests in connection with switchboard, instruments and meters I feel that this is something which will be brought about sooner or later. It would be very desirable to have such arrangements.

With reference to Mr. Dreyfus' remarks, I think any difference of opinion that might be apparent are due more to misunderstanding than anything else.

I did not intend to bring out—and I don't think Mr. Dickinson did—that accurate testing is something which can not be done, but rather that it is something which is being done right along; and the agreement obtainable between different test runs is about the same as that which he refers to.

With reference to meters correct within two per cent of accuracy—the Public Service Commission requirements, the whole paper is based on 2 per cent not being good enough.

With reference to Mr. Pickler's remarks about using the watt-hour meters, it is simply a misunderstanding. I have no objection to the use of the watt-hour meter if calibrated in place, and therefore corrected for all the errors that might influence it in use. But it is not in the same class as the portable indicating instruments, one being about five times as accurate as the other, to express it in terms of percentage.

I. E. Moultrop (by letter): Messrs. Dickinson and Robinson have very clearly outlined the essential features of commercial testing of steam turbo-generators. There is nothing in the paper which is new to the engineers of large power plants who have had to do considerable testing of this kind, still I think the authors might have placed more emphasis on a number of their recommendations.

The absolute tightness of a surface condenser is important and very difficult to determine when fresh circulating water is used. Also when the condensed steam is weighed, the temperature of the water should be taken. When the water rate of the turbine has to be determined by weighing the boiler feed the possibility of error is great and much care must be taken to eliminate such errors.

It is not easy to accurately measure the vacuum; the mercury column should be carefully checked and if possible the mercury should be boiled out before the test. All thermometers should have the same stem exposure as that under which they were tested.

I am surprised to see the steam flow meter so highly endorsed and wonder if its advocates would accept a test which showed by a steam flow meter only that the turbine failed to meet the contract guarantees.

The authors in their conclusion could well have emphasized the importance of insuring the accuracy of the electrical measurements, for I believe the liability of error in commercial testing is greater in this respect than in any other. I wish to endorse the recommendation that for commercial purposes a turbo-generator should be only tested as a combined unit and under the same adjustment it will have in regular station operation.

A very good check on a test of this kind is to work up the readings and plot the results as the test progresses, as many errors of observation become apparent at once and can either be corrected or the test can at once be repeated.

I think a little consideration of their paper will indicate that there are many power users who would find it difficult to make a satisfactory and reliable test on a new steam turbo-generator either on account of their operating conditions or by reason of the expense involved. As the manufacturers usually run the machine under steam before making shipment it should cost but little more to find a way to load the generator and make a complete test on the machine before shipment. If this were done correction could be eliminated because the steam pressure and temperature, the amount of vacuum, etc., could be made to agree with the terms of the contract. The load could be held steady and at unity power factor and a trained testing force employed which would add to the reliability of the results. I wish, therefore, to endorse the recommendation of Mr. Eglin that manufacturers should be prepared to make acceptance tests at their factory if requested by the purchasers.

In a plant of considerable size I believe there should be permanent testing facilities and periodic tests should be made on all prime movers. Steam turbines are much less liable to fall off in economy than engines yet things do occur which will seriously affect their efficiency.

The Edison Electric Illuminating Co. of Boston has such an equipment in its L. St. Station. It consists of a pair of large steel tanks each set on a platform scale in a room adjacent to the turbine room. A pipe line runs from these tanks to the condensed steam discharge of each turbine so that the manipulation of a few valves will divert the condensed steam from any turbine into these tanks. In the switchhouse a cell is equipped with special instrument transformers and arranged so that carefully calibrated test instruments can be readily installed in series with the regular switchboard instruments. By this arrangement a very good routine test can be made by the operating department at any desired time without interfering with the operation of the station, and at a slight expense.

E. D. Dickinson: It seems to me that the chief point of discussion this evening, with regard to this paper was the segregating of the turbine from the generator, and the remarks of Mr. Hodgkinson covered this rather completely. That is, if turbines are to be built and sold by themselves, the most accurate and positive method of testing is to build some device to measure the output of the machine to the satisfaction of every body, before it leaves the factory. Where turbines are built and sold with generators, it is the over-all efficiency of the unit that is of interest.

There were several questions asked, relative to the reliability of the flow meter after it had been in service some time. If I remember correctly, the gist of all was; is it an accurate device which can be put in the circuit and left there for a long period? We have had some of them, that were little more than laboratory meters, in service a long time, and they are as accurate now as when put in. Inaccurate indications will sometimes be caused by the holes in the nozzles getting clogged, but these are easily cleared.

Perhaps I did not understand Professor Robb in his remark about the use of valves for disconnecting certain sets of boilers, in order to make tests by weighing the water fed to those supplying steam for the turbine under test. We have heard of cases where valves separating different boilers and thought to be tight, were found after the tests were completed, not tight. The results were therefore valueless and the money spent had been wasted.

I wish to call particular attention to the communication from Mr. Moultrop in which he shows that accurate tests may be made in power stations, and at comparatively small expense.

The importance of being able to know at any time, the efficiency of apparatus in service should be sufficient to bring about a more general adoption of similar methods.

A paper presented at the Toronto Section of the American Institute of Electrical Engineers, Toronto, Can., November 19, 1909.

TUNGSTEN LAMPS

BY G. S. MERRILL

The perfection of the tungsten incandescent lamp as a highly efficient means of converting electrical energy into light has made it a subject of great commercial interest. The tungsten lamp has reached in a comparatively short time a most enviable position in the field of artificial illuminants. It has been developed for multiple use on commercial lighting circuits up to 250 volts, for series street lighting, for low voltage decorative, display and train lighting, and for many other purposes. Its commercial success in all these various applications bears witness to its merit as a convenient and efficient source of illumination and its production and characteristics are consequently worthy of consideration from an engineering standpoint.

A discussion of the historical side of the high-efficiency lamp development is very interesting, but as this can be found fully covered in current technical papers it perhaps is not necessary to review the line of experimental and research work which produced the modern high efficiency lamp. Neither is it necessary to describe the several different processes by which various experimenters have produced tungsten filament, since these too can be found thoroughly covered in connection with the historical development.

The process most widely used in the United States to-day is one which starts with the purest tungstic acid or anhydride obtainable as its basic material. Tungstic acid is obtained commercially from the ores wolfram, a ferrous manganous tungstate, scheelite, a calcium tungstate, and hubnerite, an oxide of tungsten and manganese. The tungstic acid as received by the lamp manufacturer is in the form of a heavy yellow colored powder and notwithstanding its purity has to undergo a most thorough further purification and special treatment in order to reduce it to a fine yellowish powder which possesses a slight porosity. This peculiar physical condition is necessary for the successful reduction of the oxide, which can be accomplished in several different ways perhaps most easily by heating to redness in a current of hydrogen. Tungsten as used in steel making is reduced from the oxide by heating with carbon in crucibles, but the resulting metal is not pure enough for the manufacture of tungsten filaments, which are seriously affected by the presence of combined carbon. It is also possible to reduce the oxide by heating with metallic zinc, the two substances being in a finely divided state and thoroughly mixed before heating.

The tungsten as obtained from the process of reduction employed in lamp manufacture retains the physical characteristics of the oxide inasmuch as it is finely divided and slightly spongy. The metal in a mass has a bright metallic luster resembling platinum. In the powdered state it is grayish black or dead black depending upon the fineness of the powder and the temperature of reduction.

After obtaining this very pure metallic tungsten, the next operation is to mix it with a binding material in order to form a plastic mass that may be squirted into the fine threadlike filaments. Various substances can be used for this purpose but some compound of carbon, oxygen, and hydrogen such as starch, sugar, camphor, etc., is usually employed. The metallic powder when mixed with such a binding material has somewhat the consistency and appearance of black putty. It is absolutely smooth and uniform and it is impossible to detect the slightest grain. This paste, as it is called, is placed in a small steel cylinder and forced, by a pressure of about 32,000 lb. per sq. in., through a small diamond die.

The die used in squirting tungsten filament consists of a suitably mounted diamond of from one-half to one carat in weight through which a very minute hole has been drilled. In the smaller dies used to-day this hole is only about 0.0014 in. in diameter which is smaller than an ordinary hair. The hole is drilled in the diamond with a steel needle, ground down so fine that it is as flexible as a hair and, as can be imagined, the drilling requires considerable time and patience. The stone when drilled is mounted in a steel casting in order to hold it against the enormous pressure used in squirting the filament.

Under such pressure the abrasion of the die even by the smooth tungsten paste is very rapid. This abrasion is a serious matter as the diameter of the hole, and consequently that of the filament squirted, constantly increases. Moreover the abrasion is not uniform, so that the hole enlarges more rapidly in the direction of one diameter than of the other, assuming when worn an elliptical shape. After enough filament for about 1,500 lamps has been squirted, it is necessary to have the die rebored, an operation which costs almost as much as the original die. A die cannot be rebored more than twice before it develops cracks or fissures which cause it to break. The next hardest material, sapphire, has been experimented with as a material for these dies but it is found that such a die is very liable to split and that it will hardly make 100 lamps before it needs re-drilling.

The filament, after squirting, has been likened in character to a filament of putty, that is, while holding its form well and being flexible to some extent, it is liable to break if bent sharply. The filament as squirted is looped back and forth on cards and after being allowed to dry is cut to form a number of single loops much as they are seen in the finished lamp.

The next operation is to heat the filaments in an inert gas, or in one chosen to act upon the particular binding material employed, until they reach a red heat which removes any moisture and lighter hydrocarbons that may be present. Each filament is then mounted in current conducting clips so that it may be heated by passing an electric current through it. During this final heating or forming, as it is termed, the filament is supported vertically with the loop downward. A very small weight (a few milligrams) is hung in the loop to prevent the filament from being distorted in shape during the heating which is usually performed in either an inert gas or in a very good vacuum, the gas, if used, being again dependent to some extent on the binding material employed. The temperature of the filament is raised gradually, allowing time for the proper reactions and physical changes to take place. During the heating, the energy input into the filament rises to about fifteen times that finally required in the lamp, and while some heat is carried away by the forming gas the temperature is undoubtedly much higher than that reached in subsequent operation.

Every trace of binding material is driven out, and the filament when finally brought to a sufficiently high temperature undergoes a sudden and marked contraction in diameter and length as the small semi-molten particles become soft enough to merge into one perfectly homogenious mass. A piece of such filament under a microscope resembles a drawn wire and while the surface is not perfectly smooth there is no indication of a granular structure.

At a dull red heat any good tungsten filament is flexible enough to be bent as desired but when cold is somewhat fragile. For this reason it is a good thing if possible to light tungsten lamps while cleaning them, the chance of mechanical breakage being then minimized. Lamp packages have been devised that eliminate a considerable amount of breakage that would result from rough handling so that, if the lamps are left in the original cartons until placed in service, and handled with even ordinary care, the question of breakage will be found to be of little importance.

In order to secure a uniform quality of filament, which is absolutely necessary for good lamp making, every step of the entire process of production even to the smallest detail must be carried through with exactness. For example the rate at which the temperature of the filament is raised during the forming process has a most important effect on the final filament structure, and must be carried out with extreme care in order to assure a perfectly uniform run of filament.

After forming, the filaments are mounted upon the familiar glass supporting rod as seen in the finished lamp, and the joint between each leg and the supporting and conducting terminal made by electrically welding the filament to the support. This makes a very perfect joint both electrically and mechanically.

The material used for the hooks and supporting wires affects the performance of the lamp to a considerable extent. Soft copper is used extensively for such supports, also, to a somewhat lesser extent, molybdenum, tungsten, tantalum, thoria, carbon, platinum, iridium, or other refractory materials. Soft copper does not alloy with pure tungsten and moreover occludes but very little gas so that it makes a very satisfactory form of supporting hook.

The process of producing a high vacuum within the bulb of a tungsten lamp is a great deal more laborious than in case of the carbon lamp. It is necessary, in order to produce a good lamp, and this applies to carbon and other types as well, to remove every trace of gas, not only that actually free at the time of pumping but that which may later be liberated from anything within the finished bulb. A good lamp vacuum is only possible through the use of very perfect exhausting machinery and through subjecting the entire lamp, filament, glass, and other parts to a proper heat treatment, during the pumping process. The heat treatment tends to drive from the glass walls and other surfaces exposed within the bulb the particles of air which cling to them in a thin film with surprising persistence. A glass bulb pumped while cold will apparently reach a high degree of exhaustion at the end of the pumping process, but, if left standing for some time, will be found to possess a very poor vacuum as judged from that required to insure good lamp performance. This is due to the gradual liberation of particles of air which, during the pumping, cling to the interior surfaces. The filament is heated intensely by passing an electric current through it while on the pump in order to drive from it and from the supporting wires, which are heated by the incandescences of the filament, any occluded gas which may later be freed from these parts and thus spoil to a certain extent the perfect vacuum required for successful operation. During the pumping process the filament temperature must be regulated with great care, the temperature being raised gradually as the bulb becomes evacuated. If, for example, the temperature should be raised, too quickly, a thin film of oxide will form on the surface of the filament which, although entirely removed by a further rise in temperature and higher degree of exhaustion, will have been found to have caused a slight change in the character of the surface of the filament, altering thereby its emissivity and radiating properties and injuring its subsequent life performance.

After pumping, the lamps are given an exhaust inspection and aging by burning at a certain percentage over voltage. If during this inspection any lamp develops or shows a bluish color or haziness within the bulb it is an indication of imperfect vacuum and the lamp is rejected. The period of burning and per cent over voltage depends somewhat on the size of the lamp, but in every case has been chosen so that if a lamp is at all likely to develop a poor vacuum it will be disclosed on this inspection.

The glass work required in making the tungsten lamp is, with the exception of the center glass stem, practically the same as in the other types of incandescent lamps.

I have now covered in a general way the process of producing the tungsten lamps, and have I hope given some slight idea as to the care required in such production. In order to show the performance of the lamps in subsequent service, I have averaged the candle-power life curves of 50 40-watt tungsten lamps which were burned on life test at constant voltage corresponding to an initial consumption of 1.25 watts per mean horizontal candle-power. The curves in Fig. 1 show the change in candle-power, current and efficiency during the period of test, which was stopped at about 1,400 hours. In order to show the life performance, a curve is given showing the per cent of lamps which were burning at the end of various periods of time. These curves, Fig. 2, are the average obtained from 80 40-watt tungsten lamps burned under same conditions as the previous

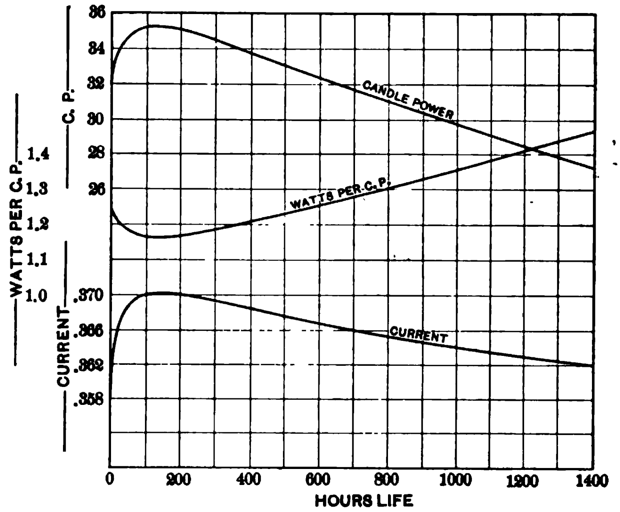

FIG. 1.—Characteristic performance of 40-watt tungsten lamps

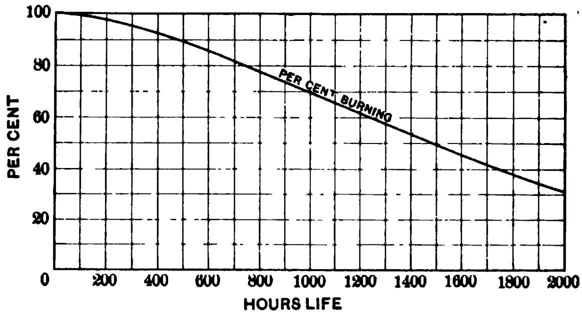

FIG. 2.—Mortality curve of 40-watt tungsten lamps

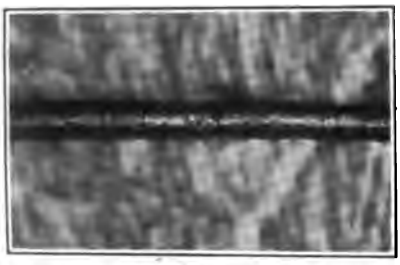

FIG. 3.—Unmounted tungsten filament

FIG. 4.—25-watt tungsten—400 hr.—alternating current

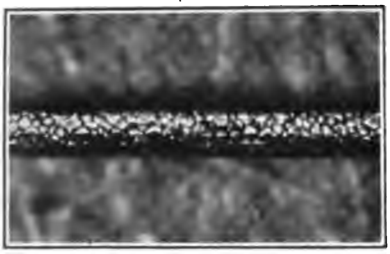

FIG. 5.—40-watt tungsten—180 hr. —alternating current

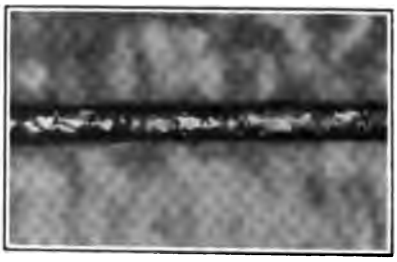

FIG. 6.—25-watt tungsten—1400 hr.—alternating current

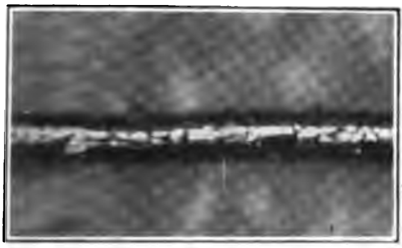

FIG. 7.—40-watt tungsten—898 hr.—alternating current

FIG. 8.—40-watt tungsten 2190 hr.—alternating current

FIG. 9.—40-watt tungsten—300 hr.—direct current

FIG. 10.—40-watt tungsten—3000 hr.—direct current

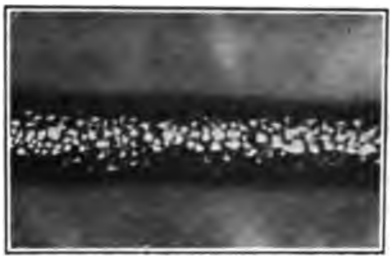

Fig. 11.—100-watt tungsten—1400 hr.—alternating current

Fig. 12.—250-watt tungsten—2000 hr.—alternating current

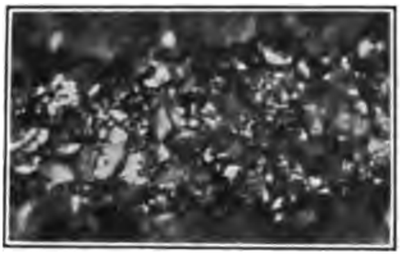

Fig. 13.—Tungsten—Street series 2000 hr.

Fig. 14.—Tungsten—street series —3349 hr.

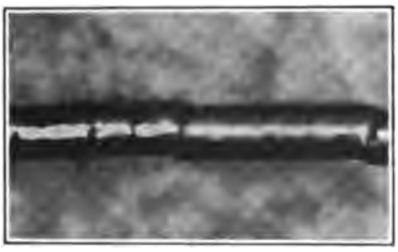

Fig. 15.—80-watt tantalum—50 hr.—alternating current

Fig. 16.—80-watt tantalum—400 hr.—alternating current

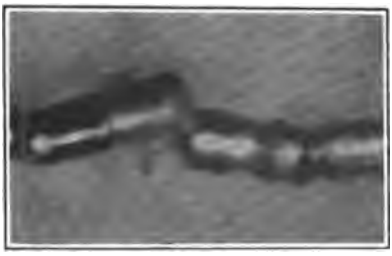

Fig. 17.—40-watt tantalum—800 hr.—alternating current

Fig. 18.—80-watt tantalum—948 hr.—alternating current

FIG. 19.—80-watt tantalum—60 hr.—direct current

FIG. 20.—80-watt tantalum—455 hr.—direct current

FIG. 21.—80-watt tantalum—1058 hr.—direct current

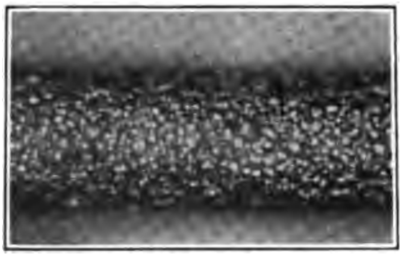

FIG. 22.—Gem—841 hr.

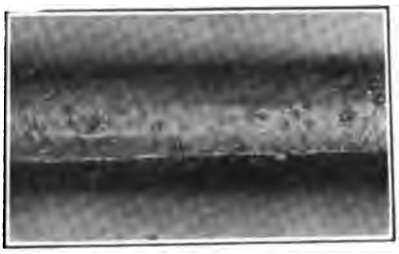

FIG. 23.—Carbon—508 hr.

test *i.e.*, at 1.25 watts per c.p. About one half of the lamps were burned in a horizontal position and the others in a vertical position, tip downward. These tests were stopped at the end of 2,000 hours.

The change in appearance of the filament during life is rather interesting, and some illustrations showing filaments taken from lamps which had burned for various lengths of time are shown in Figs. 3 to 23. For comparison, a few tantalum filaments as well as filaments from a gem and from a carbon lamp are shown.

The relation between candle-power watts, amperes, ohms, volts and watts per candle is shown by the characteristic curves of tungsten, Fig. 24.

For the normal range of operation these curves can be expressed in the form of parabolic equations a few of which are as follows:

Let C = candle-power.
e = efficiency in watts per candle.
V = voltage.
W = total watts.

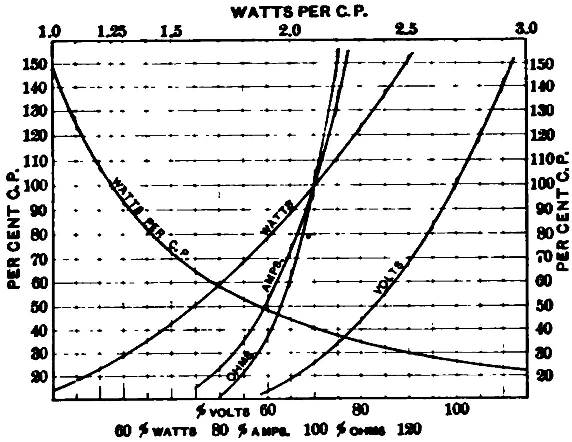

Fig. 24.—Performance of tungsten filament lamp

then

$$\frac{C_1}{C_2} = \left(\frac{e_2}{e_1}\right)^a$$

$$\frac{C_1}{C_2} = \left(\frac{V_1}{V_2}\right)^b$$

$$\frac{W_1}{W_2} = \left(\frac{V_1}{V_2}\right)^d$$

APPROXIMATE VALUES OF EXPONENTS

	a	*b*	*d*
Carbon	1.58	5.55	2.05
Gem	1.57	4.80	1.75
Tantalum	1.67	4.35	1.74
Tungsten	1.75	3.68	1.59

Values of the exponents are given not only for tungsten but for carbon, gem and tantalum as well, for purpose of comparison.

A series of values showing relation between voltage and candle-power variation for the four types of lamps has been calculated, and shows the great advantage which the metallic filament lamps, particularly the tungsten, possess over the carbon lamp.

Per cent change in voltage		Per cent change in candle-power			
		Carbon	Gem	Tantalum	Tungsten
Increase above normal	10	69.8	58.0	51.4	42.1
	9	61.4	51.3	45.5	37.4
	8	53.4	44.7	39.8	32.8
	7	45.6	38.4	34.2	28:3
	6	38.2	32.3	28.9	23.9
	5	31.1	26.4	23.6	19.7
	4	24.3	20.7	18.6	15.5
	3	17.9	15.2	13.7	11.5
	2	11.6	10.0	9.0	7.6
	1	5.7	4.9	4.4	3.7
Normal............		0	0	0	0
Decrease below normal	1	5.4	4.7	4.3	3.7
	2	10.6	9.3	8.4	7.2
	3	15.5	13.6	12.4	10.6
	4	20.3	17.8	16.2	13.9
	5	24.8	21.8	20.0	17.2
	6	29.0	25.7	23.6	20.4
	7	33.2	29.4	27.1	23.4
	8	37.1	33.0	30.5	26.4
	9	40.7	36.4	33.6	29.3
	10	44.3	39.7	36.8	32.2

An increase of 6 per cent in the voltage of a carbon lamp increases the per cent candle-power as much as an increase of 9 per cent in voltage of the tungsten lamp. While a tungsten lamp 10 per cent under voltage drops in per cent candle-power. only as much as a carbon lamp 7 per cent below normal. For a circuit where the regulation is poor, the tungsten lamp will be found to give much better satisfaction as far as variation in candle-power is concerned than the carbon lamp.

The size and length of filament required in lamps of various candle-powers and voltages varies considerably. For 110 volts the size and length varies from a diameter of 0.0013 in. and a total length of 17.4 in. for a 25-watt lamp to a diameter of 0.0060 in. and a total length of 37.56 in. for a 250-watt lamp.

The specific resistance of tungsten is about 46.5 ohms per mil-inch at a temperature corresponding to 1.25 watts per c.p. and about 9 per cent of this figure, or 4.19 ohms per mil-inch, at ordinary room temperature. This low cold resistance has led to a good deal of discussion as to the value of the starting current obtained upon closing the circuit of a tungsten lamp and its effect upon the filament.

The question is of particular importance when the lamps are turned on and off continuously, as for example in flashing sign work. We have obtained experimentally the cooling curves of several sizes of tungsten lamps, which are shown herewith, plotted as resistance against time, Fig. 25. As would be expected, the larger lamps cool much more slowly than the smaller ones, as shown by the drop in resistance. It takes the 250-watt lamp, burning at 1.25 watts per c.p., 58 seconds after being turned off, to fall to 200 per cent of its initial cold resistance, while it takes the 60-watt lamp only 20 seconds, the 25-watt lamp about 11 seconds and the small low voltage sign lamp a little over six seconds. The filament of the latter lamp is actually heavier than that of the 25-watt lamp, but, being much shorter, cools more rapidly by conduction of heat by the terminals and anchor.

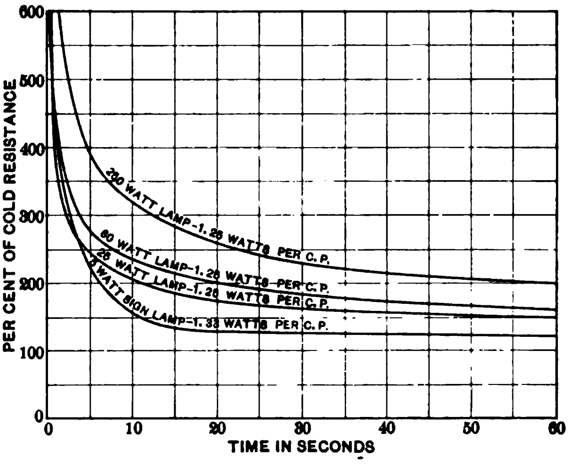

FIG. 25.—Cooling curves of tungsten lamps

In ordinary flashing sign work, four seconds can be assumed as an average period of flashing; this would allow the sign lamp to drop to only 250 per cent of its cold resistance between flashes, or the ratio of hot and cooling resistance when flashed in this way would be about one to four. This would act to greatly reduce the over-shooting effect.

From tests conducted on a few lamps flashed at various intervals, it is so far believed that flashing will have no injurious effect on the lamps in regard to life performance.

Having now covered the general method of manufacturing the tungsten lamp and a few of its characteristics we may turn our attention to the reason of its high efficiency.

A body at any temperature other than absolute zero will radiate energy in all wave lengths from zero to infinity, having a maximum radiation at a wave length which varies with the temperature. At low temperatures the actual amount of energy radiated is very small, and beyond narrow limits on either side of the maximum is infinitesimal.

The general distribution of energy so radiated is shown by the curves in Fig. 26. The total amount of energy radiated in a given time is represented by the total area under the curve and has been found to increase as the difference of the fourth powers of the temperature of the radiating body and the temperature of its surroundings. Not only does the actual rate of energy radiation vary as a function of the temperature, but the manner in which the energy is radiated also changes. This change takes place as shown by the shift in the maximum point of the curves plotted for the radiation of a body at different temperatures. The radiation from most bodies follows a very complex law and has been thoroughly investigated only for a complete radiator or theoretical black body, which is represented in the curves shown. The same general law holds for other bodies as well as the theoretical black body considered.

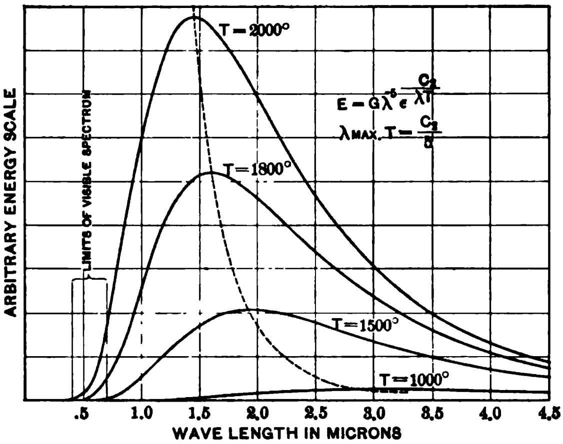

Fig. 26.—Black body radiation

Referring to the energy-wave length curves the area under the curves represents the total energy radiated by the body at the several temperatures. The visible spectrum which includes only the wave lengths capable of exciting the retina of the eye represents but a small portion of the total range of radiation and the energy radiated in the visible spectrum represents a still smaller portion of the total amount of energy radiated. The ratio of the energy radiated in the visible spectrum to the total energy radiated is an indication of the luminous efficiency and since the maximum point of the energy curve shifts toward the visible spectrum, as the temperature rises, as shown by the dotted line, the luminous efficiency increases with the temperature.

It we could secure a black body capable of operating at extremely high temperatures and a means of producing such temperature we would find a limit to our efficiency of light production at about 5000 deg. absolute at which point the maximum of the energy curve would coincide with the maximum of the sensibility curve of the eye at about the middle of the visible spectrum. If the temperature could be raised still further the luminous efficiency would decrease, as the maximum of the energy curve would then move toward the ultra violet. Consequently we see that under ordinary conditions we can raise the luminous efficiency of a body by raising its temperature. In the attempt to secure high luminous efficiency by this means we are limited by the possibility of producing a substance capable of maintaining a high temperature without disintegration.

There is another important property of some substances which has made the present high commercial efficiency of the metallic filament lamps possible. The property referred to is that of selective radiation in the short wave lengths.

We have used the term black body or complete radiator to describe a body which will radiate at any temperature a maximum amount of energy in every wave length. Such a body would also be a complete absorber and would therefore absorb all energy incident upon it. A body, which is not a complete radiator, will at a given temperature radiate less energy in each wave length than a black body at the same temperature. If the energy radiated in each wave length is reduced by a constant proportion, the ratio of energy radiated in the visible spectrum to the total energy radiated will be the same as that of a black body, and the luminous efficiency would be the same as that of a black body at the same temperature. Such a body is termed a gray body, and in place of absorbing all energy, which falls upon it, it would reflect a constant percentage of each wave length.

If a body not only radiates less energy than a black body at the same temperature, but in addition radiates a relatively larger proportion in one part of the spectrum than in another, compared to the black body it may be said to radiate selectively in that part of the spectrum. If the body radiates selectively in the short wave lengths the luminous efficiency will be higher than that of a black body at the same temperature. We would expect to find in the case of such a body that the absorption of energy would not be the same for different wave lengths but that the body would absorb a greater proportion of those wave lengths which it would radiate selectively when heated. A comparison of the reflecting power at different wave lengths for different substances is very interesting in showing how it is possible to gain in efficiency of light production by employing materials capable of selective radiation. Fig. 27 shows the percentage of energy of various wave lengths reflected from several different substances. A black body would have zero reflecting power throughout, a gray body a constant per cent throughout while a body capable of selective radiation a varying per cent. All the metals shown here have a tendency to reflect less energy in the visible spectrum than in the infra red, where the reflecting power rises to a very high value. Consequently since they absorb relatively more energy of the visible spectrum, they would, when heated, tend to radiate relatively more energy in the same part of the spectrum, and would therefore be found

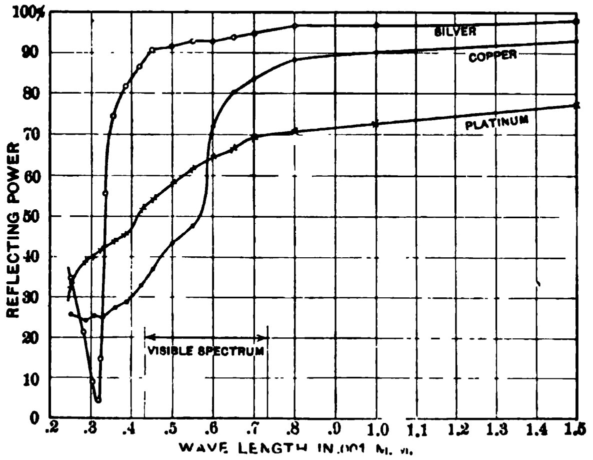

FIG. 27.—Percentage of energy of different wave lengths reflected from silver, copper and platinum*

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*Data from Landolt-Börnstein, Physikalisch-Chemische Tabellen.

to be more efficient luminous radiators than a black body at the same temperature. The relative percentage of energy in the visible spectrum to total energy at different temperatures can

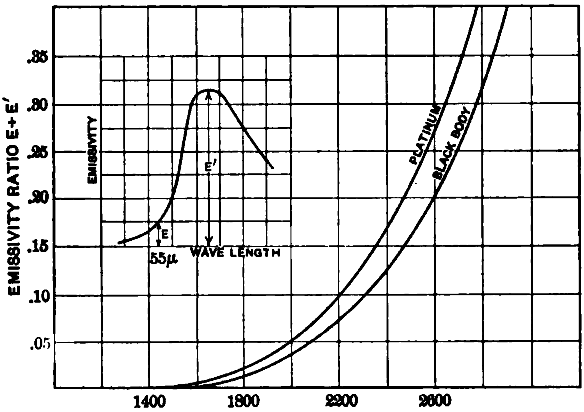

Fig. 28.—Selective radiation of platinum

be represented roughly by the ratio of the ordinate of the energy curve at 0.55 micron in the visible spectrum to the maximum ordinate. The curves shown in Fig. 28 indicate this ratio for various temperatures of a black body, and of platinum, showing the selective radiation of platinum in the shorter wave lengths. While the curves for tungsten are not available they should possess the same general characteristics as the metals shown.

Another way of showing the selective radiation is by means of actual energy curves taken through the range of principal radiation. Fig. 29 shows a series of curves determined by the Bureau of Standards showing the energy distribution of various filament materials when operated so that the light distribution is practically the same throughout the visible spectrum. It can

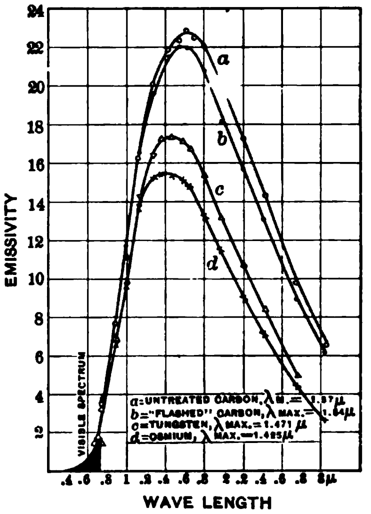

Fig. 29.—Curves of energy distribution of filament materials*

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*Coblentz, "Radiation Constants of Metals"; Bulletin of the Bureau of Standards, Vol. 5, No. 3.

be shown that the temperature of the tungsten filament in this comparison is at least as low as that of the carbon filament so that, under actual working conditions, the difference between the energy curves would be still more striking since a further gain in luminous efficiency is made possible by the higher normal operating temperature of the tungsten filament.

High commercial efficiency of incandescent lamps cannot be expected to result from high temperature alone but from a combination of high temperature with a property of selective radiation. The possibility of operating a filament at a high temperature is a very good feature but the disintegration of the filament, which increases more and more rapidly as the temperature rises places an upper limit on the temperature at which it is possible to operate a filament and still obtain a commercial life, so that we cannot look to high temperature alone for a solution of the problem. The temperature at which it is possible to operate a filament, and secure a reasonably long life, depends not so much on the melting point as upon the ability to withstand surface evaporation in a high vacuum.

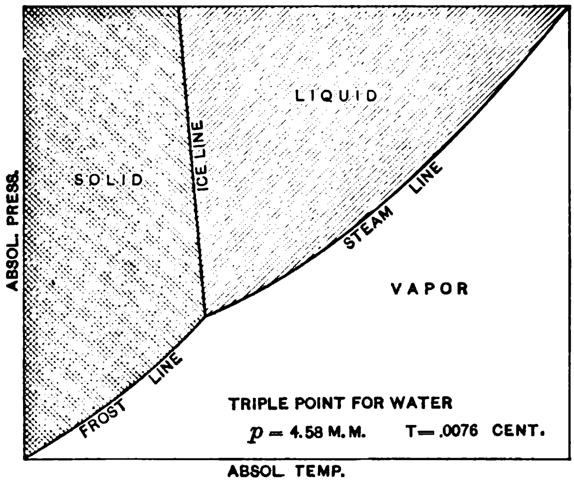

Fig. 30.—Pressure-temperature diagram

The conditions that exist in a lamp of high exhaustion in regard to melting and vaporization are rather interesting. If we plot a pressure temperature diagram for any substance we find that the three states of the substance will be represented by three areas bounded by three curves which we would call, in speaking of water, the steam line, the ice line and the frost line. See Fig. 30. The intersection of these three curves gives us the location of the " triple point ", or the pressure and temperature at which it would be possible to have the substance existing in these three states at the same time.

In an incandescent lamp bulb the pressure is exceedingly low, something of the order of 0.001 mm. of mercury, so that we may believe while not being able to prove conclusively that at normal operating temperatures of the filament we are working on a part of the diagram below the triple point, there would therefore be a tendency for the material to evaporate slowly from the filament surface, as it apparently does. That the temperature of commercial operation is not dependent upon the actual melting point may be shown by the rapid disintegration of a carbon filament if operated at the normal temperature of a tungsten filament in spite of the fact that the true melting point of carbon is probably higher than that of tungsten.

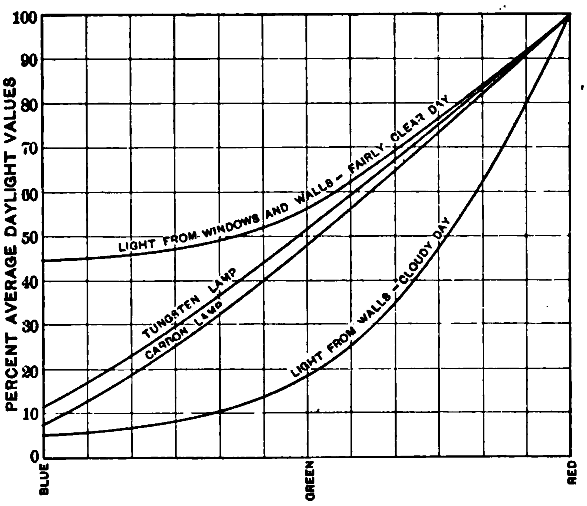

FIG. 31.—Color composition of various lights

The tungsten lamp is, because of its selective radiation and higher filament temperature, superior to the older types of incandescent lamps in the quality of its light. Under normal working conditions the tungsten favors the shorter wave lengths through the visible spectrum, giving relatively more blue radiation than the carbon lamp for an equal amount of red. The accompanying curves, Fig. 31, show the relative amounts of red, green, and blue in several types of lamps compared to daylight. The term, daylight, as ordinarily used is rather indefinite, as the proportion of red, green and blue in the light from a cloudy sky is different from that of a clear blue sky, which, again is different from that of direct sunlight. The comparison in this case is made to average outdoor daylight, as obtained from careful observation over a considerable length of time, and which is represented as 100 per cent red, 100 per cent blue and 100 per cent green.

I have drawn two other curves, which may be taken to represent the composition of light as it actually may exist in interior daylight illumination. Due to the reflection from surrounding objects, both without and within, it is usual to find the light in a room possesses a markedly different composition from the average light received directly from the sky.

An object in a room in day time is illuminated for the most part by light reflected from the walls of the room, except, of course, if it is directly in front of and close to a window. At night, with an artificial source of light within the room, the objects are illuminated for the greater part with light directly from the artificial source. The artificial source of light should therefore be of such character as to illuminate the objects in the room by its direct rays with a light of the same average quality or color value as that which illuminates them by diffuse reflection from walls and furnishings during the day. The nearer the color curve of an illuminant approaches that of the average interior light of a particular room during the day the more natural will the room appear if illuminated with such a source of light.

The question of frequency and flicker is one which often arises in connection with the use of the tungsten or other high-efficiency lamps on low-frequency power circuits. The candle-power of an incandescent body varies with the temperature. The temperature depends upon the relative rate at which energy is put into the filament and the rate at which it is dissipated by radiation, conduction and convection. When the energy is supplied at a changing rate, as by an alternating current, the temperature will fluctuate in synchronism with the power wave, or at double the frequency of the supplied e.m.f. The amount of variation in temperature during one cycle will depend upon the ressistance temperature coefficient of the filament, its mass, diameter, specific heat, emissivity, and upon the wave shape and frequency of the energy supplied. If the frequency is low enough the temperature will fluctuate over wide limits. The amount of temperature fluctuation decreases greatly as the frequency increases, due to the thermal capacity of the filament. When the frequency of the electric circuit reaches about 25 to 27 cycles the flicker of most incandescent lamps giving usual intensities of illumination becomes imperceptible, although, it may in some cases be detected momentarily by rapidly moving the eyes from one object to another. The flicker effect at a given frequency will be more noticeable with a thin filament than with a heavier one of the same material since the quantity of heat contained at a given temperature varies as the mass or diameter squared, while the radiating surface varies only as the diameter to the first power.

In comparing tungsten and carbon filaments of the same diameter we must bear in mind that the higher specific heat of carbon tends to maintain its temperature more nearly constant with varying power input than in the case of the tungsten, while its higher emissivity tends to produce a more marked variation. Since, however, the diameter of a tungsten filament is less than that of a carbon filament for same voltage and candle-power, the carbon lamp is actually found to show a less tendency to produce visible flicker.

The question of flicker further involves the ability of the eye to detect a rapid variation in luminous intensity and it has been shown that the eye becomes less sensitive to the effect of flicker, as the average intensity of the illumination decreases. We have found, from experimental work, which is as yet not complete enough for more extended discussion, that the critical frequency at which it is possible to detect flicker varies as a function involving the product of the average intensity of illumination and the per cent variation in intensity. Thus the question as to whether a given lamp will show a flicker when operated at a certain frequency depends a great deal upon the average intensity of the illumination produced.

If we judge the flicker of a lamp at a certain low frequency by viewing a large surface illuminated by the lamp we would find that as the distance between the lamp and the surface increased the flicker would become less and less perceptible, diminishing with the intensity of illumination until, beyond a certain value of illumination no flicker could be detected. This characteristic of the eye enables comparatively low frequencies to be used successfully with low values of illumination.

The question of flicker is perhaps of most importance in connection with street series lighting, since, in ordinary multiple lighting, higher frequencies are usually employed. The street series tungsten should prove capable of successful operation at comparatively low frequencies for two reasons; first, the filament is heavy, which tends to reduce the variation in candle-power throughout a cycle; and second, the low value of illumination generally used in street lighting would tend to make any varaition in intensity of illumination less perceptible to the eye.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

REPORT OF THE BOARD OF DIRECTORS FOR THE FISCAL YEAR ENDING APRIL 30, 1910.

The Board of Directors of the American Institute of Electrical Engineers presents herewith for the information of the membership its annual report for the fiscal year ending April 30, 1910. The report shows the financial status of the Institute, and includes brief statements regarding the work accomplished by the various standing and special committees

The Annual Convention was held at Frontenac, New York, June 28-July 1, 1909. The total registered attendance was 252. Thirty-six professional papers, including the President's annual address were presented and discussed.

The Board of Directors has held 10 regular monthly meetings during the year.

A number of important changes in the policy of the Institute were effected during the year. Among these was the action resulting from the proposed formation of technical sections, the object of the movement being to broaden the work and scope of the Institute so as to cover as far as possible the entire field of electrical engineering. Upon recommendation of the Law Committee, to which the matter was referred, the Board of Directors at its meeting held on November 12, 1909, adopted resolutions authorizing the President to appoint additional special committees, to promote Institute activity in their respective fields, this being determined upon as the best means of meeting the situation.

On January 14, 1910, the Board adopted resolutions authorizing the holding of Institute meetings under the auspices of Sections. The object of these resolutions has already been clearly set forth in an article by President Stillwell printed in the April 1910 PROCEEDINGS. The resolutions were printed in full in the February PROCEEDINGS. In accordance with this action a successful Institute meeting was held in Boston, February 16, 1910. Other important resolutions adopted by the Board on January 14, 1910, related to the publication of informal communications in the Institute PROCEEDINGS. These resolutions were printed in full in the February 1910 issue.

Another important act of the Board during the year was to create wider distinction between the Institute PROCEEDINGS and TRANSACTIONS. This was discussed at the meeting of the Board held on November 12, 1909, at which a resolution was adopted instructing the Meetings and Papers and Editing Committees to select from the PROCEEDINGS for publication in the TRANSACTIONS only such papers and discussions as might be deemed worthy of permanent record and in making such selection no distinction is to be made between papers presented at the Annual Convention or monthly meetings of the Institute and those presented at any meeting of any Institute Section.

Closer relations between the Institute and the Sections and Branches have been established during the year by the action of the Board in authorizing the Secretary to make a tour of the Pacific Coast and arrange to meet as many western members as possible. This tour was most successful, as may be judged by the Secretary's report to President Stillwell, published in the November PROCEEDINGS. In carrying out this policy the Secretary during the year has visited meetings or conferred with groups of members at the following places, in most of which Sections and Branches existed or have since been organized: Seattle, Portland, Oregon; San Francisco; Los Angeles; Salt Lake City; St. Louis; Washington, D. C.; Boston, Mass.; Philadelphia; Urbana, Illinois; Chicago: Ames, Iowa; St Paul; Madison, Wisconsin; Milwaukee; Fort Wayne; Lewis Institute, Chicago; Armour Institute, Chicago; Charlotte, N. C.; and Pittsfield, Mass., involving a total of approximately 17,000 miles of distance travelled.

Sections Committee..—The Sections Committee is able to report very satisfactory progress in the work of the Sections and Branches during the past year, and a healthful state of affairs at the present time.

Two new Sections have been authorized during the year—one at Portland, Oregon, on May 18, 1909, and the other at Milwaukee, Wis., on February 11, 1910. The Milwaukee Section is undertaking an important development in Section work by coöperating with a local engineering society and local sections of other national engineering societies in such a manner that the efforts of all of these various engineering bodies shall be combined into a harmonious whole, so far as that particular locality is concerned.

Five new Branches have been organized during the year, as follows:

State University of Iowa, May 18, 1909.
Agricultural and Mechanical College of Texas, November 12, 1909.
Rensselaer Polytechnic Institute, Troy, N. Y., November 12, 1909.
Colorado State Agricultural College, February 11, 1910.
North Carolina College of Agriculture and Mechanic Arts, February 11, 1910.

The following table will serve to show the activities of the Sections and Branches for the past three years:

SECTIONS	For Year Ending		
	May 1, 1908	May 1, 1909	May 1, 1910
Numbers of Sections	21	24	25
Section meetings held	141	169	187
Original papers presented	120	167	178
Attendance	7,476	16,427	16,694
BRANCHES			
Number of Branches	22	26	31
Branch meetings held	143	198	237
Original papers presented	84	158	147
Attendance	4,128	8,443	10,255

Meetings and Papers Committee.—The organization of the Meetings and Papers Committee has been materially changed during the past year by the appointment of the chairmen of the special technical committees to membership on the Meetings and Papers Committee and the enlargement of special committees. A further change has been made in holding the special technical committees responsible through their chairmen for Institute activity in the several branches of electrical science covered by them. It was also decided, early in the year, with the approval of the Board of Directors, to hold Institute meetings in different sections of the country, to encourage and develop interest and activity in the Institute work among the entire membership. The result of these changes in organization and methods has been a gratifying increased activity in the Institute work and the broadening of the scope and influence of the Institute.

During the past year this committee arranged for eight regular meetings, two largely attended special meetings, one at Charlotte and the other at San Francisco, the latter under the auspices of the High-Tension Transmission Committee. An adequate number of interesting papers were presented. These meetings partook of the general character of conventions. Two meetings were also held in coöperation with the American Society of Mechanical Engineers and two additional special meetings were held, one at New York and one at Boston.

Educational Committee.—The work of this committee for the year has consisted principally of arranging the April meeting of the Institute at New York, at which a paper on the subject of " Education for Leadership in Electrical Engineering " was presented by Dr. Samuel Sheldon.

The committee desires to emphasize the fact that the Institute has been more active in giving attention to educational matters than any of the other professional engineering organizations in the United States, and it is believed that this has been an important factor in the development of the Institute.

Electric Lighting Committee.—Regular monthly meetings of the committee have been held during the Institute year and the committee has arranged for the presentation of two papers on the subject of electric lighting at the May 17 meeting. Also, three papers have been obtained by the committee for presentation at the 1910 Convention.

High-Tension Transmission Committee.—An Institute meeting was held under the auspices of this committee on December 16, 1909. The committee also assisted in the Charlotte meeting and arranged for a Pacific Coast meeting of the Institute at San Francisco, California, May 5–7, 1910. Several valuable papers and much interesting discussion were obtained by the committee for presentation at these various meetings.

Industrial Power Committee.—Through the efforts of the committee practically all of the Sections and Branches have devoted one meeting this year to industrial power subjects. The March meeting of the Institute in New York was held under the auspices of the committee, as was also a joint meeting in Boston on February 16, 1910. A meeting was also held in New York on April 12, 1910, in coöperation with the American Society of Mechanical Engineers. An attempt is now being made to collect the papers on the subject presented before the various Sections, with the idea of publishing them in book form if feasible.

Railway Committee.—The Railway Committee has been active in obtaining papers in its field during the past year. Two Institute meetings, devoted to railway subjects, were held in New York under its auspices, and the committee has arranged for a special meeting to be held in New York on May 27, 1910. The committee has broken considerable new ground and will have several subjects to transmit to next year's committee through the Board of Directors. Among these is a suggestion for a change in policy in the manner of conducting a number of special meetings under the auspices of the Committee next year.

Telegraphy and Telephony Committee.—The meeting of the Institute at New York on February 11, 1910 was held under the auspices of this committee. A paper was presented dealing with modern automatic telephone apparatus.

Editing Committee.—Since May 1, 1909, there have been edited and published 12 numbers of the PROCEEDINGS. The total number of pages contained in these PROCEEDINGS is 2,262. Of this total, 402 pages have appeared in Section I, and 1,860 pages in Section II. Of the 1,860 pages in Section II, 1,257 pages were devoted to technical papers, and 556 pages to discussions. Volume XXVIII of the TRANSACTIONS, consisting of the papers and discussions during the calendar year 1909 and the report of the Board of Directors for the fiscal year ending April 30, 1909, contains 1,572 pages. Volume XXVIII will be issued in two parts. Part I, consisting of 752 pages, will contain the papers and discussions presented between January 1, 1909, and the session of June 29, 1909, at the Frontenac Convention. Part II, consisting of 820 pages, will contain the papers and discussions presented between the session of June 29, 1909 at the Frontenac Convention, and December 31, 1909; also the paper read by Mr. H. G. Stott before the Toronto Section on December 18, 1908.

From May 1, 1909 to April 30, 1910 there have been published in full in the PROCEEDINGS five papers read before various Sections and Branches, in addition to four abstracts of such papers, which appeared in Part I of the PROCEEDINGS.

The Editing Committee has gone carefully over the discussions which have been submitted by the Sections and Branches, and has also given its attention to the discussions presented at the New York meetings, to the end that much matter of temporary value has been eliminated and a higher standard of composition as well as material has been maintained. The committee has had under consideration the introduction of metric equivalents in the Institute publications, and has recommended to the Board of Directors that the suggestion of the Standards Committee relating to metric equivalents be given a trial should the Meetings and Papers Committee concur. The Editing Committee also has under consideration the publication of the material presented at joint meetings with other societies.

Standards Committee.—The Standards Committee has held five meetings in New York during the year. The committee has not undertaken a revision of the Standardization Rules this year, but has confined its work in that direction to preparing a separate list of recommended additions and amendments to the rules. This list is being prepared, and will be submitted at a later date.

The committee has had under consideration a revision of the Institute Copper Wire Table. Prior to undertaking this work, however, the committee consulted the Bureau of Standards concerning the most reliable and advantageous data to employ. The Bureau has taken these questions under consideration.

At its meeting held on December 16, 1909, the committee voted to recommend to the President and Board of Directors of the Institute the adoption of a by-law providing that metric equivalents shall be printed in parentheses after numerical expressions in English units in the Institute publications. This vote was communicated to the President on January 5, 1910, and the recommendation is now being jointly considered in conference between the Editing, and Meetings and Papers Committees.

International Electrotechnical Commission.—The U. S. National Committee of the International Electrotechnical Commission has held five meetings since December last. No convention or unofficial gathering of the Commission has been held during the year, but it is expected that an unofficial gathering will be held in Brussels in the week commencing August 7, 1910.

The following countries are now represented by national committees on the Commission: Argentina, Austria-Hungary, Belgium, Canada, Denmark, France, Germany, Great Britain, Italy, Japan, Mexico, Spain, Sweden, and the United States.

Informal communications have been exchanged with the General Secretary's office in London on the subject of a tentative plan for initiating international standardization in the direction of stationary direct-current generators and motors for continuous-service constant-potential operation.

Informal communications have also been exchanged with members of other national committees in regard to a proposed preliminary list of nine symbols for international adoption in electrical engineering, and the answers received have been very encouraging.

It is hoped that international progress may be made by the Commission in both of the above directions; namely, towards international standardization of machinery, and towards international standardization of symbols used in electrical engineering.

Library Committee.—We submit herewith our report giving the more important features of the growth and operation of the Library for the year ending April 30, 1910, together with a statement of the present condition of the several funds and expenditures for the year.

The gifts to the Library through its members and others have reached a total of 975 volumes and pamphlets. 287 volumes have been added through purchase and 54 volumes have been received through exchange for the PROCEEDINGS of the Institute. The total additions are therefore 1320 titles.

In the table of statistics given below a large number of pamphlets has been added which was received in the previous year but which had not been listed or accessioned at the time of the last report.

The total valuation is shown in the table below and a complete list of donors with the number of volumes or pamphlets presented by each is as follows:

DONORS

ADAMS, S. C	3
AERONAUTIC SOCIETY OF NEW YORK	1
ALLEGEMEINE ELEKTRICITATS GESELLSCHRAFT	3
ALMANNA SVENSKA ELEKTRISKA AKTIEBOLAGET	1
ALUMINIUM COMPANY OF AMERICA	5
AMERICAN CIVIC ASSOCIATION	1
AMERICAN INSTITUTE OF ARCHITECTS	2
AMERICAN MINING CONGRESS	3
AMERICAN RAILWAY ASSOCIATION	7
AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS	1
AMERICAN SOCIETY OF ENGINEERING CONTRACTORS	1
AMERICAN STREET AND INTERURBAN RAILWAY ASSOCIATION	6
ARMSTRONG CORK COMPANY	1
ARNOLD, B. J	1
ASSOCIATION OF LICENSED AUTOMOBILE ENGINEERS	1
ASSOCIATION OF VERMONT ENGINEERS	1
BAEYER, O. V	1
BAKER ELECTRIC COMPANY	2
BENTLEY, E. M	1
BOSTON SOCIETY FOR CIVIL ENGINEERS	1
BOSTON TRANSIT COMMISSION	1
BROOKLYN ENGINEERS CLUB	1
BURCH, E. P	1
BUREAU OF LONGITUDE, PARIS	1
CALDWELL, EDWARD	22
CAMBRIDGE (MASS.) BRIDGE COMMISSIONERS	1
CANADIAN ELECTRICAL ASSOCIATION	1
CANADIAN ENGINEER	1
CARNEGIE INSTITUTE OF WASHINGTON	4
CARNEGIE LIBRARY OF PITTSBURGH	1
CIVIC LEAGUE OF SAN FRANCISCO	3
CLARK, MYRON C. PUBLISHING COMPANY	1
CLAYTON, W. B. AND CRAIG, J. W	1
CLEVELAND ENGINEERING SOCIETY	1
COHRANE PUBLISHING COMPANY	1
COLUMBIA UNIVERSITY	9
COMISION 4 CONGRESO CIENTIFICO (CHILE)	3
CONNECTICUT BUREAU OF LABOR	1
CUSHING, H. C., JR	1
ELECTRIC TRADES ASSOCIATION OF THE PACIFIC COAST	1
ELECTROCHEMICAL & METALLURGICAL INDUSTRY	1
ENGINEERS CLUB OF CENTRAL PENNSYLVANIA	1
ENGINEERS CLUB OF PHILADELPHIA	1
ENGINEERS CLUB OF ST. LOUIS	1
ENGINEERS CLUB OF TORONTO	1
ENGINEERING STANDARDS COMMITTEE	1
FIDELITY & CASUALTY COMPANY OF NEW YORK	1
GENERAL ELECTRIC COMPANY (INCOMPLETE)	3

GESELLSCHAFT FUR DRAHTLOSE TELEGRAPHIE, BERLIN	1
GILBRETH, F.B	1
GUYE, P. A	1
HEDENBERG, MR	1
HOPELI, U	3
HUELS, F. W	1
HUNTINGTON, MR	1
L'INDUSTRIE DES TRAMWAYS ET CHEMINS DE FER	1
INSURANCE SOCIETY OF NEW YORK	2
INTERNATIONAL AMERICAN SCIENTIFIC CONGRESS	1
ISOLATED PLANT COMPANY	1
JENKS, W. J	4
KANSAS GAS, WATER, ELECTRIC LIGHT & STREET RAILWAY ASSOCIATION	1
KANSAS UNIVERSITY & ENGINEERING EXPERIMENT STATION	1
KENNELLY, A. E	5
KING, MOSES	1
LEWIS INSTITUTE	1
MCMILLAN COMPANY	3
MAILLOUX, C. O	1
MARTIN, JOHN	1
MARTIN, T. C	10
MASSACHUSETTS GAS & ELECTRIC LIGHT COMMISSIONERS	1
MASSACHUSETTS INSTITUTE OF TECHNOLOGY	1
MCGRAW-HILL BOOK COMPANY	117
MICHIGAN ELECTRIC ASSOCIATION	1
MONTANA STATE COLLEGE OF AGRICULTURE & MECHANICS ARTS	1
MUNICIPAL SCHOOL OF TECHNOLOGY MANCHESTER	2
MUNICIPAL ENGINEERS IN THE CITY OF NEW YORK	2
NATIONAL ASSOCIATION OF CEMENT USERS	1
NAIONAL ASSOCIATION OF COTTON MANUFACTURERS	1
NATTIONAL FIRE PROTECTION ASSOCIATION, BOSTON	1
NATIONAL SOCIETY FOR THE PROMOTION OF INDUSTRIAL EDUCATION	2
NEW ORLEANS SEWERAGE & WATER BOARD	1
NEW YORK CITY BOARD OF MAGISTRATES	1
NEW YORK PUBLIC SERVICE COMMISSION, 2ND DISTRICT	22
NEW YORK PUBLIC SERVICE COMMISSION, 1ST DISTRICT	15
NEW YORK STATE EDUCATIONAL DEPARTMENT	2
NEW YORK STATE LABOR DEPARTMENT	1
NEW YORK STATE WATER SUPPLY COMMISSION	1
NEW YORK ELECTRICAL SOCIETY	1
NEW YORK UNIVERSITY	1
OHIO INDEPENDENT TELEPHONE ASSOCIATION	3
PFUND, RICHARD	3
PERU MINISTERO DE FOMENTO	1
PHYSIKALISCH TECHNISCHEN REISHSANSTALT	13
PITTSBURG CHAMBER OF COMMERCE	1
POTAMIAN BRO	1
ROBSON & ADEE	1
ROCHESTER ENGINEERING SOCIETY	1

SHELDON, SAMUEL	1	
SIEBEL, F. P	1	
SOCIETE INDUSTRIELLE DE L'EST NANCY	1	
SOCIETY OF NAVAL ARCHITECTS & MARINE ENGINEERS	11	
SPON & CHAMBERLAIN	4	
SPRINGER, J	1	
STONE & WEBSTER	1	
SUBMARINE SIGNAL COMPANY	9	
SYDNEY UNIVERSITY ENGINEERING SOCIETY	1	
TELEFUNKEN WIRELESS TELEGRAPH COMPANY	27	
TELEGRAPHIC HISTORIAL SOCIETY OF NORTH AMERICA	2	
THOMPSON, S	1	
TRAUTWINE J. C., JR. & J. C. 3RD	2	
U. S. CENSUS BUREAU	2	
U. S. COAST & GEODETIC SURVEY	8	
U. S. GEOLOGICAL SURVEY	8	
U. S. INTERSTATE COMMERCE COMMISSION	1	
U. S. LIBRARY OF CONGRESS	4	
U. S. NAVY DEPARTMENT	2	
U. S. STEAM ENGINEERING BUREAU	1	
U. S. WAR DEPARTMENT	1	
UNIVERSITY OF ILLINOIS—ENGINEERING EXPERIMENTAL STATION (12 NOS. I VOL.)	12	
UNIVERSITY OF OKLAHOMA	2	
UTAH UNIVERSITY OF ENGINEERS	1	
VAIL, T. N	1	
VAN NOSTRAND D. & COMPANY	8	
VILLARS, GAUTHIER	1	
WEAVER, W. D	2	
WENTWORTH, MR	1	
WESTERN ELECTRIC COMPANY	482	
WESTERN UNION TELEGRAPH COMPANY	1	
WESTINGHOUSE ELECTRIC & MANUFACTURING COMPANY	2	
WILEY, JOHN & SONS	1	
WIRELESS INSTITUTE OF NEW YORK	1	
WISCONSIN RAILROAD COMMISSION	1	
WORCESTER POLYTECHNIC INSTITUTE	1	
WYNKOOP, H. S	1	
DONORS UNKNOWN	30	
		979

Other Accessions:

Purchases	287	
Exchanges	54	341
Total Accessions		1320

In the report of one year ago there was outlined a new arrangement under which the library staff had been working. This same arrangement has continued this year with the same staff of employees.

The following tabulation gives the state of the five funds from, which the Library committee is entitled to draw.

Donations (General Library Fund)

Dr.		Cr.	
Balance May 1, 1909	$251.51		
Interest May 1, 1910	6.53	Unexpended	$258.04
	$258.04		$258.04

Mailloux Endowment Fund ($1,000)

(Proceeds for the maintenance of certain sets of periodical publications.

Balance May 1, 1910	$30.35		
Interest May 1, 1910	$30.00	Unexpended	$60.35
	$60.35		$60.35

International Electrical Congress of St. Louis, 1904 Fund

Invested in New York City 4½% Bonds			$2268
Additions to the fund			25
Total fund			$2293.80
Balance on hand May 1, 1909	$124.72	Expended	$85.60
Interest to May 1, 1910	90.00	Unexpended	129.12
	214.72		214.72

Weaver Fund.

Balance on hand May 1, 1909	$65.44	Unexpended	$65.44
	$65.44		$65.44

Institute Appropriation Account.

Dr.		Cr.	
Appropriation for the year ending October 1, 1910	$3,500.00	Librarian and assistants	$1,569.69
		Cataloguing	255.02
		Desk attendant	138.67
		Insurance	80.33
		Binding	377.25
		Books	301.50
		Subscriptions	258.75
		Furniture and Fixtures	167.72
		Miscellaneous	116.80
			$3,265.73
		Unexpended	234.27
	$3,500.00		$3,500.00

The general statistics of the Library and its valuation are shown in the following tabulation:

STATISTICS OF LIBRARY, MAY 1, 1910

Source	Volumes	Pam-phlets	Valuations
Report of May 1, 1909	13,515	565	$24,566.23
Purchases	287		522.94
Gifts and exchanges	1063		769.95
Old material accessioned		714	100.00
	14865	1279	$25,959.12

In the following table are given the figures for the total valuation of the library property:

Books	$25,959.12
Stacks	1,761.05
Furniture, Catalogues, cases, etc	376.00
	$28,096.17

LIBRARY ATTENDANCE

	Day	Night	Total
May 1909	462	221	683
June "	484	198	682
July "	472	Closed	472
August "	472	Closed	472
September "	434	220	654
October "	471	238	709
November "	479	223	702
December "	545	301	846
January 1910	460	286	746
February "	416	232	648
March "	439	256	695
April "	488	272	760
Total May 1909–April 1910	5622	2447	8069

NEW INDEXING

The very valuable set of telephone litigation records presented to the library a few years ago, comprising about 100 volumes have been thoroughly catalogued during the year. The total number of card entries required for this set was about 1300 and these are now incorporated in the general card catalogue of the library.

The general catalogue has also been increased by the addition of cards bearing all of the entries in the two-volume bibliography of the Wheeler collection published last year.

The splendid gift of the Western Electric Company deserves special mention. This consists of 482 volumes of United States Patent Office Certified Specifications, including a copy of every specification from May 30, 1871 to March 1896 and of every electrical specification from July 1887 to December 1907. The set makes a splendid foundation for a patent library. During the year the volumes of certified specifications from April 1896 to December 1906 were purchased, making the set now in the library complete from the beginning of the certified series to the end of 1906, and it is expected this will soon be brought up to date.

Another gift worthy of special mention is the Diary of Samuel F. B. Morse presented by Mr. Thomas A. Edison. This diary is 13 inches in length by 8 inches in width, a formal book of white ruled paper bound in stiff boards. The book contains some 45 pages of copies of official correspondence with the United States Treasury by Morse as Superintendent of Electromagnetic Telegraphs, followed by about 8 pages of personal notes. The dates range through 1843 and 1844 while some of the later entries are made in 1848. A full and sympathetic description by Mr. T. C. Martin of this interesting book with fac similes of some of its entries is printed in the Metropolitan Magazine for April 1910, under the appropriate title " From One Genius to Another: a forgotten diary of S. B. Morse and how it was found by Thomas A. Edison."

Mr. Edward D. Adams has continued his contributions to the library as in previous years by the donation of the PROCEEDINGS and TRANSACTIONS of the Royal Society of London, and new volumes of the International Catalogue of Scientific Literature. He has also as heretofore had these volumes bound at his expense.

The " C. O. Mailloux Fund " of $1000 has again been used to maintain the four important periodical sets which were originally presented to the library by Mr. Mailloux.

Law Committee.—Various questions have been submitted to this committee for consideration and report within the last year. The most important work of the committee, however, has been in connection with its report on the proposed formation of technical sections of the Institute, and its work in respect to the proposed amendments to the Constitution.

Conservation of Natural Resources Committee.—Owing to the series of investigations which have been in progress in Washington during the greater part of the year, into affairs connected with the conservation of natural resources, the committee deemed it inadvisable to take any active part in connection with conservation until the above mentioned investigations have been completed.

Edison Medal Committee.—On May 18, 1909, the committee awarded to Trygve Jensen, a graduate student of the University of Illinois, the student Diploma of Merit and a cash sum of $150, for his record of research, entitled, " Operation of a 100,000-volt Transformer."

The revised by-laws of the committee, made necessary by the new trust deed, executed on March 26, 1908, were approved by the Board of Directors on May 18, 1909, and are now operative.

The work of the committee during the past year was particularly signalized by the award of the Edison Medal for the first time since the trust creating the medal was established in 1904. The award, for the year 1909, was made on December 16 last to Dr. Elihu Thomson, " For Meritorious Achievement in Electrical Engineering and Arts, as Exemplified in his Contributions Thereto During the Past Thirty Years." The parchment certificate constituting the official notice of the award was presented to Dr. Thomson at the annual dinner of the Institute on February 24, 1910, and the gold medal will be ready for presentation at the annual meeting on May 17.

It is believed that the administrative affairs of the Medal Committee have now been brought into such efficient and working order as to insure hereafter an annual award of the medal.

John Fritz Medal Board of Award.—The John Fritz Medal for 1910 is to be presented to Alfred Noble, for notable achievements as a civil engineer. A special committee has arranged for the presentation, which will be made in the fall of this year. This will be the sixth award of the Medal since its first presentation to Lord Kelvin in 1905.

Board of Examiners.—The Board has held 10 meetings during the year It has considered and reported to the Board of Directors a total of 1,397 applications for Associate election, Student enrolment, and transfer to the grade of Member. A summary of these applications is as follows:

Recommended for election as Associates	814
Recommended for enrolment as Students	507
Recommended for transfer to the grade of Member	47
Not recommended for election as Associates	3
Not recommended for transfer to the grade of Member	26
Total number of applications considered	1,397

The Board has received much assistance during the year from its Local Representatives, of which there are now seven, located in various cities in the United States, Canada, and Mexico.

Membership Committee.—During the year this committee has been active in bringing the advantages of Institute membership to the attention of desirable non-members.

In response to the Committee's general letter of November 8, 1909 requesting the membership to submit names of desirable candidates for admission as Associates, over 1500 names were suggested. All of these were communicated with by letter, accompanied by printed matter regarding the work of the Institute.

The number of applications received from November 1, 1909, at which time the present committee became active to April 30, 1910, is 558 and the total number received during the entire year is 848.

The present total membership and the increase during the past year are indicated below:

	Hon. Mem.	Mem.	Assoc.	Total
Membership, April 30, 1909	1	607	5,792	6,400
Additions:				
New Associates			910	
Transferred		48		
Deductions:				
Died		6	25	
Resigned		2	108	
Dropped		6	482	
Transferred			48	
Membership April 30, 1910	1	641	6,039	6,681

Net increase during the year in membership....................281

The net increase in membership was affected by the recent change in the by-laws. Formerly, a member could be in arrears for three years' dues before being dropped from membership, but under the present by-laws any member who on May 1 is in arrears for one year's dues is dropped as delinquent. This resulted in an unusually large number being dropped on May 1, 1909.

Resignations.—The following Members and Associates have resigned during the year in good standing.

Members.—Robert Hammond, F. M. Pedersen.

Associates.—G. A. Archer, L. T. Arnold, E. R. Avery, J. W. Aylsworth, L. Beauchamp, A. C. Babson, W. A. Baehr, R. Balfour, A. Balsley, W. C.

Barnes, M. H. Bentley, H. Binney, C. O. Bourne, J. Broich, C. C. Brown, M. C. Canfield, Eugene Carpenter, S. D. Coffin, F. W. Conn, A. S. Cross, E. H. Cutler, E. W. Cutler, W. B. Dodds, W. A. Drysdale, H. S. Elliott, W. C. Farnell, C. H. Felker, W. S. Finlay, F. H. Foster, Thomas French, Jr., W. H. Glenn, E. W. Goffin, H. de C. Hamilton, W. L. Harraden, W. W. Harris, A. S. Hart, R. Hawxhurst, F. J. Heavens, G. Hellebuck; S. M. Henry, C. W. Hogan, M. B. Holt, E. H. Hoppenstadt, J. H. Hubbs, C. Huper, C. S. Jameson, A. S. Kellogg, A. D. Kenyon, W. A. Kohn, E. Landon, E. C. Laudenberger, M. LeBlanc, A. J. Lowndes, D. Lowson, G. W. MacDonald, H. R. Markel, H. B. Marsh, Hobart Mason, E. M. McCleary, J. H. McConnell, J. L. McKay, W. A. McTaggart, H. S. Meyer, H. M. Migenault, W. H. Miller, N. N. Moneypenny, H. B. Morrell, L. H. Mueller, J. E. Murphy, G. B. Nichols, J. P. O'Donohue, W. N. Parsons, W. W. Patrick, W. J. Peaker, J. Peterson, F. L. Pircher, C. H. Porter, R. H. Read, I. W. Reynolds, C. L. Riley, C. E. Robertson, E. E. Rojahn, C. R. Scott, L. M. Schmidt, H. H. Seaman, C. E. Sedgwick, Sebastian Senstius, G. A. Sherman, S. Aylmer-Small, O. C. Snider, W. M. Stine, H. F. Strickland, A. E. Swan, A. S. Terry, G. C. Thomas, W. H. Tolman, G. A. Tower, L. Van Cott, J. Vandergande, J. H. Warder, F. Wenner, Jefferson Wetzler, R. Wilkander, S. E. Woodbury, L. M. Wright, A Wunderlich, R. E. Wyllie, L. G. Yochum.

Total resignations, 110.

Deaths.—The following deaths have occurred during the year:

Members.—C. B. Dudley, A. A. Knudson, J. J. Mahoney, J. T. Marshall, Townsend Wolcott.

Associates.—E. T. Alburger, Jr., F. C. Almond, J. W. Bridge, E. A. Briscoe, C. L. Buckingham, W. D. Buckman, H. J. Buddy, A. H. Demrich, T. Hirokawa, S. J. Houston, J. R. Jacobson, G. A. Joffe, A. P. Kennedy, D. Kos, I. Loveridge, W. W. Lyon, Jr., Robert Mitchell, A. W. K. Pierce, C. J. Toerring, J. C. Reilly, Ralph Scott, F. N. Simpson, G. W. Thompson, F. G. Tracy, H. E. Wagganan, C. I. Zimmerman.

Total deaths, 31.

Delinquent.—Dropped as delinquent during the year, 482.

Building Fund.—The amount collected from subscribers during the year was $2,552.15. The interest on the bank balances amounted to $585.25. These items make a total to the credit of the Building Fund during the year, of $3,137.40. A payment of $27,000. on account of the principal of the mortgage, was made during the year.

LAND, BUILDING AND ENDOWMENT FUND.

RECEIPTS.		DISBURSEMENTS.	
Before appointment of Committee	$ 6,100.00	Paid United Engineering Society, acct. of contract	$ 8,000.00
Collected by Committee	145,881.05	Paid United Engineering Society, acct. of mortgage	126,000.00
Interest on balances	5,967.01	Paid United Engineering Society, acct. of interest	19,529.45
Reimbursement by Institute	9,221.95	Expenses of Committee	10,440.73
		Balance in bank, May 1, 1910	3,199.83
Total	$167,170.01	Total	$167,170.01

RECEIPTS AND DISBURSEMENTS PER YEAR PER MEMBER.

During each fiscal year for the past seven years.

Year	1904	1905	1906	1907	1908	1909	1910
Membership, April 30th, each year.	3027	3460	3870	4521	5674	6400	6681
Receipts per Member.	$13.66	$12.32	$12.77	$12.21	$13.01	$13.21	$13.35
Disbursements per Member:	$12.02	$10.72	$10.48	$11.62	$11.73	$10.49	$12.03
Credit Balance per Member	$0.64	$1.60	$2.29	.59	$1.28	2.72	1.32

Finance Committee.—The following correspondence and financial statements form a complete summary of the work of this Committee.

May 17, 1910.

Mr. Lewis B. Stillwell,
President American Institute of Electrical Engineers,
No. 33 West 39th Street, New York City, N. Y.

Dear Sir: In accordance with past practice, your Finance Committee respectfully submits the following annual report:

During the past year the Committee has held monthly meetings, has passed upon the expenditures of the Institute for various purposes, and otherwise has performed the duties prescribed for it in the Constitution and By-Laws. Messrs. Peirce, Struss & Company, the chartered accountants, have audited the Institute books, and attached hereto is their certificate of the Institute's finances.

In company with your Treasurer and a member of the firm of chartered accountants, the Committee has examined the securities held by the Institute, and find them to be as stated in the accountants' report.

It is of interest to call attention to an additional payment of $27,000 towards the liquidation of the Institute indebtedness on the land on which the United Engineering Society's Building stands. By the payment of this sum, we have anticipated our obligations up to 1919, thereby proportionately reducing the annual interest payment.

In closing this report it seems proper to call attention to the fact, that the income for the Institute, estimated for the year in advance, has been exceeded by the actual income, so that even with an increased budget of expenditures by reason of the Institute's extended activities, it has been possible to close the fiscal year with a comfortable surplus.

Respectfully submitted,
Calvert Townley,
Chairman Finance Committee.

New York, May 10, 1910.

Mr. Calvert Townley,
Chairman Committee on Finance.

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, 1910.

The results of this examination are presented in four exhibits, attached hereto, as follows:

Exhibit A. Balance Sheet, April 30, 1910.

Exhibit B. Receipts and Disbursements for general purposes for year ended April 30, 1910.

Exhibit C. Receipts and Donations for designated purposes also expenditures for year ended April 30, 1910.

Exhibit D. Condensed Cash Statement.

We beg to present attached hereto our certificate to the aforesaid exhibits.

Yours very truly,
(Signed) Peirce, Struss & Co.
Certified Public Accountants.

New York, May 10, 1910.

Mr. Calvert Townley,
Chairman, Committee on Finance.

Dear Sir: Having audited the books and accounts of the American Institute of Electrical Engineers for the year ended April 30, 1910, we hereby certify that the accompanying Balance Sheet is a true exhibit of its financial condition as of April 30, 1910, and that the accompanying statements of Cash Receipts and Disbursements are correct.

(Signed) Peirce, Struss & Co.
Certified Public Accountants.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

BALANCE SHEET, APRIL 30, 1910.

EXHIBIT A.

ASSETS.		
CASH:		
Land, Building and Endowment Fund	$3,199.83	
General Library fund	258.04	
Compounded Membership fund......	5,018.24	
Mailloux fund, principal............	1,000.00	$9,476.11
General Cash in bank	17,802.98	
Mailloux fund, interest..............	60.35	
Weaver donation....	65.44	
International Elec. Congress of St. Louis Library fund, interest..........	154.92	
Total cash deposit..	18,083.69	
Secretary's petty cash on hand.....	750.00	18,833.69
Land, Building and Endowment fund, accrued interest..	70.37	
General Library fund accrued interest..	2.69	
Compounded Membership fund accrued interest.....	58.31	
International Electrical Congress of St. Louis, 1904, Library Fund accrued interest....	45.00	176.37
International Electrical Congress of St. Louis 1904, Library Fund, Bonds...........	2,268.00	2,268.00
New York City 4½% Gold Bonds......	30,000.00	
Premium on bonds.	1,952.50	31,952.50
Westinghouse Electric & Mfg. Co's. stock............		50.00
Equity in Engineering Societies Building (25 to 33 West 39th St.).........	353,346.61	
One-third cost of land (25 to 33 West 39th St.)....	180,000.00	533,346.61
Library Volumes and Fixtures.........	27,309.14	
Transactions.......	7,446.25	
Office Furniture and Fixtures.........	6,692.20	
Works of Art, Paintings, etc.........	2,543.60	
Badges............	517.05	44,508.24
ACCOUNTS RECEIVABLE:		
Members for current dues.............	660.00	
Members for past dues, suspense account............	7,794.00	
Members for entrance fees.............	325.00	
Miscellaneous.......	494.18	
For Advertising....	2,356.25	
Accrued interest on Bonds...........	675.00	
Accrued interest on bank balance.....	219.25	12,523.68
Total Assets......		$653,135.20

LIABILITIES AND SURPLUS.		
FUNDS:		
Land, Building and Endowment Fund	$3,270.20	
General Library Fund............	260.73	
Compounded Membership Fund.....	5,076.55	
Mailloux Fund......	1,060.35	
International Electrical Congress of St. Louis 1904, Library Fund:		
Bonds...........	2,268.00	
Cash, on deposit.	154.92	
Accrued Interest.	45.00	$12,135.75
Reserve, for Furniture and Fixtures.		1,568.78
Accounts payable, subject to approval by the Finance Committee.......		4,558.34
United Engineering Society (for cost of land)..........		54,000.00
Total Liabilities..		72,262.87
SURPLUS:		
In Cash............	17,802.98	
New York City bonds	31,952.50	
In property and accounts receivable.	531,116.85	580.872.33
Total Liabilities and surplus.		$653,135.20

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

RECEIPTS AND DISBURSEMENTS FOR GENERAL PURPOSES FOR YEAR ENDED APRIL 30, 1910.

EXHIBIT B.

RECEIPTS.		
Entrance Fees	$4,265.00	
Current Dues	59,943.37	
Past Dues	5,541.75	
Advance Dues	112.50	
Students Dues	3,984.00	
Transfer Fees	500.00	
Badges	1,875.00	
		76,221.62
Sales, Transactions, etc.	1,477.43	
Subscriptions, Proceedings	1,669.57	
Advertising	7,727.00	
Binding	136.10	
Exchange	26.74	
INTEREST:		
Bonds	1,350.00	
Bank Balance	591.42	
		12,978.26
		$89,199.88

DISBURSEMENTS.		
Stationery and Printing	$2,924.98	
Postage	2,466.81	
General Expenses	2,350.67	
Meeting Expenses	3,318.54	
Section Meetings	7,257.99	
Badges purchased	1,694.74	
Salaries	9,915.50	
Interest on Mtge	3,240.00	
Bibliography	741.18	
Office Furniture	497.65	
Advertising Expense	3,267.38	
Year Book and Catalogue	2,616.16	
Express	466.47	
Miscellaneous	20.70	
		$40,778.77
PROCEEDINGS:		
Printing, paper, binding, engraving	16,096.86	
Salaries	3,400.00	
		19,496.86
TRANSACTIONS:		
Vol. 27		8,623.46
Vol. 28		2,595.87
LIBRARY (including salaries)		3,265 73
UNITED ENGINEERING SOCIETY.. Assessments for office space		5,333.35
Total		80,094.04
Excess Receipts over Disbursements		9,105.84
		$89,199.88

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