TRANSACTIONS

OF THE

AMERICAN INSTITUTE

OF

ELECTRICAL ENGINEERS

JUNE TO DECEMBER, 1916

VOL. XXXV, PART II

PUBLISHED BY THE
AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS
33 WEST THIRTY-NINTH STREET
NEW YORK, N. Y., U. S. A.
1916

Press of McIlroy & Emmet, 22 Thames Street, New York

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Presented at the 33d Annual Convention of the American Institute of Electrical Engineers, Cleveland, O., June 29, 1916.

THE EFFECT OF HIGH CONTINUOUS VOLTAGES ON AIR, OIL, AND SOLID INSULATIONS

BY F. W. PEEK, JR.

ABSTRACT OF PAPER

The dielectric strength of air, oil and solid insulations was determined for d-c. voltages up to 150 kv.

The d-c. visual corona voltage is practically equal to the maximum a-c. corona voltage for wires varying in radius from 0.013 cm. to the largest sizes. The variation of d-c. and a-c. corona voltages with air density is the same over a large range. The laws already given for a-c. voltages apply equally well for d-c. voltages in terms of maximum values.

The spark-over of gaps is the same on alternating current and direct current for equal maximum voltages when the gap is such that spark-over precedes corona. Thus, for the sphere gap the same laws apply for a-c. or d-c. voltages. This is true at various air densities.

When corona precedes spark-over there is generally a difference in a-c. and d-c. spark-over voltages. For a non-symmetrical gap, spark-over at normal air density takes place at the lowest voltage when the electrode surrounded by the denser field is (+). At low air densities spark-over takes place when the electrode surrounded by the denser field is (−).

Insulators spark-over at the lowest voltage when the cap, or electrode surrounded by the denser field, is (+). The (+) spark-over voltage generally corresponds closely to the maximum a-c. spark-over voltage.

The d-c. spark-over voltages in oil generally correspond closely to the maximum a-c. spark-over voltages. In wet oil the d-c. spark-over voltage is lower than the a-c.

The d-c. breakdown voltages of solid insulations, in good condition, are generally higher than the maximum a-c. voltages. This is especially so when the time of application is long and the insulation is thick. The d-c. breakdown voltage on insulations tested apparently increases directly with the thickness, while the a-c. breakdown voltage increases at a lesser rate. Laws are given.

When the insulation is moist, the d-c. and maximum a-c. breakdown voltages are generally approximately the same.

It appears that high-voltage direct current would be useful in certain high-voltage cable testing, etc.

HIGH CONTINUOUS or "direct-current" voltages were obtained from the 60 cycles alternating by means of a kenotron rectifier in combination with condensers and inductance coils.[1] A sketch of the connections used is given in Fig. 1.

1. These tests were made with kenotrons loaned by Dr. Dushman of the Research Laboratory of the General Electric Company.

The condensers are charged up to the maximum of the alternating voltage wave. They remain at this voltage if there is no leakage, and no power is being taken at A. If current flows at A the condensers become partly discharged between the maximums of two waves and there is a double frequency ripple on top of the " d-c. " voltage across A. With a given current taken at A the amplitude of this ripple decreases with increasing condenser capacity and increasing inductance. With a given capacity and inductance the ripple decreases with decreasing current at A. With a given condenser and inductance the amplitude of the ripple decreases with increasing supply frequency.[2] The variation is less for connection 1*a* than 1*b*. Fig. 2 is an oscillogram of a wave taken with connection as shown in Fig. 1a and 0.05 amperes flowing—60-cycle supply. (This

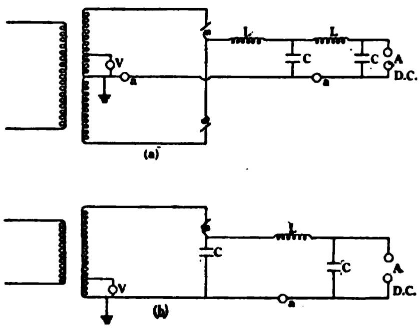


FIG. 1—CONDENSER CAPACITY = 0.064 MICROFARAD

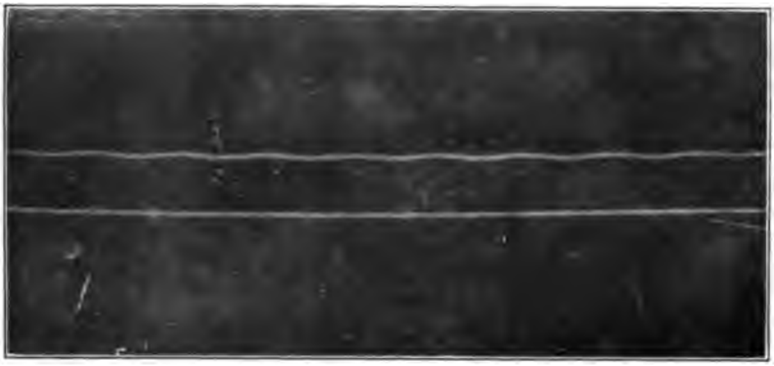
is many times the current flowing in the following tests.) Since in the following tests, the current flowing up to breakdown was practically negligible, there was no appreciable ripple on the voltage wave. Voltage was first measured with a static voltmeter, and by maximum of the wave on the voltmeter coil. When no power was taken the static voltmeter checked with the maximum of the alternating wave, and later, with sphere-gap measurements.

AIR

Sphere Gaps. Sphere-gap curves were taken on 6.25- and 12.5-cm. spheres. The continuous, or d-c., voltage required to spark over a given gap was found to be $\sqrt{2}$ times the required

2. See discussion by Dr. Hull, *G. E. Review*, March 1916.

The author wishes to acknowledge indebtedness to Mr. B. L. Stemmons for his skillful assistance in making experiments and calculations.



[PEEK]

FIG. 2—WAVE OF RECTIFIED VOLTAGE (25 KV., 0.05 AMPERE, 7-28-15).

Note: There was no appreciable ripple in voltages used in the tests. When the above oscillogram was taken a comparatively large current was allowed to flow in order to exaggerate the ripple.

1 3 4 5

1 3 4 [PEEK]

FIG. 9

effective sine wave alternating or a-c. voltage, that is, the d-c. spark-over voltage and the a-c. maximum voltage are equal. See Fig. 3. This is true for various air densities as shown in Fig. 4. The d-c. spark-over voltage curve of a sphere may, therefore, be calculated from the formula already given for a-c. voltages.[3]

$$e = g \frac{x}{f}$$

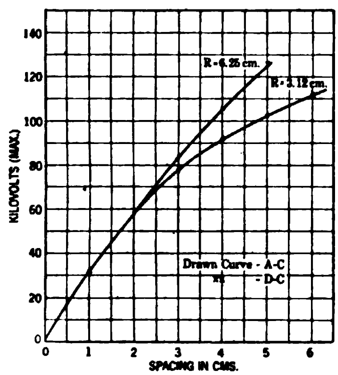


FIG. 3—A-C. AND D-C. SPARK-OVER VOLTAGES FOR SPHERES

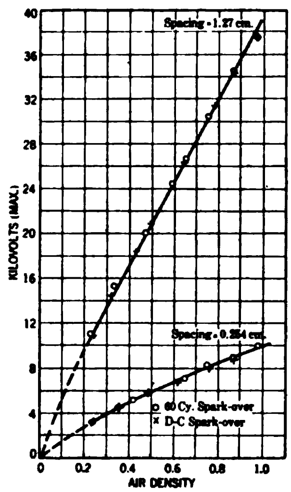


FIG. 4—SPARK-OVER VOLTAGES OF 2.54 CM. SPHERES AT VARIOUS AIR DENSITIES

Where

$$g = 27.2\delta\left(1 + \frac{0.54}{\sqrt{\delta R}}\right)$$

x = spacing in cm.

$$\delta = \frac{3.92\, b}{273 + t}$$ b = barometric pressure in cm. t = temperature, deg. cent.

R = sphere radius in cm.

$$f = \phi\left(\frac{x}{R}\right)$$ (See reference below.)

3. F. W. Peek, Jr., *The Sphere Gap as a Means of Measuring High Voltages.* TRANS. A. I. E. E., Vol. XXXIII, 1914, p. 923.

This voltage may also be found by multiplying the a.c. effective voltages given by the standard curve by $\sqrt{2}$.

Needle Gaps. The d-c. needle gap spark-over voltage corresponds approximately to the maximum a-c. spark-over voltage

TABLE I.
A-C. AND D-C. SPARK-OVER VOLTAGES OF 2/0 NEEDLES IN AIR.

Spacing, cm.	Kilovolts 60 cycle (max.)	Kilovolts d-c.
5.1	51.0	52.0
7.6	62.5	63.0
10 2	76.5	73 5
12.7	88.3	82.5
15.3	98.3	90.5

over a considerable range. At the higher values the continuous spark-over voltage seems to be less than the maximum alternating. The results are plotted in Fig. 5.

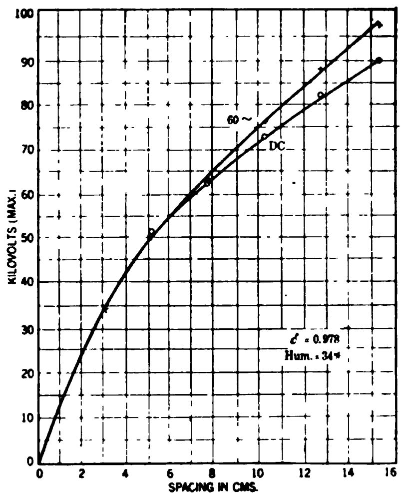


FIG. 5—SPARK-OVER OF 2/0 NEEDLES IN AIR

Corona. Visual corona and spark-over tests were made on concentric cylinders.[4] Typical data are given in Table II,

4. See D-c. Corona Investigations of Watson, *Electrician*, London, 1909-1910, *Journal Inst. of Elec. Eng's*, June 1910. Also, Farwell, TRANS. A. I. E. E., Vol. XXXIII, 1914, p. 1631.

and plotted in Fig. 6. In this test the outer cylinder was 3.81 cm. in radius. The polished inner cylinders or wires and tubes varied from 0.0038 cm. to 1.11 cm. radii.

TABLE II.

D-C. AND A-C. VISUAL CORONA AND SPARK-OVER VOLTAGES

(CONCENTRIC CYLINDERS—NORMAL AIR DENSITY $\delta = 1$)

R radius outer cylinder cm.	r wire radius cm.	R/r	Corona					Spark-Over		
			60 cycle calc. kv.(max)	D-c. + kv.	D-c. − kv.	A-c. $g_{v\,max}$ kv./cm	D-c. g_v kv./cm	60 cy. kv. max.	D-c. + kv.	D-c. − kv.
3.81	0.0038	1000.0	4.9	6.4	6.4	186.0	244.0	..	Vibrates be-	
3.81	0.0129	295.0	8.4	8.4	8.3	113.0	113.0	70.0	fore sparkover	
3.81	0.0573	66.5	17.2	17.2	17.2	71.5	71.5	40.0	52.8	61.0
3.81	0.130	29.3	25.2	25.2	25.2	56.9	56.9	25.5	48.8	54.5
3.81	0.239	16.0	33.5	33.8	33.8	51.0	51.3	33.9	47.5	52.8
3.81	0.635	6.0	48.9	49.0	49.0	42.9	43.0	48.1	49.5	53.2
3.81	1.110	3.4	54.7	54.8	54.8	40.5	40.6	54.5	54.5	55.5

These data show that the maximum a-c. and the d-c. corona voltages are practically equal for wires over a large range of sizes. When the wire is positive the visual corona point is quite sharp and definite; when the wire is negative the slightest irregularity causes brush discharges at fairly low voltages. The percent difference between the positive and

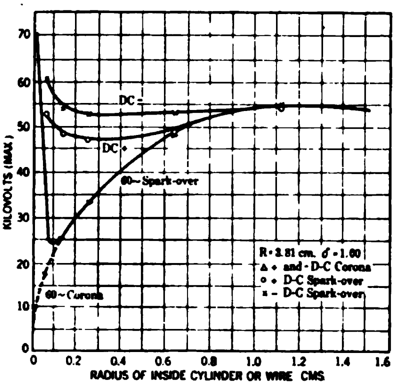


FIG. 6—A-C. AND D-C. CORONA AND SPARK-OVER FOR VARIOUS SIZES OF WIRE (CONCENTRIC CYLINDERS AT NORMAL AIR DENSITY).

negative glow point cannot be great. Since this point is indefinite on the negative, the recorded value will depend to some extent on whether the observer considers the first brushes or the complete glow as the visual point. Even on apparently highly polished wires, when negative, the voltage for complete glow is generally several per cent higher than for local brushes.

The negative glow voltage will thus generally be read higher than the positive glow voltage. The spark-over voltages are equal when $\frac{R}{r} < \epsilon$ or where corona does not precede spark-

TABLE III.
D-C. AND A-C. VISUAL CORONA VOLTAGES
(CONCENTRIC CYLINDERS AT VARIOUS AIR DENSITIES)

R	r	R/r	δ	A-c. calc. 60 cy. kv(max.)	D-c. + kv.	D-c. − kv.	A-c. calc. g_v kv/cm. (max.)	D-c. g_v + kv/cm.	D-c. g_v − kv/cm.
2.90	0.0573	50.5	0.995	15.8	15.8	15.8	....	70.5	....
2.90	0.0573	50.5	0.838	14.2	14.2	14.2	....	63.2	....
2.90	0.0573	50.5	0.770	13.2	13.5	13.2	58.6	60.0	58.6
2.90	0.0573	50.5	0.720	12.6	12.7	12.4	56.0	56.5	55.2
2.90	0.0573	50.5	0.522	10.3	10.3	10.0	45.9	45.9	44.5
2.90	0.0573	50.5	0.363	7.9	8.1	7.8	35.1	36.0	34.7
2.90	0.0573	50.5	0.214	5.7	5.8	5.6	25.3	25.8	24.9

over. Where corona precedes sparkover the d-c. voltage is higher than the a-c. The d-c. spark-over voltage is higher when the wire or conductor of the greatest field intensity is (—). This is shown in Fig. 6.

TABLE IV.
D-C. AND A-C. VISUAL CORONA VOLTAGES.
(CONCENTRIC CYLINDERS AT VARIOUS AIR DENSITIES.)

R radius outer cylinder cm.	r radius wire cm.	R/r	δ	A-c. calc. 60 cy. kv(max.)	D-c + kv.	D-c. − kv.	A-c. calc. g_v (max.)	D-c. g_v + kv/cm.	D-c. g_v − kv/cm.
2.90	0.239	12.1	1.00	30.0	30.0	30.0	50.5	50.5	50.5
2.90	0.239	12.1	0.915	28.0	27.8	27.8	47.0	46.8	46.8
2.90	0.239	12.1	0.857	26.3	..	26.2	44.2	....	44.0
2.90	0.239	12.1	0.824	25.7	25.5	..	43.3	42.9	..
2.90	0.239	12.1	0.797	25.1	..	25.1	42.2	....	42.2
2.90	0.239	12.1	0.720	23.1	23.1	..	38.8	38.8	....
2.90	0.239	12.1	0.680	22.1	..	22.1	37.1	37.1	....
2.90	0.239	12.1	0.550	19.1	19.2	19.3	32.1	32.2	32.4
2.90	0.239	12.1	0.435	15.7	15.7	16.0	26.4	26.4	26.9
2.90	0.239	12.1	0.357	13.5	13.5	..	22.7	22.7	....
2.90	0.239	12.1	0.260	10.7 ·	10.9	11.6	18.0	18.4	19.5
2.90	0.239	12.1	0.082	4.8	4.4	4.6	8.07	7.4	7.75

Effect of Air Density on Corona and Spark-over of Wires. The visual corona and spark-over voltages were measured for concentric cylinders at various air densities. An outer cylinder of glass coated with the foil was used for these tests. The air was exhausted and the corona and spark-over voltages measured at different air pressures. The apparatus was the same as that used in a-c. tests and already described[5]. The results

5. F. W. Peek, Jr., *Law of Corona*, A. I. E. E. TRANS., 1912, 1913.

are given in Tables III, IV and V, and plotted in Figs. 7 and 8.

The data in Tables III and IV show that the maximum a-c. and the d-c. visual corona voltages correspond down to $\delta = 0.3$. The difference is not great even at $\delta = 0.08$. The difference at the lower values of δ may be due to the difficulty in determining the exact starting point in these cases.

TABLE V.
D-C. AND A-C. SPARK-OVER VOLTAGES.
(CONCENTRIC CYLINDERS AT VARIOUS AIR DENSITIES.)

R radius outer cylinder cm.	r radius wire cm.	R/r	δ	60 cy. kv. max.	D-c. + kv.	D-c. − kv.
2.90	0.239	12.1	0.075	4.2	4.8	4.6
2.90	0.239	12.1	0.250	10.6	11.1	10.8
2.90	0.239	12.1	0.354	12.5	14.2	14.4
2.90	0.236	12.1	0.477	16.8	17.2	18.3
2.90	0.239	12.1	0.660	21.6	22.0	23.5
2.90	0.236	12.1	0.760	24.2	24.5	26.3
2.90	0.239	12.1	0.890	27.2	27.2	30.0
2.90	0.239	12.1	1.000	30.1	30.5	3.7

See corona data on this cylinder—Table IV.

Spark-over data are given in Table V for a 0.239-cm. wire. At the higher values of δ the positive spark-over voltage is lower than the negative and closely follows the maximum a-c. The positive seems to be slightly higher than the negative for very low values of δ.

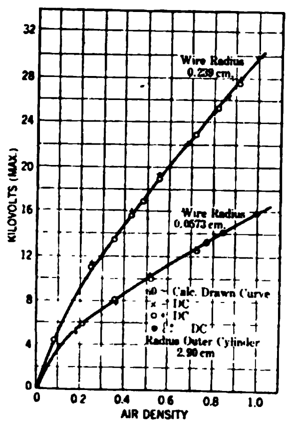


FIG. 7—VARIATION OF A-C. AND D-C. VISUAL CORONA VOLTAGES WITH AIR DENSITY

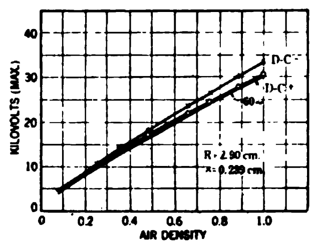


FIG. 8—D-C. SPARK-OVER OF CONCENTRIC CYLINDERS AT VARIOUS AIR DENSITIES

These tests show that the formula already given for a-c. corona may also be used for d-c. corona over a wide range of wire diameter, air density, etc.[6] The d-c. corona voltage is

6. F. W. Peek, Jr., *Law of Corona and Dielectric Strength of Air.* A. I. E. E. TRANS., 1911, 1912.

practically equal to the maximum a-c. corona voltage over a large range of conductor diameters.

The d-c. visual corona voltage in kilovolts is

$$e_v = g_v r \log_e \frac{R}{r} \quad \text{wire in a cylinder}$$

$$e_v = 2 g_v r \log_e \frac{R}{r} \quad \text{parallel wires}$$

Where

$$g_v = g_0 \delta \left(1 + \frac{0.3}{\sqrt{\delta r}}\right) \text{ kv. per cm.}$$

where $g_0 = 31$ (concentric cylinders)

$g_0 = 30$ (parallel wires)

$$\delta = \frac{3.92\, b}{273 + t} \qquad b = \text{barometric pressure cm.} \quad t = \text{degrees centigrade.}$$

Surface Spark-over of Insulators. Spark-over tests were made on several standard insulators shown in Fig. 9. The results are given in Table VI. The spark-over voltage is highest when the cap or electrode around which the field intensity is highest is (−). This checks with the impulse tests.[7] When the cap is (+) the d-c. spark-over voltage generally very nearly coincides with the maximum a-c. spark-over.

TABLE VI.
SURFACE SPARK-OVER OF SUSPENSION INSULATORS.

Insulator number	60 cycle kv. (max.)	D-c. kv.	
		cap +	cap −
1	116.0	117.5	127.5
2	99.0	99.0	106.0
3	126.0	132.0	139.0
4	111.5	128.0	135.0
5	119.0	128.0	135.0

Oil

The "corona" and spark-over characteristics of oil are very similar to those of air. Practically the same laws are followed

7. F. W. Peek, Jr., *The Effect of Transient Voltages on Dielectrics.* A. I. E. E. Trans., Vol. XXXIV, 1915.

for a-c. voltages in both oil and air.[8] This apparently also holds for d-c.

Needle gap spark-over voltages for oil are given in Table VII

TABLE VII.
D-C. AND A.C SPARK-OVER TESTS ON 2/0 NEEDLES IN NO. 8 TRANSIL OIL AT 25 DEG. CENT.

Needle gap cm.	60 cycle kv. (max.)	D-c. kv. (max.)
0.317	21.2	21.7
0.635	34.7	33.5
1.27	50.5	50.2
1.91	65.0	66.0
2.54	86.5	82.5

and plotted in Fig. 10. The d-c. voltages correspond to the a-c maximum.

The effect of moisture on the strength of oil for a-c. and d-c voltages is given in Table VIII and Fig. 11.

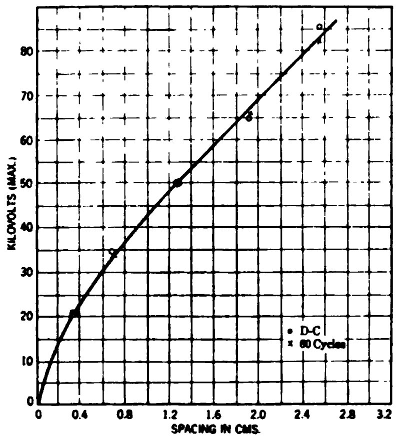


FIG. 10—A-C. AND D-C. SPARK-OVER VOLTAGES OF 2/0 NEEDLES IN NO. 8 TRANSIL OIL AT 25 DEG. CENT.

When the oil is wet the d-c. breakdown voltage is lower than the a-c. breakdown voltage. This is probably due to lining up of water particles under direct current.

8. F. W. Peek, Jr., *Law of Corona and Spark-over in Oil.* *G. E. Review*, August, 1915, also *Dielectric Phenomena in High-Voltage Engineering.* Chap. IV.

Solid Insulations

In air and in oil there is no appreciable loss until local breakdown occurs in the form of corona or brushes. In solid insulations loss starts as soon as voltage is applied and generally in-

TABLE VIII.
EFFECT OF MOISTURE ON THE DISRUPTION OF NO. 8 TRANSIL OIL AT 25 DEG. CENT.
(Between 1.27 cm. Diameter Disks at 0.5-cm. Spacing.)

Parts water added in 10,000	60 cycle kv. (max.)	D-c. kv.
0	62.3	61.5
0.5	33.5	34.7
1.0	33.4	34.3
2.0	31.7	30.2
5.0	27.3	24.7
10.0	25.4	23.0

creases as the square of the voltage. The heating which results increases the loss and weakens the insulation. Practically all solid insulations absorb moisture. The interstices in the non-homogeneous structure become filled with moisture and gases.

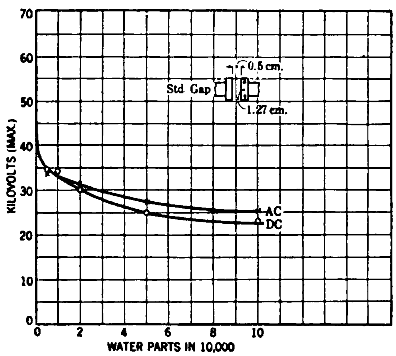


Fig. 11—Effect of Moisture on Disruptive Strength of No. 8 Transil Oil At 25 Deg. Cent.

This makes, in effect, not only a complicated arrangement of resistances, but also of resistances and capacities in series throughout the material. Where the conducting paths extend through from terminal to terminal, either alternating or direct current can flow. But where the conducting paths extend partly through the structure they are, in effect, resistances in series with capacities; only alternating current can flow through these paths. The effective resistances as measured by alternating current and by direct current are quite different except in those solid insulations in which the " conducting " paths are arranged from terminal to terminal. The voltage distribution, heating, etc., will generally not be the same for a-c. and d-c. voltages. In the homogeneous materials, air and oil, d-c. breakdown voltages correspond to the maximum 60-cycle a-c. breakdown voltages. In most solid insulations relatively higher d-c. values should be

TABLE IX.

VARIATION OF 60-CYCLE PUNCTURE VOLTAGE WITH TIME OF APPLICATION ON VARNISHED CAMBRIC.

TESTS BETWEEN 2.5-in. PLATES, 1½-IN. RADIUS EDGE, IN NO. 6 TRANSIL OIL.

Temperature deg. cent.	Sheets in.	Thickness mm.	kv. (max.)	Time sec.
25	1	0.30	24.8	2.3
		(12 mils)	21.3	12.0
			19.5	17.3
			17.7	41.5
			15.9	198.0
			14.2	900.0
100	1	0.30	14.5	2.0
			13.2	7.0
			12.6	11.0
			12.0	25.0
			10.8	620.0
			9.9	1400.0
25	2	0.60	29.8	213.0
			26.7	700.0
			25.6	1418.0
25	3	0.90	53.0	8.0
			45.2	51.5
			42.5	80.0
			41.7	138.0
			38.9	370.0
			37.1	905.0
25	4	1.20	69.3	4.0
			65.0	13.0
			64.3	15.0
			55.8	39.0
			53.0	80.0
			50.8	155.0
			47.3	580.0

expected, especially in insulations where the a-c. and d-c. "resistances" are decidedly different.

Varnished Cambric. Because of the effects of heating due to losses, voltage-time curves are necessary in order to compare the strengths of solid insulations. A-c. and d-c. voltage-time curves

TABLE X.

VARIATION OF D-C. PUNCTURE VOLTAGE WITH TIME OF APPLICATION ON VARNISHED CAMBRIC.

TESTS BETWEEN 2.5-IN PLATES, 1¼-IN. RADIUS EDGE, IN NO. 6 TRANSIL OIL.

Temperature deg. cent.	Sheet in.	Thickness mm.	kv. (max.)	Time sec.
25	1	0.30	28.8	8.3
			27.2	20.0
			25.5	54.0
			23.8	94.0
			22.1	363.0
			20.4	668.0
			18.8	5400.0
100	1	0.30	21.0	1.5
			20.3	2.0
			19.6	38.0
			18.6	72.0
			17.0	600.0
			15.9	470.0
			15.2	1920.0
25	2	0.60	52.5	26.0
			50.0	50.0
			47.0	230.0
25	3	0.90	80.3	68.0
			77.5	130.0
			77.2	350.0
			75.5	1400.0
25	4	1.20	127.2	7.0
			120.0	16.0
			115.2	45.0
			110.0	100.0
			107.5	185.0
			105.0	330.0
			104.6	730.0

were taken on varnished cambric. The insulation under test was placed in transil oil between 5-cm. diameter brass plates with rounded edges. A given voltage was applied and time noted until breakdown occurred. The break-down voltages for various thicknesses of varnished cambric in the approximately uniform field between parallel plates is given in Tables IX and X and plotted in Figs. 12 and 13.

Fig. 12 shows that the d-c. puncture voltage for a given thickness of cambric and for a given time of application is higher than the maximum a-c. puncture voltage. Fig. 13 shows that both the a-c. and d-c. puncture voltages decrease with increasing temperature. (The temperature referred to is that of the oil bath in which the insulation is immersed.)

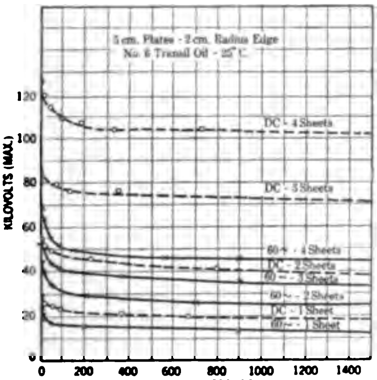


FIG. 12—VARIATION OF D-C. AND A-C. PUNCTURE VOLTAGES WITH TIME OF APPLICATION—VARNISHED CAMBRIC

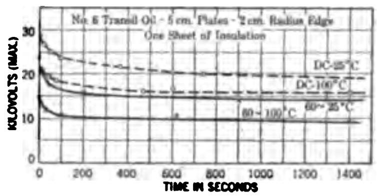


FIG. 13—EFFECT OF TEMPERATURE ON THE A-C. AND D-C. DISRUPTIVE STRENGTH OF VARNISHED CAMBRIC

The curves between puncture voltage and time are closely approximated by the equation[9]

$$e = e_0 \left(1 + \frac{a}{\sqrt[4]{T}}\right) \text{ kilovolts}$$

or the unit strength by

$$g = g_0 \left(1 + \frac{a}{\sqrt[4]{T}}\right) \text{ kv. per mm.}$$

Where

e = puncture voltage in time T, kilovolts (max.)
T = time in seconds.
e_0 = puncture voltage for $T = \infty$, kv. (max.)
g = breakdown gradient in time T, kv. per mm.
g_0 = breakdown gradient in $T = \infty$, kv. per mm.
a = constant depending upon the kind and thickness of the insulation and the frequency.

9. F. W. Peek, Jr., *Electrical Characteristics of Solid Insulation, G. E. Review*, November, 1915. Also Dielectric Phenomena in High-Voltage Engineering. Chap. VII.

This equation seems to hold well for a range of time between $T = 1$ and $T = \infty$. The breakdown voltage is plotted with $\frac{1}{\sqrt[4]{T}}$ in Fig. 14. The result is a straight line from which the above relation is obtained.

In Fig. 15 the a-c. and d-c. breakdown voltages of varnished

TABLE XI.

A-C. AND D-C. PUNCTURE VOLTAGES OF VARNISHED CAMBRIC FOR VARIOUS THICKNESSES AND TIME OF APPLICATION

Time of application, seconds		∞	100	50	10	2
Sheets	Thickness mm.	Kilovolts to puncture (max.)				
1	0.30 a-c.	11.0	16.5	17.5	20.5	25.5
	0.30 d-c.	18.0	23.5	24.5	27.5	32.5
2	0.60 a-c.	20.0	31.0	33.0	39.0	47.0
	0.60 d-c.	43.0	49.5	51.0	55.5	62.5
3	0.90 a-c.	30.0	42.0	45.0	52.0	62.0
	0.90 d-c.	70.0	79.0	81.0	86.0	95.0
4	1.20 a-c.	37.0	52.0	55.0	64.0	78.0
	1.20 d-c.	96.0	111.0	114.0	123.0	137.0
		Gradient kv. per mm. (max.)				
1	0.30 a-c.	36.6	55.0	58.5	68.5	85.0
	0.30 d-c.	60.0	75.0	82.0	92.0	108.0
2	0.60 a-c.	33.3	51.5	55.0	65.0	78.0
	0.60 d-c.	72.0	82.0	85.0	92.0	104.0
3	0.90 a-c.	33.3	46.5	50.0	57.9	69.0
	0.90 d-c.	77.5	87.5	90.0	95.5	105.0
4	1.20 a-c.	30.9	43.3	45.8	53.2	65.0
	1.20 d.c.	80.0	92.5	95.0	102.0	106.0

cambric for the time, $T = \infty$, are plotted with thickness. As $T = \infty$, this is the highest voltage that the insulation will withstand indefinitely without puncture. For this material, at thicknesses from 0.3 mm. to 1.2 mm., the puncture voltage increases directly with the thickness, that is, the d-c. unit breakdown strength or gradient is constant. The unit strength of solid insulations under a-c. voltages decreases with increasing thickness. For a-c. voltages[10]

$$g = g_0\left(1 + \frac{a}{\sqrt{t}}\right)$$

or

$$e = g_0\, t\left(1 + \frac{a}{\sqrt{t}}\right)$$

For d-c. voltages apparently

$$g = g_0$$

$$e = g_0 t$$

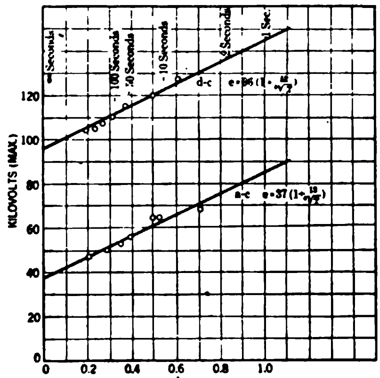


FIG. 14—VARIATION OF A-C. AND D-C. PUNCTURE VOLTAGES WITH TIME

4 sheets (1.20 mm.) Varnished cambric voltage plotted with $1/\sqrt[4]{T}$.

where

e = breakdown voltages of thickness t.
t = thickness in mm.
g = unit strength for thickness t, in kv. per mm.
g_0 = constant
a = constant depending upon the kind of insulation, time and frequency.

The curves in Fig. 16 correspond to those in Fig. 15 for T = 2 seconds.

It can be seen from the above relations that the ratio between the d-c. and a-c. puncture voltages for solid insulations cannot

10. F. W. Peek, Jr., *Electrical Characteristics of Solid Insulation, G. E. Review*, November 1915. Also Dielectric Phenomena in High-Voltage Engineering.

be constant but must increase with increasing thickness of insulation, especially where the time of application is long. This is shown graphically in the ratio curves in Figs. 15 and 16. Thus, in Fig. 16, where the time is two seconds, or relatively short, the d-c. puncture voltage very nearly corresponds to the a-c. maximum puncture voltage where the thickness is not great. In Fig. 15, where the time is a maximum, the d-c. puncture voltage is 2.5 times the a-c. maximum puncture voltage or 3.5 times the a-c. effective voltage for a thickness of 1.2 mm.

Some of the d-c. puncture values (Tables X and XI) for single sheets of cambric apparently have a lower unit strength than a

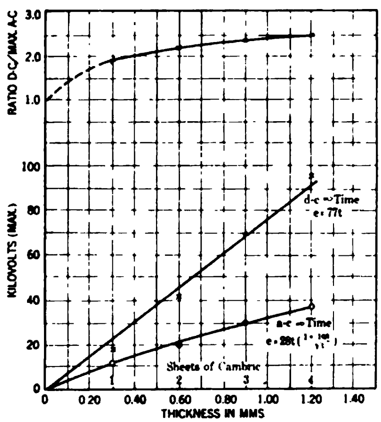


FIG. 15—VARIATION OF A-C. AND D-C. BREAKDOWN VOLTAGE WITH CONSTANT TIME

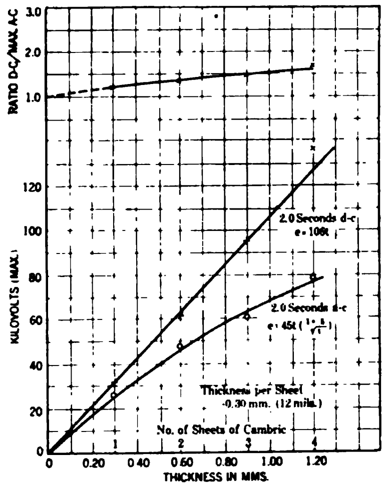


FIG. 16—VARIATION OF A-C. AND D-C. BREAKDOWN VOLTAGE WITH CONSTANT TIME

greater number of sheets. This is undoubtedly due to a greater probability of weak spots on a single sheet. Results of the same consistency cannot be expected or obtained on solid insulations as on gaseous and liquid insulations.

The thickness range of the insulation in the above tests was not great; it was limited by the available voltage (150 kv. direct current). It is *possible* that the d-c. unit strength will not remain approximately constant over a wide range.

Wet Insulations. Some 2.4-mm. (3/32-in.) treated pressboard was soaked in water and then partly dried out. A-c. and d-c. tests were made on this poor insulation. The results are given in Table XII.

5 kv. was thrown on the insulation, after the first minute the voltage was increased to 7.5, then to 10, etc., until breakdown occurred. If breakdown occurred before the end of the minute the time was recorded in seconds. For example, in the first a-c. test, insulation No. 6 withstood the voltage for 60 seconds at 5.0 kv., 60 seconds at 7.5 kv. and 5 seconds at 10 kv. when breakdown occurred. It will be noted that the d-c. and a-c. maximum breakdown voltages average about the same in this insulation, which

TABLE XII.

A-C. AND D-C. TESTS ON WET INSULATIONS

0.24-CM (3/32-in.) VACUUM TREATED PRESSBOARD.

(Soaked in water and partly dried.)

Ins. test no.	Megohms res.		Kilovolts max.) 5.0	7.5	10.0	12.5	15.0	17.5	20.0	225
	TIME (Figures show time in seconds at various voltages.)									
6	(120)	a-c.	60	60	5					
			60	60	50					
		d-c.	60	60	12					
			60	60	20					
9	(300 - 1500)	a-c.	60	60	60	60	2			
			60	60	60	17				
		d-c.	60	60.	40					
			60	60	38					
4	(1000 − α)	a-c.	60	60	50					
			60	60	50					
		d-c.	60	60	60	60	17			
			60	60	30					
5	(2000 +)	a-c.	60	60	60	60	60	60	60	10
			60	60	60	60	60	60	30	
		d-c.	60	60	60	60	60	0		
			60	60	60	60	0			

was conducting from terminal to terminal. In some of the tests, in fact, breakdown takes place at a lower voltage on direct current than alternating current. This is, perhaps, due to a better lining up of moisture by direct current. Some of this insulation, dry and in perfectly good condition, was then tested in the same way. Starting at 5 kv. the voltage was increased every 60 seconds in 2.5-kv. steps until breakdown occurred; breakdown resulted on alternating-current when 70 kv. (max.) was reached; on direct-current when 130 kv. was reached.

Similar tests were made on sections of paper-insulated cables that had absorbed varying amounts of moisture. In those sections in the worst condition as indicated by low puncture voltages, the d-c. and a-c. maximum puncture voltages averaged about the same. In the sections in the best condition the d-c. puncture voltage was somewhat higher than the maximum a-c. voltage.

There is considerable difficulty in practise in making a-c. voltage tests on long lengths of cables, due to the size of the apparatus, which is necessarily large on account of charging current. The necessary kilovolt-amperes often amount to several hundred. The wave shape is often distorted by the leading current, the apparatus is difficult to move about etc. D-c. tests would eliminate these difficulties, as very small apparatus would be required, providing such tests would detect faulty sections, etc. It cannot be said that a given d-c. voltage is equivalent to a given a-c. voltage. The above tests indicate, however, that faulty sections of cable could be as equally well located by d-c. tests as by a-c. tests. In cases of cracks, etc. the air- or compound-filled space would be broken down at the same maximum voltage on direct current or alternating current. In case of a fault due to moisture the breakdown would apparently take place at about the some voltage, alternating current or direct current. In the case of a cable in good condition there would be much less likelihood of injury by direct current than by alternating current of the same maximum voltage. A d-c. voltage equal to the maximum of the a-c. test voltage would, therefore, seem suitable for such tests.

DISCUSSION ON "THE EFFECT OF HIGH CONTINUOUS VOLTAGES ON AIR, OIL AND SOLID INSULATIONS" (PEEK), CLEVELAND, OHIO, JUNE 29, 1916.

John B. Whitehead: We have again to acknowledge our debt to Mr. Peek for a most valuable contribution to our knowledge of the electric strength of air, and now also that of liquid and solid insulation.

Referring to Mr. Peek's observations on the comparison of alternating and continuous voltage at which corona appears; I have recently been conducting, in conjunction with Mr. W. S. Brown, a series of similar experiments. The results of these experiments show some variation from those obtained by Mr. Peek.

The expressions for the critical corona voltage in terms of the diameter of the conductor, as given by Mr. Peek and as given in my several papers on "The Electric Strength of Air," differ somewhat but not widely. Experiments by Farwell and others on corona forming continuous potentials differ as between positive and negative potentials, and reveal some question as to whether there is any agreement between alternating and continuous corona potentials. In view of these differences our experiments have aimed to take alternating and continuous observations on the same apparatus, under the same conditions and with the electroscope and such other precautions as to measurement as would insure accurate results. The method used for obtaining d-c. potential is the same as that shown by Mr. Peek in the lower half of Fig. 1. That is, we have used a kenotron with one side of the circuit grounded. Our experiments have differed, however, in the method of measuring the continuous voltage. For this we have used a standard d-c. Weston voltmeter, with series-connected, non-inductive resistance aggregating a million and a half ohms. Mr. Peek, apparently has depended on the ratio of transformation of his high-tension transformer as an indication of his d-c. voltage. For our alternating voltages we have used the ratio of transformation of the transformer together with careful oscillograms on the low-tension side for determining the maximum values.

Our results show a marked difference between positive and negative corona voltages for a range of wires between 0.07 and 0.23 cm. diameter. When the wire is negative the corona forming voltage within this range varies from 6 per cent to about 2½ per cent higher than positive. Mr. Peek states, as shown by Table II that within the corresponding range and indeed throughout the entire range of his observations, there is no difference between positive and negative corona forming voltage.

Mr. Peek, as usual, has contributed a most interesting paper. In my opinion the value of it would be greatly enhanced if it contained a better description as to the conditions of accuracy under which the observations were taken. For example, a static voltmeter seems to have been relied on for the continuous voltage measurements. My experience with this type of instrument leads me to feel that it is far from accurate. One would also like to know the general conditions under which the maximum value of the alternating voltage was determined on the low voltage side and how often throughout the range of voltage used. No statement is made as to how closely any of the observations may be repeated. In connection with the puncture tests on solid insulation it would be particularly interesting if Mr. Peek has been able to secure uniform results with repeated observations of the puncture tests on single sheets of material.

One must always envy the exceptional facilities which Mr. Peek is able to bring to bear on his experimental problems. A uniform source of continuous potential up to 150 kv. offers promise of many valuable observations.

William Baum: Whenever the subject of high continuous voltages has come up in the past in the engineering societies it was admitted with regret that we had no definite data on d-c. corona and puncture voltages. We know now with certainty that the d-c. puncture voltage is 2.5 times the a-c. maximum puncture voltage, or 3.5 times the a-c. effective voltages for an insulation thickness of 1.2 mm. where the time of test is a maximum.

This brings back to my mind the old claim of Mr. Thury and his followers that an effective alternating pressure of 10,000 volts imposes on insulation a stress of the same order of magnitude as a d-c. pressure of 25,000 volts.

It appears now that Mr. Thury was right when he claimed that d-c. cables require less insulation than a-c. cables designed for the same voltage, so that if d-c. voltage has advantage of lower disruptive effects, as Mr. Peek has shown for normal operating conditions, this would make the application of high-tension d-c. current for transmission purposes more favorable. Indeed the Thury system, although it has met with some criticism in this country, has further advantages which, I believe, have never been pointed out sufficiently until the present time.

Without wanting to go into the details of the high-tension d-c. system for transmission, I take this opportunity of calling attention to the multi-circuit feature which makes a constant d-c. system especially efficient for inter-connecting a number of stations, systems or net-works for the transfer of power. One of the most important applications would be that to long distance railroading, as transcontinental lines, by inter-connecting by such a series system the substations of the railroad, and all available sources of power near the railroad.

Mr. Peek has suggested the testing of cables by direct current, and I agree with him that faults in cables installed could be found just as easy or easier with direct current than with alternating current. Anybody who has had to do with cable testing in installations appreciates the independence of the source of electric power which would exist if we could make use of the kenotron rectifier described in the paper in connection with a small transportable gasoline-electric set, or similar high-tension direct-current rectifiers which have been in use abroad for a number of years, and which are known as the Geoffroy & Delore and Delon apparatus. In fact, the Siemens-Schuckert works have made puncture tests with their Delon rectifier which check very close with Mr. Peek's own exhaustive and defined experiments.

I believe that Mr. Peek should continue his investigations and extend them over long lines of cables which have been installed, so that no doubt may arise in the minds of those who question the applicability of high-tension direct current; for testing purposes and transmission systems.

Stanley Farwell: I can remember when I was working on corona that I went to Mr. Peek's papers and Dr. Whitehead's papers and used them more or less as text-books. My work has been entirely with direct-current corona, and on that account I am unable to make any comparison between that and the alternating-current corona. In my work it did seem to me that the d-c. corona lends itself better, perhaps, to the study of the physical nature of corona than does the alternating current.

In the work I did, I started out to do certain definite things, but I found as I went along, the things I started to do got further and further from me, because I ran into so many new things that apparently had not been explained. I went to one of the best physicists I knew and got him to try to help me out on the physical explanation of the formulas such as are given in Mr. Peek's papers and Dr. Whitehead's papers and my own. I found, after a while, that we got up against a stone wall.

At the University of Illinois, they are now working on some further experiments, and are taking different gases, trying to study them, and get some knowledge of the physical laws underlying corona. I used air entirely, and I found that when working with parallel cylinders, the change in the composition of the air, due to corona, seemed to cut quite a figure. We are now trying to get away from that by using simple gases.

C. E. Skinner: All of us who have had to do with insulation and insulation testing have many times wished we had available direct current so that we could get away from some of the complications which constantly beset us in the testing of insulation with alternating current. We have variables enough without the extras that come in due to the variations from frequency, wave form and things of that kind. Insulations are about the most difficult things to investigate, because of the fact that there are such an enormous number of variables coming in to mask results.

Our own work has been more along the line of the measuring of the losses at high voltages. The condition we have to meet in practise is that we have stresses due to alternating current and some of the important features in connection with this phenomenon are in connection with losses which occur in the insulating material.

For some time I have had some experiments going on with a view to seeing if we could not determine beforehand when insulation was in condition to break down, before it actually broke down. All of our early work was based on breakdown values after the breakdown occurred, and I am very pleased to see that some recent work indicates the possibility of predicting very definitely when insulation is in a condition to break down, before it actually does break down, by a fairly simple measurement of power factor and losses.

Mr. Peek's paper brings out a new method. It gives us a new rule. With each new instrument we enter a new field of investigation, and I am very sure that this paper marks the beginning of a very important era of work along these general lines.

Chester L. Dawes: Mr. Peek has produced some very interesting and important results, but I should like to add to, or amplify some of the explanations which he presents. In Fig. 6 which shows the spark over between concentric cylinders, the 60-cycle curve gives low values of voltage for small values of r; these values increase to a maximum with increase in r after which they decrease. That is, the greater thickness of air has a lower dielectric strength than the thinner layer until a certain ratio of R/r is reached. At first this does not seem reasonable, but the following explanation to me seems rational. The impressed

voltage $$E = \frac{g\, x \log_{10} R/r}{0.434}$$

where g is the gradient at which air breaks down, and x is the radius to the air where the gradient is g. This assumes that the corona has the effect of increasing the diameter of the conductor to x. If this assumption were correct the voltage E could be increased until $x = \frac{R}{\epsilon}$ before spark over would occur. Therefore it would seem that the spark over voltage would be the same for all central conductors whose radius $r \leqq \frac{R}{\epsilon}$. That is, the relation if plotted would be similar to the upper d-c. curve shown in Fig. 6. However the corona surrounding the central conductor is not the same as a metallic conductor of the same diameter for no corona would exist about the metallic conductor. The corona formation about the smaller wires is emitting ions that are projected into the outside layer of air which is supporting the stress. These ions produce others by collision, etc. and the outside layer of air breaks down at a much lower voltage than it would if the corona formation had acted like a metallic conductor. The smaller wires produce a larger number of these ions and a lower spark-over voltage results as shown in Fig. 6. I should like to ask if any reason can be given for the d-c. voltage following a different law than the a-c. in Fig. 6.

As Mr. Peek states, solid insulation like cambric may behave quite differently when tested with d-c. than it does when tested with a-c., which partly is due to the fact that the insulation is composed of an infinite number of minute capacitances and conductances arranged in various series-parallel combinations. When a direct current is impressed across a piece of insulating material there is an initial rush of displacement current which drops off very rapidly at first and then more slowly until after some time it reaches an essentially constant value. This decay of current is almost logarithmic. It may be several minutes before the current reaches its constant value. The above phenomenon is often called "absorption." It is due to the minute condensers constituting the insulation, being charged through high resistances. Therefore the voltage distribution in the insulation will be materially different at the end of charge than it is at the beginning and with alternating current. At the end of charge the distribution is determined entirely by the conductance relations in the insulation and at the beginning of charge and also with alternating current the distribution of potential is determined almost entirely by the capacitance relations in the insulation. It would seem reasonable therefore to find the short time d-c. tests checking more closely than the a-c. tests. The fact that they do not, I should say was due to the fact that the period of two seconds or so was long enough for the direct-current distribution of potential to assume very nearly the final steady state.

The author shows that d-c. breakdowns are practically the same as the a-c. breakdowns when the insulation has a low resistance. Outside the question of the alignment of moisture particles, I believe that the explanation lies again in the manner in which the potential distributed itself through the insulation. When the resistance is low the a-c. distribution of potential is determined more by resistance than it is by capacitance, so the breakdown should be more nearly the same as it is with direct current. This is also true in transil oils. The best grades have a much lower insulation resistance than other well-known solid insulators. Also the oil molecules being mobile, can quickly arrange themselves to make the capacitance a maximum. Therefore little "absorption" can be found in oils.

I should not recommend that direct current be used for testing cables except perhaps in a few instances. It might be applied to homogeneous single-conductor cables provided that sufficient allowance be made to account for unknown hysteresis effects and the foregoing factors. I believe that the heating is negligible at ordinary frequencies. It would be out of the question to test graded cables and the ordinary twin-conductor and multi-conductor cables with direct current, as the voltage distribution throughout the various insulations when in service is determined by the capacitance relations, whereas, in the d-c. testing it would be determined by conductance relations.

Clayton H. Sharp: As I understand it, Mr. Peek advocates the use of continuous voltage for cable testing for the reason that under certain conditions the continuous voltage is more severe on the cable than the alternating voltage, whereas yesterday, he objected to the use of the high-frequency oscillatory voltage in testing transmission insulators for the same reason.

John B. Taylor: Has comparison been made between the voltage as determined by the transformer ratio; by electrostatic voltmeter; and by what, at first sight, would be the normal way to measure the high d-c. voltages,—plenty of resistance and standard d-c. voltmeter?

In work with extra high-voltage alternating current there has been much doubt as to the correctness of the values of high voltages, so it is surprising to see in a presentation of d-c. high-voltage experiments the reliance which is placed on a-c. instruments, ratio of transformation and the electrostatic voltmeter.

The Thury system of d-c. series high-voltage transmission of power has been referred to. Service experience in Europe extending over a number of years has demonstrated the practicability of working underground cables and other insulators under continuous voltages higher than has been attempted with alternating current. This advantage of the Thury system from the insulation standpoint has been well recognized and there are other advantages such as opportunity to save copper by using earth-return circuit without inductive disturbances to telegraph and telephone lines. Lack of flexibility in distribution to many consumers unfortunately has interfered with more general introduction of the system. Mr. Peek's curves in Figs. 12 and 13 indicate how much more a cable may be expected to stand under d-c. stress than a-c. stress. Similar tests should be made on completed cable samples containing splices and for much longer time than the 1500 seconds.

Continuous high voltages (higher even than the 150 kv. of the paper) have long been available from "friction" and "influence" electrostatic machines. Large numbers of small storage cells have been connected up, and series of small d-c. generators have been assembled for experiments and testing at voltages at one time regarded extremely high. The complication of many small d-c. generators and the bulk, unreliability and small power output from static machines possibly makes the use of a-c. generators with step-up transformer and rectifying "kenetron" the most practicable high continuous d-c. experimental device.

Cable failures occur principally at splices due to,—cracked insulation from bending and handling; damaged insulation from overheating (drying out, soldering, lead wiping, or hot compound);

insufficient insulation thickness or poorer grade at splice than in run of the cable; introduction of moisture; presence of air cavities (possibly at reduced pressure resulting from contraction of compound on cooling.)

These different weaknesses probably have different ratios for standing a-c. and d-c. stresses. Particularly an air space in the field between conductors might be expected as result of continued thermal or chemical local action to fail more readily on a-c. stresses. Mr. Peek suggests testing cables with direct current of value equal to maximum of accepted a-c. testing values. His results in Figs. 12 and 13 would seem to call for a higher direct current than this. Perhaps twice the effective a-c. voltage would be comparable.

F. W. Peek, Jr.: Referring to the questions of Dr. Whitehead and Mr. Taylor, the voltages were checked by means of a known liquid resistance in series with a milliammeter, and also by a known resistance in series with an oscillographic vibrator, across the high-voltage lines.

Dr. Sharp misunderstood my remarks on "high frequency." I think my meaning will be clear when reference is made to the written discussion.[1] I did not condemn high-frequency tests, as such, but gave an illustration to show how easy it is to misinterpret the results of such tests.

I have not advocated direct current for cable testing. I have simply pointed out that it looks very promising, for the following reasons:

I. Air, oil and insulating liquids break down at d-c. voltages equal to the maximum a-c. voltages.

II. Solid insulations containing moisture break down at approximately the same maximum voltages on alternating and direct current.

III. Solid insulation, *in good condition*, require a direct-current voltage much higher than the maximum alternating-current voltage to cause breakdown.

It thus seems that most faults will be located equally well on a-c. or d-c., if a d-c. voltage equal to the maximum of the a-c. testing voltage is used. This follows because large cracks filled with air or oil will be broken down at the same maximum voltage on a-c. or d-c. (see I above); wet insulation will break down at approximately equal voltages on a-c. or d-c. (see II above); injury is much less likely to occur to solid insulation in good condition on d-c. (see III above).

Although the laboratory tests indicate very promising results, I believe it important that practical experience be gained in the field, before recommendations are made for extensive or general use of this form of testing. Naturally, the principal use of the d-c. test would be in the field where a portable set is necessary. All cables should be given the a-c. test in the factory.

1. Discussion of papers of Messrs. Creighton and Marvin, Cleveland, Part 1 this volume.

When the fault occurs in the cable it is often desirable to burn it out to low resistance so that its position can later be located by a bridge. Our laboratory tests indicate that this can be done with the d-c. testing set. The time required to burn out a fault in this way depends upon the condition of the sheath. If the sheath has been broken open a greater time will be required than if the sheath is intact. The time will vary from 1 to 5 minutes.

In making the d-c. corona tests we found, as a rule, that the visual corona point was quite sharp and definite when the wire was positive. When the wire was negative, however, it was often quite difficult to determine this point definitely. The slightest surface irregularities cause the negative corona to brush at fairly low voltage. It is quite possible that the negative corona voltage is a few per cent higher than the positive corona voltage, the exact difference, however, if there is any, will depend to a considerable extent, upon the observer and what is defined as the critical point.

L. T. Robinson: I think one of the greatest advantages in cable testing by direct current is that you can get along without an undue amount of apparatus—you are required to furnish only the energy for testing the cable and not a big charging current, and therefore you do not need a big 50-kw. transformer to test a small cable, but maybe a 3 or 5-kw. transformer, which is a great advantage.

F. W. Peek, Jr.: I wish to say, as a matter of interest, that it may require from 1000 to 2000 kv-a. to test long lengths of cable on alternating current whereas similar tests may be made on direct current with from 3 to 5 kv-a. That is one of the reasons why d-c. testing suggests itself, and why, I believe, it is worth trying out in practise. It will often be a question of a d-c. test or no test at all, and not which is best.

Presented at the 33d Annual Convention of the American Institute of Electrical Engineers, Cleveland, O., June 29, 1916.

THE CORONA VOLTMETER

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ABSTRACT OF PAPER

An instrument is described in which the first appearance of corona is used as a measure of the applied voltage.

Three methods for detecting the first appearance of corona have been developed, in addition to the method of visual observation. These methods involve the use of the electroscope, the galvanometer, and the telephone respectively.

For a given wire, in fixed relation to the opposite side of the circuit, corona-forming voltage depends on the density of the air, that is, on the pressure and temperature. The corona voltmeter consists of a grounded metal cylinder, with a central conductor on which corona is formed. Both cylinder and conductor are enclosed in a larger, air-tight cylinder, in which the pressure can be varied by a hand pump. This variation in pressure provides the means by which a wide range of voltage reading is possible. The calibration of the instrument is absolute, that is, can be calculated, or may be obtained by comparison with existing standards.

The voltmeter is set for a given voltage by adjusting the pressure to a value calculated from the dimensions of the instrument and taken from a calibration table or curve. When the ascending voltage reaches the value for which the voltmeter is set, corona begins, and this is sharply indicated by any one of the three methods mentioned. To measure an unknown voltage, the pressure is gradually lowered from some higher value and is read at the instant corona appears. A table of calculated values, or a calibration curve then gives the unknown voltage.

Tests showing the constancy and permanence of the instrument are described.

INTRODUCTION

DURING a number of years' intermittent experiment on the phenomena attending the electric break-down of air, one of the most striking observations has been the extreme sharpness, in an ascending range of voltage values, with which this break-down occurs in the form of corona on clean round wires. Under suitable conditions of observation, critical voltage readings repeat themselves to an accuracy equal to that within which the usual direct reading instrument can be read, *i.e.*, of the order of one-tenth of one per cent. This fact has led one of the authors in his papers[1] describing the experiments, to point

1. For references see bibliography at end of paper.

several times to its value as a method for measuring high voltage. It has been shown beyond question that the appearance of corona depends on the maximum value of the alternating current wave.

That the visual appearance of corona might be used as a means of measurement of the maximum value of the voltage wave was apparently first suggested by H. J. Ryan[2] in his notable paper of 1904. His suggestion, however, does not seem to have extended beyond the visual observation of the light given out by corona, which naturally is only visible in darkness. Reliance on visual observation therefore, practically precludes the use of the method except perhaps for laboratory purposes. This and the fact that the correction factors for variations of temperature and pressure have only recently been definitely fixed[3], probably explains the absence of attempt, up to this time, to make use of the appearance of corona as a measure of voltage.

The fact that air in the neighborhood of the corona is ionized, that is, possesses high electric conductivity, has been extensively utilized by one of the authors[1] as a means of detecting the presence of corona. A charged electroscope in a suitable location near a high-voltage conductor discharges with marked suddenness on the appearance of corona. The electroscope, then, may be used as a detecting instrument free from the limitations of visual observation of the light of the corona. Other means of detection have also been developed and will be described in this paper. With a suitable detecting instrument therefore the corona becomes far more accessible as a high-voltage indicator.

Little need be said as to the importance of a convenient and reliable method for measuring the maximum value of high alternating voltage. The question is answered by the fact that the electric strength of all insulating material is dependent on the maximum value of applied voltage. The needle gap as a means of measurement may also be passed with only brief comment. Although long the standard of the Institute, its unreliability is now universally recognized. It may be stated, however, that under properly chosen conditions and with points having angles greater than 20 degrees, quite uniform results may be obtained. The thorough investigation of the needle gap by Weicker[4] has shown its limited value and many weaknesses.

The sphere gap has been strongly advocated as an instrument free from many of the objections to the needle gap. The authors of this paper cannot claim familiarity with this instrument, and therefore, hesitate to call attention to its apparent limitations. It is fair, however, to point out that the results of different observers using the sphere gap are not in agreement, that the results of a single observer frequently differ by several per cent, and that as shown by Peek[5], the calibration curve is widely different for the cases of both terminals insulated, and one terminal grounded. Its accuracy therefore is very sensitive to the proximity or presence of other objects in the neighborhood, due to their influence on the electrostatic field. Attempts have also been made to derive mathematical expressions from which it should be possible to calculate the spark-over voltage of any given sphere gap. However, the results of Russell[6] in this direction have been attacked by de Kowalski and Rappel[7], and the subsequent discussion indicates that there is considerable doubt whether it is possible to calculate accurately the electric intensity within the sphere gap. Therefore notwithstanding the adoption by the Institute of the sphere gap as a standard, no apology is necessary in describing an instrument which seems to be free from some of its imperfections.

Recent papers before the Institute by Chubb[8] and by Sharp and Doyle[9] have described crest voltmeters utilizing the rectifying properties of hot cathode tubes. The arrangement proposed by Sharp and Doyle is especially simple and promising. Both types should prove valuable for low-voltage readings although the use of a vacuum tube is an undesirable feature for general utility. On high voltage, series condensers or resistance are apparently necessary, and therefore introduce well-known uncertainties.

Principle of the Corona Voltmeter

The corona as a means of measurement possesses the great advantage that it obeys a definite law upon which close agreement now obtains among many observers. If it is possible to foretell with a good degree of precision the value of voltage at which corona will begin on a clean round conductor, an absolute calibration is therefore also possible. This paper describes an instrument in which the first appearance of corona may be accurately and conveniently detected, and which may be set readily and without trouble for any voltage within a considerable range.

From the nature of the corona it will be evident that an instrument using it as an indicator of voltage can make no pretense to a direct-reading scale. No more can the needle gap or the sphere gap. The corona voltmeter as now described, however, possesses, among other advantages, two important features, which in the absence of a direct-reading scale, are very good substitutes. (1) Convenience of observation. (2) A wide range of voltage without manipulation or adjustment of the instrument.

Methods of Observation

The appearance of corona obeys a rigid law only when the wire or rod on which it appears is accurately placed on the axis of a hollow cylinder forming the opposite side of the circuit. This arrangement has therefore been chosen for the voltmeter. In the present form the outer cylinder is grounded, thus presenting the advantage of screening the wire from outside influence and permitting close approach to it without danger.

Three methods of observing the beginning of corona, not including visual observation, have been developed; the electroscope, the galvanometer, and the telephone.

The Electroscope. The electroscope is the most sensitive instrument for detecting the state of ionization or conductivity in a gas. Since the corona is attended by copious ionization the use of the electroscope for detecting corona involves only the question whether the electroscope can be brought into suitable proximity of the corona without disturbing the electric field upon which the formation of the corona depends.

If the outer grounded cylinder surrounding the rod or wire on which the corona is formed is perforated with a few small holes, and an insulated electrode connected to a charged electroscope is brought up close to these holes on the outside, the first appearance of corona causes an immediate discharge of the electroscope. The close coincidence between the appearance of corona and the electroscope leak or discharge was described in the first paper of one of the authors, on the "Electric Strength of Air."[1] So copious is the ionization with the very first appearance of the visual corona that it is not necessary to use a particularly sensitive electroscope. A roughly constructed instrument using a large strip of aluminum foil instead of gold leaf has been used with good advantage.

In order to meet the possible requirement of moving from place to place, a portable electroscope has been developed. This instrument has only one leaf which, in its zero or discharged position, rests against a rigid member. Means are provided whereby in this position the leaf is pressed throughout its entire length against the rigid member by a flap made of the paper which separates the successive layers of gold leaf in the books in which the leaf is usually furnished. This flap is readily adjustable from outside the instrument, which can thus be handled without danger to the gold leaf. The instrument is also furnished with means for adjusting the sensibility. Since the strip of gold leaf swings through a circular arc it may be calibrated, although this is not necessary for the purpose of indicating the first appearance of corona. Direct visual observation of the discharge of the electroscope is possible but is not as accurate as when it is viewed through a telescope.

The electroscope may be charged from a 120-volt, direct-current circuit, either directly or by a parallel-series connection of small condensers.

The Galvanometer. If the outer grounded cylinder be drilled with small holes fairly close together over its entire surface, and if the electrode formerly used for the electroscope be extended in area so as to form an outer cylinder surrounding that forming one side of the high voltage circuit, a very greatly increased volume of ionized gas may be utilized. If this outer cylinder or electrode is brought close to the grounded cylinder and is connected to ground through a galvanometer and source of continuous potential, the galvanometer should deflect when the gas between the two cylinders is ionized. The outer or electrode cylinder must of course, be carefully insulated.

The object of this arrangement is to detect the presence of corona with a less sensitive instrument than the electroscope. The results as described below indicate that under proper conditions this arrangement serves admirably for its purpose. In the larger of the two voltmeters to be described, a portable needle galvanometer with a direct reading scale and sensitivity of 10^{-5} amperes may be used. For the smaller voltmeter a more sensitive galvanometer is necessary. Up to this time a reflecting galvanometer with telescope has been used, of sensitivity in the neighborhood of 10^{-7} amperes. The magnitude of its deflections indicates that the more sensitive forms of needle galvanometer may, if necessary, be used with this instrument also. For portable purposes, the needle galvanometer is obviously the more desirable.

A continuous voltage is necessary in the use of the galvanometer. The 240-volt, three-wire circuit has been used in the experiments, provision being made for 120 volts positive or negative on the galvanometer and electrode. The arrangement is markedly more sensitive for negative than it is for positive electrode, owing to the differences in the properties of negative and positive ions and consequently the resulting values of the ionization currents.

The Telephone. The corona emits a sound which is gathered and intensified if the region surrounding the corona forming wire is enclosed. Earlier experiments showed that if the perforated grounded cylinder or corona tube has its ends capped and is enclosed in an outer jacket of any kind provided with a single hole to which the ear may be placed, the first appearance of corona is attended by sound of considerable volume. If a cone, connected by tubes to ear pieces is added, the sound is further intensified, and in fact, becomes quite loud.

As described below, the corona voltmeter in its present form involves a variation of the gas pressure in the corona tube. This of course, will prevent a direct listening to the sound. In order therefore, to take advantage of the sound, a telephone transmitter has been inserted into a side tube and connected with twin receivers in the usual head-piece form, on the outside. Obviously gas pressure has no influence on the proper operation of the telephone transmitter. This arrangement has been found to work admirably, and indeed, has been found quite as reliable as either of the foregoing methods for indicating the initial presence of the corona.

Visual Observation. Any of the foregoing methods may be checked in a darkened space by visual observation. In the present work the two forms of instrument have been provided with plate glass disks at their ends, permitting detection of the first appearance of visual corona. As numerous tests have shown that the indications of all three of the foregoing methods are simultaneous with the appearance of corona, the use of the visual method has been limited to the purposes of inspection and checking.

Range of Observation

At atmospheric pressure and temperature, a given diameter of wire or rod, placed in a given outer tube, will form corona at one and only one definite value of voltage. Hence to obtain any range in an instrument using corona under atmospheric conditions would require a change in the diameter of the outer cylinder or of the inner conductor, or in the use of a wire or rod of varying diameter. A change from one conductor to another is not impossible but is manifestly troublesome and objectionable, save perhaps, under laboratory conditions. The use of a conductor of varying diameter is not feasible on account of the small temperature variations due to the presence of corona and on account of the necessity of visual observation.

Corona-forming voltage depends on the pressure and temperature of the air. The values of the voltage at which corona forms on a given wire under any conditions of temperature and pressure are now well-known. The density of the gas is the determining factor and variations of density cause quite wide differences in the value of the corona forming voltage.

A prominent feature of the corona voltmeter as here described is that the pressure in the corona tube is controlled and varied and constitutes the means whereby the instrument is set for a given voltage. Adjustment of the pressure throughout a wide range is quite easy and thus provides practically any desired range of voltage value. In this way values of air density which necessitate a troublesome correction at atmospheric pressure, are eliminated, and in fact, are turned to account in providing a ready means of extending the scale of the instrument. One wire or rod serves for the whole range, and no adjustments other than that of the pressure are necessary. There is in fact, no limit to the range other than that due to the insulation of the air tight bushings, through which connection is made to the corona forming rod, and that set by a safe gas pressure within the instrument. In the two forms of instrument described below, in the smaller a working range between 20,000 and 50,000 volts is obtained with a pressure of 30 cm. below, and 60 cm. of mercury above, atmospheric pressure. A corresponding range with 100,000 volts as a maximum and the same range of pressure is obtained in the larger instrument.

Description of Voltmeters

100,000-volt type

The first type, designed after a number of preliminary experiments, for a range of 100,000 volts is shown in Fig. 1. It consists of an outer steel shell 45.7 cm. outside diameter and 44.4 cm. inside diameter. The ends are enclosed with plate glass disks 1.9 cm. thick, held between flanges, and each supporting in a hole in its center a 100,000-volt porcelain bushing. This outer shell provides a chamber in which the pressure may be varied; the voltmeter proper is inside. The picture shows some of the various terminals and auxiliary apparatus. The length of the outer shell over flanges is 190 cm. The length of the whole instrument over insulator bushings is 238 cm.

Fig. 2 is a descriptive drawing showing the various parts. In order that certain features may be emphasized no attempt has been made to make the drawing to a uniform scale. The central conductor on which corona is formed, shown at *A*, consists of about 40 in. (101.5 cm.) of Stubb's tool steel, 0.635 cm. in diameter. At either end, just outside the cylinder *B*, the central conductor is suitably joined to rods of larger diameter which extend through the porcelain bushing *E* at either end. The object of this enlargement is to make certain that the electric

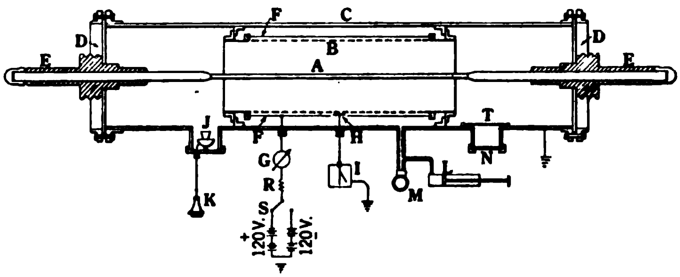
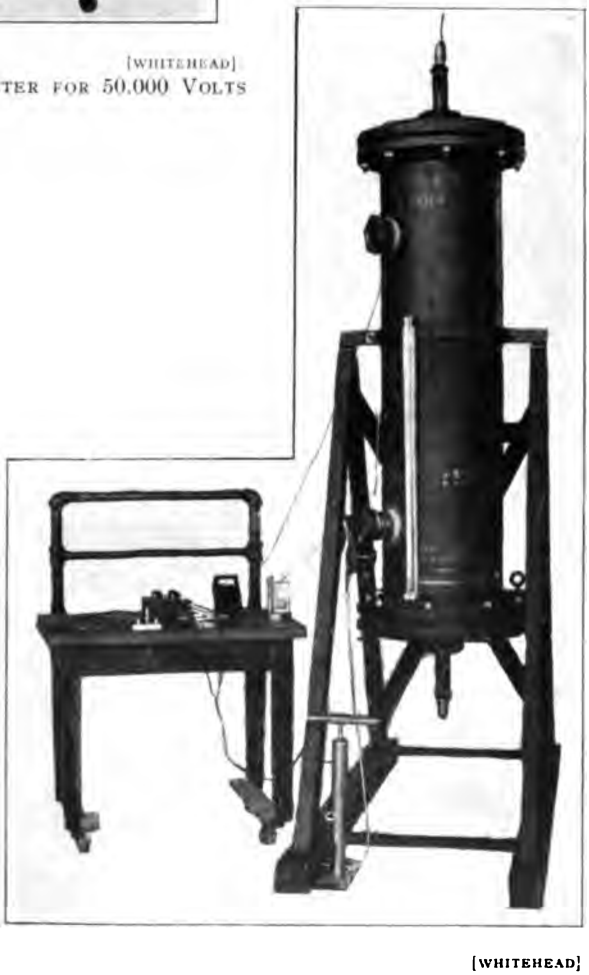


FIG. 2—CORONA VOLTMETER FOR 100,000 VOLTS—CENTRAL SECTION AND CONNECTIONS OF AUXILIARY APPARATUS

discharge occurs only within the region inside cylinder *B*. This outer cylinder *B* is 92 cm. long, 30.7 cm. in diameter, is perforated over its entire surface with holes 1.58 cm. in diameter, and is electrically connected to the outer shell *C*, which is in turn connected to earth. The insulators *E* are cemented to the glass disks *D*, which in turn are held between soft rubber gaskets and the flanges on the outer tube. The final centering of the central conductor is accomplished at the ends of the insulators, the central openings of which provide free play for this purpose. *F* is a thin metal cylinder surrounding, and very close to, the perforated cylinder *B*. It is insulated and connects through a sulphur bushing with the galvanometer *G* and a source of continuous potential *S*. *H* is a small electrode fitting in a hole in *F* but not touching it, and connected through a sulphur bushing with an electroscope, *I*, whose case is connected to earth. *J* is

[WHITEHEAD]
FIG. 3—CORONA VOLTMETER FOR 50,000 VOLTS



[WHITEHEAD]
FIG. 1 CORONA VOLTMETER FOR 100,000 VOLTS

a telephone transmitter fitting into a side tube shown in Fig. 1. *L* is an ordinary hand air pump for either pressure or vacuum; together with the gauge *M* it is connected to the main containing cylinder. *N* is a small side tube with glass top through which the thermometer *T*, recording temperature inside the tube, may be observed. All permanent joints were sealed with a cement made from litharge and glycerine, while those holding the glass and cap nuts on the end of the central conductor consisted of soft rubber gaskets. No particular care was given to the elimination of unnecessary joints, and it has been found possible to maintain pressure as high as 60 cm. above atmosphere over periods quite sufficient to insure constancy of observation.

In designing the instrument as described above, liberal allowances were made in all dimensions. It was the first instrument in which pressure was applied and in order to provide also for thorough inspection and access to all parts, it was realized that it would probably be found unnecessarily large. This proved to be the case. The indications of the appearance of corona by the several methods already described were so satisfactory that it was soon found that the instrument could be made smaller without sacrifice of reliability.

The only limitation which has been found in this first type of instrument is in the insulation. If too large a central conductor is used, say above 1.75 cm. diameter, the high voltage required to start corona causes a spark between the conductor and the outer casing at the edge of the insulator bushing due to a region of high electric intensity. This trouble is entirely eliminated by the use of a smaller corona conductor, with ends of larger diameter, as already described. Corona then appears at lower voltages at atmospheric pressure and the spark-over voltages at the bushing are never reached. The voltage at that point only rises when pressure is on the tube and sparking is then suppressed.

The pressure in this tube has only been carried to 62 cm. of mercury. This means a total thrust of 2100 lb. (952.5 kg.) on each of the plate glass disks at the ends. While the central conductor can probably be relied on to take up a part of this thrust the pressure has not been carried higher up to this time for fear of breaking the glass disks. It is not necessary to have the whole end of the tube of glass, as small openings only are required for observing visually, the appearance of corona. Therefore, in a tube of the general dimensions given, it should be quite easy to reach pressures far in excess of that mentioned. Our experience indicates that the chief limitation of the instrument is the insulation of the bushing leading the voltage to the central corona forming conductor.

50,000-VOLT TYPE

As a result of the experiments with the foregoing instrument, another was designed for 50,000 volts in which effort was made to reduce the dimensions without impairing its reliability. Fig. 3 shows a general view. In all respects the details of the instrument are the same as those already described in connection with the larger type, except that is this smaller type the telephone has been omitted. This was done largely because of the difficulty and time required for setting into the outer cylinder a branch tube large enough to hold the telephone transmitter, the diameter of the main cylinder being only 12.7 cm. Observations are in no wise dependent on the use of the telephone and this was not considered as a necessary feature for an experimental type of instrument.

The principal dimensions for the smaller instrument are as follows: Outer tube, 12 cm. inside diameter, 24 cm. diameter over end flanges, length over flanges, 52 cm., length over all, 76 cm. The inside or corona tube is 9.51 cm. inside diameter and 29 cm. long. Central conductors or rods of various diameters have been used. In the experiments described below the rod was of tool steel, 0.396 cm. in diameter.

In this instrument as in the other, the limit has been found in the insulation of the end bushings. In the form shown, brush discharge begins at 65,000 volts over the inside surface of the glass ends. As the insulators were home-made, by making the whole instrument somewhat longer, and improving the insulation, there seems to be no reason why this instrument could not be used for even higher values. The pressure required to reach above 50,000 volts was only 66 cm. of mercury above atmosphere.

Pressure is adjusted and varied in the tubes without trouble by means of an ordinary hand pump, for both vacuum and pressure, about 46 cm. long, and of the type used for bicycle and automobile tires. A valve with small opening permits easy adjustment of pressure.

OBSERVATIONS AND TESTS

Power was taken from a 10-kv-a., 100,000-volt transformer fed by a 7.5-kv-a., motor-driven, smooth body, surface-wound, single-phase generator, specially designed to give a smooth wave. The set was designed for frequencies between 45 and 120 cycles and was equipped for close speed and generator field control within wide ranges.

Throughout the experiments a frequency of 60 cycles was maintained. Variation of the transformer primary voltage was accomplished by varying the field current of the generator.

The transformer is of the core-type, having all of its coils wound on one side of the magnetic circuit of rectangular shape. It is provided with two primary coils, each for 110 volts. It also has a tertiary coil with the same number of turns as one primary coil. All of these coils are close to the core. The high-tension winding consists of a large number of pan-cake shaped coils set side by side over the primary and filling a large portion of the central opening of the magnetic circuit. The transformer was designed for operation at any frequency between 20 and 120 cycles. The ratio of high-tension to tertiary coil turns is 833.36.

All observations have been made with the outer tube of the voltmeter, one end of the tertiary coil, one end of the primary and one end of the high-tension winding all connected to ground. In the observations of the smaller voltmeter the primary coils were connected in series while on the larger they were in parallel The value of the generator voltage in both cases ranged from 20 volts up to about 100. It will be seen therefore that all observations were taken at comparatively low values of the magnetic density in both the generator and transformer. Power for the direct-current motor and also for the generator field was taken from a storage battery, giving most of the time practically perfect conditions as to constancy.

The general method of taking observations was, with secondary connected to the central conductor of the voltmeter, to raise the voltage gradually, observing the electroscope and galvanometer, and listening with the telephones, singly or all together Simultaneous readings of all three were possible by using a reflecting galvanometer, and throwing, with suitable mirror arrangements, the image of the electroscope leaf into the telescope used for reading the galvanometer. As soon as any one or all of the instruments indicated the appearance of corona the voltage was read by an electro-dynamometer type of voltmeter on the terminals of the tertiary coil of the transformer. A large number of oscillograms were taken during the course of the experiments which, with the voltmeter readings, serve to give the crest factors of the voltages in the tertiary coil.

Special interest attaches to the extreme constancy with which the corona is indicated by any one of the four methods described and to the closeness with which the four methods agree among themselves.

The readings in Table I were taken by two observers. One observer would read the electroscope or galvanometer or listen with the telephone while gradually raising the voltage. As soon as indication of corona appeared he would tell the other observer to read the voltage. The voltage would then be lowered by an indeterminate amount and the process repeated. The readings with each type of indicating instrument were taken singly, the several sets following one immediately after the other.

As a general thing the electroscope leaf would stand apparently perfectly still, its normal rate of leakage being extremely small. With the appearance of corona the leaf would discharge in periods varying between one and five or six seconds depending upon the size of the conductor and the condition of its surface. The rate of leak attendant upon the appearance of corona is always sharply marked, and there is no difficulty in distinguishing it even when at its slowest.

TABLE I.

COMPARISON OF ELECTROSCOPE, GALVANOMETER, AND TELEPHONE AS INDICATORS OF PRESENCE OF CORONA

	Critical volts on tertiary coil. 0.633 cm. diam. rod in 30.7 cm. tube					
Electroscope.......	48.75	48.75	48.8	48.8	48.75	48.75
Galvanometer. ...	48.8	48.8	48.75	48.8	48.75	48.7
Telephone.........	48.8	48.8	48.75	48.8	48.8	48.75

The galvanometer deflection is also sharply marked. With the approach to corona voltage the galvanometer stands at zero or with a small deflection due to leakage over the insulation of its electrode, the deflection being practically constant. With the appearance of corona the galvanometer takes a sharp increase of deflection the amount of which is dependent upon its sensitivity. In the mirror galvanometer already mentioned, the amount of this sudden deflection was 6.5 mm. No fine adjustment of the voltage increase could bring the deflection below this value. With the less sensitive needle galvanometer already described, the deflection was considerably less, of the order of one mm. which, however, is readily detectable. These deflections increase rapidly with even a small increase of the voltage above the corona forming point.

With reference to the telephone, it has already been stated that with the approach to corona voltage there is no sound in the telephone, but the instant corona appears a very pronounced note is heard.

A number of preliminary tests with various sizes of central conductor were made on each type of voltmeter. These tests had as their principal object the study as to how the values obtained would agree with the formulas given by various experiments connecting the critical surface intensity of a conductor with its diameter and with the temperature and pressure.

TABLE II.
COMPARISON OF OBSERVED AND CALCULATED CORONA VOLTAGES

Diam. rod cm.	Critical volts			δ	Critical surface intensity	
					Obs.	Calc.
0.238	21.6	21.7	21.8	1.014	59,400	59,800
0.317	24.6	24.7	24.6	1.014	55,500	55,400
0.396	27.6	27.6	27.6	1.017	53.800	54,000
0.477	30	30	29.9	1.017	50,700	51,200

The method followed in these tests has been the same as that used by one of the authors in his papers on "The Electric Strength of Air." This method involves the reading of the critical voltage on the low-tension side, the measurement of the wave form on the low-tension side, and the assumption that the ratio of transformation of the transformer is that of the number of turns in primary and secondary. This method has been found to give very uniform results for moderate values of the secondary voltage.

Table II shows the results with four sizes of rod in the smaller voltmeter. The results calculated from the expression for the surface intensity,

$$E = 32\left(\delta + 0.296\sqrt{\frac{\delta}{r}}\right)\ \text{kv/cm.} \qquad (1)$$

are also given in one column of the table. It will be seen that the agreement is quite close. The constants of the above expression are those which were first proposed by one of the authors. Peek's corresponding expression gives a value in the neighborhood of 31 instead of 32 for the principal factor of the right hand member of the expression. Further evidence, leading to the conclusion that the higher value is the correct one, is given in our results below in which the density of the air is varied through wide limits.

A number of tests were also taken with various sizes of central conductor in the larger voltmeter. The observations were taken under the same conditions of accuracy and care, and could also be repeated as often as desired. The values of voltages, however, as read on the low-tension side, and reduced to the high-tension side in the method described, were always lower than the values calculated from the expression just given. This discrepancy was found to be due to a rise in voltage in the secondary circuit, owing to its leakage reactance and to the charging current of the larger voltmeter, this rise having no equivalent in the tertiary coil.

The primary current of the transformer increased from 2.9 to 4.3 amperes on connecting the larger voltmeter, the power input of the primary remaining practically unchanged. The arrangement of the coils in the transformer has already been described and indicates clearly the probability of leakage reactance in the high-tension winding which has no counterpart in the tertiary coil on which the voltage was read.

Calibration

The calibration of any of the types of instrument heretofore used for measuring crest voltages has always been an uncertain factor. The usual method has been comparison with a standard needle or sphere gap, or with low-voltage voltmeter readings corrected for crest factors. But, as is well known, both types of spark gap must themselves be calibrated, since it is not certain that even the sphere gap will break down at a voltage which can be calculated in terms of the separation and the diameter of the spheres. It is now stated, with considerable confidence, that a tertiary coil can be so wound in a high-tension transformer that it will reflect accurately the value and wave form of the voltage in the high-tension winding. While this may be true, the evidence is still lacking, and the reason is that there is no certain method of measuring the high-tension voltage directly in terms of laboratory standards.

It is the opinion of the authors of this paper that the desired standard of voltage for values above 10,000 or 15,000 is available in the corona forming on a clean wire centered in an outer cylinder. All observers are now agreed that corona forming voltages repeat themselves with the greatest degree of accuracy under the same conditions of temperature and pressure, and further, the variations due to temperature and pressure are now understood. The constants which give the actual value of critical corona voltage for a given size wire as determined by different observers, agree very closely. It would appear then, that the only thing necessary to fix an absolute standard of high voltage is the formation of a committee who should conduct, under properly considered conditions, a series of experiments for the determination of the figure for the electric strength of air which could be used as a standard. This quantity is undoubtedly a definite physical constant, and it is only necessary to eliminate all source of error in experiment to determine it accurately.

The corona voltmeter as already described, can of course, be calibrated by exactly the same means which are used for the calibration of the standard spark-gaps. In view, however, of the uncertainty of such calibration, the authors have preferred to compare the indications of the instruments with values of corona forming voltage as deduced from formula (1), in which E is the electric intensity at the surface of the wire, at which corona is formed, in kilovolts per centimeter, and δ is the density factor given by the expression

$$\delta = \frac{3.92 \times p}{273 + t} \qquad (2)$$

in which p is the pressure in cm. of mercury, and t is the temperature in centigrade degrees. The constants of formula (1) have been checked a number of times by one of the authors. The values found by Peek and others are in close agreement.

50,000-*Volt Type.* In Table III, are given the results of a series of observations with varying pressures on the smaller type of voltmeter. The readings taken were: voltage on the tertiary coil, air pressure, as measured on a mercury pressure gauge, temperature inside the tube, and oscillograms of the tertiary coil voltage in order to obtain the crest factors. The oscillograms have an average amplitude of 2.2 cm., and a length at the base of about three cm. The ordinates were measured at distances of one mm. As so measured, the crest factors varied uniformly between 1.45 and 1.44, over a range of tertiary coil voltage from 20 to 45 volts covering the range of observation.

The values of the corona surface intensity, as observed and

TABLE III.
OBSERVATIONS WITH 50,000 VOLTS CORONA VOLTMETER

Pressure cm.		Temp. deg. cent.	δ	Ter. Coil volts		Crit. surf. intens. volts per cm.		Max. volts
Obs.	Corr.			Eff.	Max.	Obs.	Calc.	
− 34	43.5	27	0.569	17.8	25.9	34,390	34,200	21,580
− 33	44.5	27	0.581	18.	26.2	34,760	34,800	
− 32.8	44.7	27	0.584	18.2	26.4	35,120	34,940	....
− 26.9	50.6	27	0.661	20.	29.1	38,600	38,450	....
− 26.4	51.1	26.5	0.668	20	29.1	38,600	38,750	24,200
− 25.8	51.7	26.5	0.676	20.3	29.5	39,150	39,120	....
− 17.5	60	26.5	0.785	22.8	33.1	43,920	43,760	....
− 17.2	60.3	26.5	0.789	22.8	33.1	43,920	43,920	....
− 17.	60.5	26.5	0.791	22.9	33.2	44,140	44,000	27,700
− 11.8	65.7	26.	0.861	24.4	35.4	47,000	47,300	....
0.	74.7	26.	0.979	27.	39.1	51,950	52,350	....
0.	74.7	20.5	0.997	27.5	39.8	52,900	53,150	....
+ 15.	86.9	20.5	1.160	30.7	44.5	59,020	60,050	37,100
15.3	87.2	20.5	1.164	30.8	44.6	59,220	60,200	....
25.2	97.1	21.	1.294	33.7	48.8	64,750	65,600	....
26.3	98.2	21.	1.309	34.	49.2	65,350	66,200	....
27.7	99.6	21.	1.327	34.4	49.8	66,050	66,900	41,500
33.4	105.3	22.	1.4	35.9	51.9	68,900	69,000	....
34.2	106.1	22.	1.410	36.2	52.3	69,400	70,000	....
38.3	110.2	23.	1.460	37.3	53.9	71,600	72,400	....
38.6	110.8	23.	1.468	37.5	54.2	71,900	72,700	45,100
45.1	117.	23.	1.549	39.2	56.6	75,200	76,000	....
45.9	117.8	23.	1.560	39.5	57.0	75,700	76,400	....
53.1	125.	24.	1.650	41.5	59.9	79,500	80,100	....
54.2	126.1	24.	1.664	41.8	60.3	80,050	80,700	50,300
56.7	128.6	24.	1.697	42.2	60.9	80,800	82,000	....
60.7	132.6	25.	1.744	43.5	62.7	83,250	83,800	....
61.9	133.8	25.	1.760	43.6	62.9	83,480	84,500	....
63.3	135.2	25.	1.778	44.0	63.4	84,700	85,200	52,800
66.	137.9	26.	1.807	44.8	64.6	85,700	86,400	53,800

also as calculated from the expression given above are given in the last two columns of the table. In Fig. 4 a curve is drawn between the critical surface intensity and the density factor. The solid curve gives the relation as calculated, and observed values are indicated by crosses. It will be observed that at higher values of pressure the observed values are slightly lower than those calculated. This is partly due to the fact that the observations were taken with very slowly-diminishing pressure owing to leaks in the tube. Much time and trouble was saved by closing some of the necessary openings in the tube with rubber gaskets instead of sealing them permanently. These gaskets leaked slowly at the high pressures. It is also possible that a rise in secondary voltage due to leakage reactance and charging current was present at the higher values of voltage.

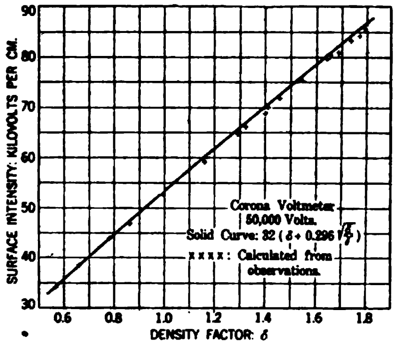


FIG. 4—CALCULATED AND OBSERVED VALUES OF VOLTAGE AT DIFFERENT VALUES OF AIR DENSITY

100,000-*Volt Type.* The larger type of instrument has been operated with a number of different sizes of central conductor and through the range of pressure between 65 cm. and 136 cm. of mercury corresponding to a range of voltage between 50,000 and 110,000 maximum values. Table IV gives a typical

TABLE IV.
OBSERVATIONS WITH 100,000 VOLT CORONA VOLTMETER

Pressure cm.		Temp. deg. cent.	δ	Ter. coil volts		Crit. surf. intens. volts per cm.		Max. volts
Obs.	Corr.			Eff.	Max.	Obs.	calc.	
− 10.6	64.7	21.7	0.861	40.5	60.7	41,300	43,150	50,600
− 6.4	68.9	21.7	0.918	42.4	63.5	43,250	45,450	53,000
− 5.8	68.9	20.8	0.920	42.9	64.3	43,750	45,500	53,600
0.	74.7	20.7	0.996	45.9	68.8	46,800	48,650	57,400
+ 6.	80.7	20.9	1.076	48.6	73.0	49,580	51,800	60,800
11.3	86.0	21.	1.146	51.1	76.6	52,120	54,650	64,000
16.2	91.0	21.1	1.212	53.4	80.8	54,450	57,400	66,700
21.1	96.0	21.2	1.278	55.7	83.5	56,820	59,850	69,600
27.6	102.5	21.3	1.365	58.4	82.7	59,600	63,300	73,000
33.9	109.0	21.4	1.451	61.1	91.6	62,320	66,550	76,400
37.7	112.8	21.5	1.502	62.9	94.2	64,150	68,600	78,600
43.3	118.5	21.6	1.576	64.3	96.5	65,700	71,350	80,300
48.2	123.5	21.7	1.643	65.9	98.7	67,200	74,050	82,400
55.7	131.0	21.8	1.742	68.5	102.8	69,800	77,900	85,600
61.4	136.7	21.9	1.818	70.8	106.1	72,100	80,800	88,500

series of observations with a steel rod 0.635 cm. in diameter as the central conductor. The table also contains a column giving the values calculated from the expression for the critical surface intensity as affected by temperature and pressure to which reference has already been made. The curves of Fig. 5 show the relation between the critical surface intensity and air density as calculated from formula (**1**) and also values as estimated from the readings of the voltmeter on the tertiary coil.

As will be noted, with ascending values of air density and therefore critical voltage, there is an increasing difference between the values calculated from formula (**1**), and those estimated from the low-voltage readings. As stated earlier in the paper, the explanation lies in a voltage rise due to charging current taken by the capacity of the larger corona voltmeter, and the leakage reactance of the high-tension winding of the transformer, which is not proportionally reflected in the voltage at the terminals of the tertiary coil. The amount of this rise would evidently be greater, the greater the value of the charging current of the voltmeter tube; that is, the higher the value of the impressed voltage. The curve of the observed values, therefore, shows values lower than those actually reached at the high-tension terminals. In the case of the 50,000-volt instrument, owing to the very much smaller capacity, this influence, if present at all, was scarcely noticeable.

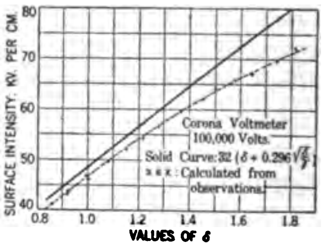


FIG. 5 — COMPARISON OF VOLTAGE AS INDICATED BY READING ON TERTIARY COIL WITH CALCULATED VALUES AT DIFFERENT DENSITIES OF AIR

The above results, therefore, with the larger instrument are not to be considered as an attempt at calibration. They show rather, that in applying a range of voltage and pressure to the instrument to test its value, a method which has been commonly relied on for indicating high-tension voltages in transformers is revealed as subject to large error. In fact, the observations as taken constitute a conspicuous example of the value of the corona voltmeter in checking the ratio of transformation between the tertiary coil and the high-tension winding of a transformer. The only open question is the accuracy of formula (**1**), and this formula, both as to the value of its constants, and the form in which the values are related, is agreed upon with only slight divergence among many experimenters.

Aside from all question of the accuracy of the above deductions the instrument has been carried through a range of voltage between 50,000 and 100,000 volts. Particular values of voltage as indicated by the instrument on the low-tension side, and by the appearance of corona, may be repeated as often as desired within a fraction of one per cent. If a suitable method of calibration can be devised, a calibration curve between the voltage and pressure may be drawn giving an absolute calibration of the instrument in terms of pressure and temperature.

Method of Measurement of Voltage

The instrument is susceptible of usage in two ways. (1) It may be set for a given voltage and the applied voltage gradually raised until the desired value is reached, as indicated by the instrument, or (2) with an unknown voltage applied to the terminals, the pressure in the tube may be gradually lowered until corona appears.

The first of these methods would be that commonly used in the testing of insulation. In applying this method the necessary operations are as follows: Read the temperature in the corona tube, take from a table or curve, calculated from the dimensions of the instrument, the value of pressure which, with the observed temperature, corresponds to the voltage required. Adjust the pressure to this value by means of a hand pressure and vacuum pump. Gradually raise the voltage from some lower value until the presence of corona is indicated by one of the methods already described.

Table V gives the values of pressure for the 50,000-volt instrument for voltages between 20,000 and 50,000 at temperatures between 10 deg. and 30 deg. cent. The values have been calculated as follows:

The inner tube having a diameter 9.51 cm., and the central rod a diameter of 0.396 cm., it may readily be shown that for a difference of potential V between the central conductor and the outer tube, the electric intensity at the surface of the central conductor is 1.593 V. The critical corona forming surface intensity as calculated is $32\,(\delta + 0.665\,\sqrt{\delta})$. Equating the two expressions and giving V any desired value, we obtain corresponding values of δ. Formula (2) gives the value of δ. Since p is the pressure in centimeters of mercury and t is the temperature in centigrade degrees, we at once obtain for any observed temperature, a pressure to which the tube may be adjusted in order to show corona at the particular voltage V for which p has been calculated. Obviously a series of curves can be drawn to take the place of the table if desired.

TABLE V.

PRESSURES IN CM. MERCURY, AT WHICH 50,000-VOLT CORONA VOLTMETER MUST BE SET TO INDICATE VARIOUS VALUES OF VOLTAGE AT DIFFERENT TEMPERATURES

Max. volts	Temperature, degrees centigrade																
	10°	15°	16°	17°	18°	19°	20°	21°	22°	23°	24°	25°	26°	27°	28°	29°	30°
20,000	37.2	37.8	38.0	38.1	38.2	38.4	38.5	38.6	38.7	38.9	39.0	39.2	39.3	39.4	39.5	39.7	39.8
25,000	49.8	50.7	50.9	51.0	51.2	51.4	51.6	51.8	52.0	52.1	52.3	52.5	52.7	52.8	53.0	53.2	53.3
30,000	63.0	64.2	64.4	64.6	64.8	65.1	65.3	65.5	65.7	66.0	66.2	66.4	66.7	66.8	67.1	67.3	67.5
35,000	76.2	77.5	77.8	78.0	78.3	78.6	78.9	79.2	79.4	79.7	80.0	80.2	80.5	80.8	81.0	81.3	81.6
40,000	90.3	91.9	92.2	92.6	92.8	93.2	93.5	93.8	94.2	94.5	94.8	95.1	95.4	95.7	96.0	96.4	96.7
45,000	103.8	105.7	106.0	106.4	106.8	107.2	107.5	107.9	108.2	108.7	109.0	109.3	109.7	110.0	110.4	110.8	111.2
50,000	118.1	120.2	120.6	121.0	121.4	121.9	122.3	122.8	123.2	123.6	124.0	124.4	124.8	125.2	125.6	126.0	126.5

In the second method mentioned, in which it is desired to measure the value of an unknown voltage, it is only necessary to run the pressure in the tube up to a value corresponding to a voltage known to be above that to be measured. The pressure may then be lowered rapidly by allowing the air to escape until corona appears. Having approximated the voltage by this means the pressure may be raised again above the value at which corona appears and then lowered as gradually as desirable in order to establish any particular degree of accuracy of observation. The table of pressures as described above may also be used in this case. In using this method it is inadvisable to lower the pressure by any considerable amount below the corona forming pressure. If this is done the volume of corona increases greatly, which may result in spark-over, and which if allowed to continue will make it necessary to clean the surface of the central conductor.

Pressures may be read if necessary on an ordinary mercury gage. If this is done it is also necessary to read the actual value of the atmospheric pressure. However, pressure gages are available which read absolute pressure directly, thus obviating the necessity of making the additional observation of atmospheric pressure.

Permanence of Calibration

It is well known that the condition of the surface of the central conductor as regards inequalities has an important bearing on the sharpness with which corona will appear. Small specks of dirt cause regions of high electric intensity which form sparks or point discharges at voltages below that corresponding to corona for the smooth conductor. In the use of the instrument as described, therefore, it is important that the central conductor should be carefully cleaned before insertion into the outer tube.

No special difficulty is met in so cleaning the surface of the wire that no preliminary sparks appear and so that the appearance of corona is not only sharply marked but may be repeated many times without a variation in the value of the corresponding voltage.

Time Tests. In order to test the possibility of the repetition of the readings, a series of observations were taken on a voltmeter differing somewhat from those described, extending over a period of five months. This voltmeter was open to the air and subjected only to atmospheric variations of the density.

Readings of the corona voltage were taken four or five times a week throughout the period, and showed when corrected for temperature and pressure a maximum deviation of six-tenths of one per cent from the calculated value. In this series of observations the wire was cleaned every day or two.

Permanence of Surface. In order to determine whether, and to what extent, the surface of the wire deteriorates with use, a number of tests were conducted on brass, nickel, and silver plated rods in addition to copper and steel rods commonly used. These tests consisted of the running of the instrument continuously with voltage slightly above the corona forming voltage, interrupting the run at intervals to see to what extent if any, the observed corona voltage had been lowered. One per cent excess voltage will result in a well formed corona, while five per cent excess gives one of marked volume and sound. The results were as follows:

Brass rod, 0.234 cm. diameter, primary voltage at start 61.2; run for 44 minutes at one per cent excess voltage with a number of intermediate readings. Corona voltage at end of test 61 volts, a change of about one-third of one per cent.

Nickel plated rod, 0.24 cm. diameter, voltage at start 61.5, run for 48 minutes, at one per cent excess voltage with intermediate readings, voltage at end 61.1 volts a decrease of less than two-thirds of one per cent.

Silver plated rod, 0.24 cm. diameter, corona voltage at start 61.5, run for 42 minutes and from one to 5 per cent excess voltage, with intermediate readings; corona voltage at end of test 61.5 volts, thus showing no deterioration.

The lowering of corona-forming voltage in the first two of these wires is in a great measure accounted for by the elevation in temperature in the tube due to the presence of corona and is not all due to deterioration of the surface. Thus in the case of the brass wire the temperature rose during the test from 23.9 to 25.2 deg. In the case of the nickel rod the temperature rose from 25.4 to 26.5 deg. In the case of the silver rod the rise in temperature was only from 26.9 to 27.3 deg. The conclusion from these tests therefore, is that the life of any polished conductor for the purpose of observing corona should be quite long for any material which does not oxidize freely in the air.

It is quite obvious that the design of the corona voltmeter as already described, permits the ready removal of the central conductor in case it should be suspected that the surface is not clean. The use of the telephone as a detector indicates very promptly the presence of any single points of discharge, such points having a characteristic sound in the telephone which is quite different and of a very much lower intensity than that corresponding to full corona.

DIMENSIONS

The dimensions of the corona voltmeter are apparently determined by three factors; the diameter of the corona tube, the length of this tube, and the requirements of insulation of the connection to the central conductor where it passes through the ends of the outer or pressure cylinder.

The diameter of the corona tube is largely determined by the maximum voltage. It has a simple well-known relation to the diameter of the inside conductor for any particular value of corona forming voltage. The most advantageous relation of these two diameters has not yet been determined. For example, no direct study has been made of the increase that is possible in the diameter of the central conductor before the formation of corona is coincident with that of spark-over. For smaller sizes of conductor it is possible to raise the voltage by considerable amount above that at which corona starts without resulting spark-over. With increasing diameter of conductor, however, this possible range above corona voltage becomes narrower. From a number of indirect observations, the present experiments seem to indicate that a ratio of diameters of the inner conductor to outer cylinder greater than 0.1 is apt to be attended by spark-over. These observations have largely determined the sizes of central conductor which have been used in the two instruments described above.

The length of the interior or corona cylinder may be considerably less in each case than those adopted in the two types of instrument as described. In order to determine the length absolutely necessary a number of experiments have been made on tubes of the same diameter but of varying lengths, under atmospheric conditions. With tubes 6.35 cm. in diameter and rods 0.317 cm. in diameter, observations of corona voltage were made with tubes of lengths four, two, one and five tenths, and one diameters in length. The observations show that with decreasing length there was no perceptible rise in the corona voltage until two diameters of length was reached. For this length there was an apparent rise in the corona voltage of about one-half of one per cent; for one and one-half diameters a rise of about one per cent, and for one diameter of length corona voltage was about three per cent higher than for tubes of lengths four or more diameters.

It should be noted, however, that the use of the galvanometer as the indicating instrument requires a longer inner tube in order to make available a sufficient amount of ionization for the deflection of an instrument of ordinary sensitivity. There are obvious advantages in the use of a galvanometer, and it is our opinion that on this account it is not advisable to attempt a corona tube shorter than three diameters.

The requirements of insulation of the leading-in conductors add the greatest proportion to the length required for the whole instrument. The conditions here are much the same as at the leading-in terminal bushings of a transformer. The inner end of such a bushing can be brought fairly close to the inside cylinder but must not disturb the distribution of the electric field within that cylinder nor introduce any regions of higher intensity outside the cylinder.

The observations on the two instruments as described indicate that it would not be possible to reduce the dimensions of the smaller type without limiting its range. The larger type, however, is unnecessarily large in every direction. The outer cylinder can be reduced somewhat in diameter as can also its length without modification of the interior corona cylinder and central conductor. The interior cylinder can also be reduced somewhat in length without seriously inpairing the accuracy of the reading of the indicating instrument. Apparently it should be possible to construct a corona voltmeter for 100,000 volts with an over all length of about two meters and a maximum outside diameter of 45 to 50 cm.

The question of the extreme reduction of the dimensions of instrument as well as that of direct calibration, can only be determined by further investigation. It is the hope of the authors to carry forward such investigations. The present paper has as its principal object to show that it is possible to construct and operate a voltmeter based on the corona principle, which possesses an absolute calibration, a wide range, a high degree of constancy, and several other advantages over existing instruments for the reading of high voltage. Thanks are extended to Dr. W. B. Kouwenhoven and Mr. W. S. Brown for their assistance with the oscillograms and in other particulars throughout the work.

SUMMARY

The following conclusions seem to be justified by the experiments which have been described:

1. An instrument making use of the appearance of corona as an indication of the maximum value of alternating voltage has been devised and constructed in two sizes for ranges 20,000 to 50,000 volts and 40,000 to 100,000 volts respectively.

2. The principle of operation depends on a natural constant and the calibration of the instrument is definitely determined by its dimensions. This calibration may be supplemented by calibration with any existing standards.

3. In setting for different voltages no alterations in dimensions nor other manipulation is necessary. Variations in setting require changes in air pressure only. The necessary changes may be effected with a hand pump.

4. Three, and if necessary, four means of observing the indications of the instrument are described. They may be used simultaneously, thus serving as checks upon each other.

5. No spark-over, nor arc, nor energy consumption occurs in the operation of the instrument.

6. No series resistance nor condensers are necessary to its operation.

7. Observations may be repeated rapidly and any number may be taken with one setting.

8. The calibration is within wide limits, independent of wave form and frequency. It is also independent of electrostatic influence of neighboring conductors and objects.

9. It is readily constructed in portable form.

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DISCUSSION ON "THE CORONA VOLTMETER" (WHITEHEAD-PULLEN), CLEVELAND, OHIO, JUNE 29, 1916. (SEE PROCEEDINGS FOR JUNE, 1916.)

L. W. Chubb: Dr. Whitehead's paper brings before us a new standard voltmeter which I think, if all the irregularities can be taken out of it, should displace the sphere gap as the primary standard. There is some doubt as to the practicability of the scheme for a working or secondary standard.

In the earlier papers Dr. Whitehead has given us an idea of the sharp indications of the appearence of corona and his Table I in the present paper certainly is an exhibit of remarkable observations by three different methods; and we are to understand that the fourth method also checks equally well. The structure has a great advantage over the sphere gap, in that it is independent of extraneous objects. Dirt specks, oil, etc., to a certain extent, affect both types of meters but the enclosed wire is less apt to have dirt settle on it.

Several other schemes for crest voltmeters have been described in the TRANSACTIONS and I have had experience with all of them, including the Ryan type of corona voltmeter. One of the old students of Prof. Ryan set up a cone-shaped corona voltmeter in the laboratory several years ago, and tests showed that the indication of transients was its greatest advantage. When a surge in voltage would come, you could see the corona shoot toward the large diameter end of the cone. As a practical instrument, however, and for indications of steady voltage it did not seem to be a success. In all our experience, the scheme which was reported in my paper at the midwinter convention last February, we still believe is the most practical and the best for all around testing.

I would like to ask Dr. Whitehead a few questions in regard to the paper. In the first place he speaks of not having an absolute method of calibration, and points out that the value of the instrument depends upon a calibration, which can be accepted universally. At the present time the calibration depends upon an empirical formula for the electric strength of air. I believe if the method of calibration is used, that was presented in our 1913 paper, the author will obtain great satisfaction, because it is an absolute method which works from the high-tension side and depends only on a current or potential standard and the physical dimensions of a guard-ring air-condenser.

The crest-factor calculations in the paper are carried out too far. I have found that it is very hard to calculate crest factors accurately with small amplitude oscillograms, and unless a voltage measuring method is used which derives voltage from the high-tension winding and corrects for the crest factor, there may be an appreciable error.

I was surprised at the inaccuracy of the tertiary coil in the tests. It was more than is usually to be expected and the difference between tertiary voltage and calculated voltage should have been checked by tests with parallel variable-load reactance. I would ask whether humidity has any effect on the results and whether there is any appreciable error in reading the air temperature inside of the tube It seems to me that the adiabatic expansion and compression, due to rapid change in pressure, will cause temperature changes which cannot be followed by a sluggish thermometer. I would suggest that a test be made to measure the same voltage, first by holding the voltage constant and letting out the air, then by holding the pressure constant and raising the voltage.

I would ask whether improper centering and vibration of the wire will affect the calibration, and whether the author would expect two voltmeters built to the same specifications with the usual workshop precision, to check accurately

Clayton H. Sharp: It seems clear to me that Dr. Whitehead has given us a splendid instrument, which, although the exact value of the constant may not be known, is superior to anything we have now for the purpose of standardizing high-voltage measurements. It may not make an everyday working instrument, perhaps for the same reason that the Siemens electrodynamometer is not a good working instrument; that is, that it requires an extra manipulation to give a reading, namely an adjustment of the pressure of the air. Hence it is not so quick as a direct-reading instrument might be, but as a standard instrument it seems to leave little to be desired, when once the correct value of the constant in the equation has been determined.

James R. Craighead; We should give Dr. Whitehead credit for the procedure he pursued in the development of this instrument. It was, in the first place, simply an instrument used in air, and without special standardization of conditions other than the exact dimensions of the physical apparatus. In its present form, it shows a degree of accuracy which should be amply satisfactory for its use as a standard, and the reason for that accuracy is the fact that the conditions have been so carefully controlled.

One further point—as soon as you inclose a high-voltage conductor and have corona develop, there is an ionization of the air, which is used as an indication of the actual development of corona. On some instruments of a somewhat similar character, I have observed that a certain amount of that ionization remains for a considerable period of time in the enclosed air, and I should like to ask Dr. Whitehead whether he has any difficulty in repeating immediately and frequently successive observations within this enclosed chamber without any device for ventilating in order to produce air that is free from ionization.

The point that Mr. Chubb mentioned in regard to the change of temperature that is associated with change of pressure, seems to me to be especially important. If we are to measure a voltage by the use of an air pressure, we are going to pump air at a definite temperature into a cylinder, and then a change of temperature will be going on within the cylinder to some extent as the pressure diminishes, and an accurate record of the temperature at the moment when the corona appears might be diffcult to obtain.

C. Francis Harding: The paper presented by Dr. Whitehead marks another signal advance toward the much desired primary standard for high-voltage measurement to supersede the needle and sphere spark gaps.

In analyzing this problem of the measurement of high voltages care should be exercised not to confuse methods suitable for fairly accurate practical measurements, with the requirements of a primary standard of voltage. A primary standard, if I understand the term aright, should be based upon fundamental laws, a knowledge of which, together with the constants of design of the apparatus will enable such a primary standard voltage to be reproduced under any local conditions which may exist. This is not possible with the needle spark gap and there is probably some error in the hypothesis and therefore in the values of calculated voltages for the sphere gap. Several investigators have pointed out the rather large errors possible, due to varying local conditions such as foreign matter upon the spheres, distorted electrostatic field between spheres, effects of varying air pressure, temperature, humidity, frequency, etc. Furthermore the present dual standard of needle and sphere gaps for use below and above 50 kv. respectively is particularly objectionable since the two standards can not readily be made to coincide at the transition point where both should be correct. Such a method gives only an instantaneous indication of the voltage and the measurement itself, by means of the spark-over, is quite likely to disturb the circuit to such an extent as to prevent the maintenance of the desired voltage in the circuit, not to mention the impossibility of a permanent indication of the same. Both spark-over methods, although valuable for practical tests are unsuited for use as permanent primary standards.

The application of a definite ratio of transformation either from a constant-potential transformer or from a voltmeter coil of a high-voltage transformer to the present primary standard of voltage has apparently been used for practical measurements with considerable accuracy. I do not see that one can ever hope to use it however as a high-voltage standard, since it is dependent upon the condition that this coil inclose the average flux of the secondary coils under all conditions of load and power factor. While this condition may be closely approximated by carefully locating the voltmeter coil, one would not feel safe in predetermining such a ratio from design data. There is no way to prove that such a calculation is accurate save by the spark gaps, and the latter have been in turn based upon the ratio method in the first place. In the paper under discussion considerable error has been reported for one particular placing of the coil. The speaker has found it necessary, in the determination of corona losses upon transmission lines, where the voltmeter coil was used as a convenient intermediate agent, to plot calibration curves between standard volts determined by the present sphere-gap standard, and voltmeter coil readings for each change of secondary connections. For example, the addition of 800 feet of No. 4 B & S transmission line with a 12-foot spacing will offer sufficient capacity at 180 kv. to cause the actual ratio curve to depart 8 per cent from the straight line calculated from the constant ratio which is accurate at lower voltages. In this transformer the voltmeter coil is made up in two parts, each of diameter of the average secondary coil and so placed as to inclose as nearly as can be predetermined the average flux of the secondary. This error is about the same as that reported by Dr. Whitehead for the voltage coil method with the capacity of the 100-kv. corona voltmeter in circuit.

In looking further for possible primary voltage standards it would seem logical to investigate the possibilities of making use of the force action in a uniform electrostatic field just as our low-voltage instruments make use of uniform electromagnetic fields. The former are quite as readily produced at high voltage as are the latter at low voltages.

In a written discussion of the paper on "Crest Voltmeters", the speaker outlined briefly some work by Messrs. Phelps, Wright and Holman carried on during the last two years at Purdue University upon the use of force action between parallel plates at high voltages, in which the theoretical calculated constant ratio between voltage and distance between plates for a constant force action was very closely checked in actual tests. This apparatus, constructed upon the principle of the Kelvin attracted disc electrometer, may have some possibilities as a primary standard for high voltages, although not suitable for use in a portable secondary voltmeter.

Another investigator, Mr. L. L. Bouton, also of Purdue University, has this year shown conclusively that there is little of value to be expected from an instrument based upon the attraction between metal spheres of large size, for, although test values can be reproduced more readily and are probably less influenced by local conditions than the spark gap, yet accurate theoretical determination of the field and the resulting force action between spheres is very difficult when the diameters of the spheres are large with respect to the distance between their centers.

The paper under discussion presents another apparently very fertile field for the study of possible high-voltage standards. Although many factors are involved which should and probably can be readily held constant in such an instrument, this apparatus has the advantage of several check readings for determining the critical voltage. It would seem also that if the dielectric strength of air under specified conditions were standardized, that this method of determining voltages would be entirely reproducible.

I wish to emphasize as forcibly as I may, the importance of the early study of this problem of high-voltage standards by the proper committee of the Institute. The use of high voltages has become so general that we must have something more definite to use as a reference, a standard which may be reproduced at any time with any local conditions, guaranteeing a test voltage determined by the use of proper constants calculated from the dimensions of the apparatus involved and the fundamental laws of the electric and magnetic circuits.

F. W. Peek, Jr.: I have heard a great many arguments for and against the various methods of measuring high voltages. It is generally a question of which method is most convenient and most adaptable to any given investigation. All of the methods discussed have their advantages and disadvantages. In investigating high voltages of extremely short duration, durations in the order of a millionth of a second, I have found the sphere gap necessary. When the sphere gap is properly used, it is not difficult to use it in that way, it will measure correctly a-c. voltages, d-c. voltages, and transient or lightning voltages. I will not say more about the measurement of transient voltages here, but will refer you to my paper read in San Francisco, September 1915. This paper also gives the characteristics of transient corona produced by voltages lasting only one-millionth of a second; it is possible to see this corona and to detect whether the wire is positive or negative.

Jacob Kunz: It is possible to add still another instrument to measure d-c. or a-c. voltages. Dr. Whitehead has used the electroscope, the galvanometer, and the telephone. It is possible still to add to those corona-measuring devices an instrument which directly indicates pressure, because as soon as the corona starts, either d-c. or a-c. corona, the pressure increases noticeably and measureably. It is very easy in the case of air with voltages only as high as 10,000 volts to get an instantaneous increase of the pressure to say 3 cm. of mercury. This new voltmeter, which is based on the increase of the pressure due to the corona itself, is very accurate, and we have found recently you can use this increase of pressure by means of an aneroid barometer to measure voltage or current; the positive corona current, at least being proportional to the increase of the pressure, so that by an aneroid barometer, one can also measure currents and potential differences.

This brings out a precaution which has been taken in this instrument of Dr. Whitehead's, namely, that it uses change of pressure in order to find the starting point of the corona, but when the corona starts, then the corona itself changes its pressure. There is a reaction of the pressure, as the corona increases the pressure itself increases, and if you keep the corona going, in a little while heat will be developed, which has to be taken into account also.

Concerning the constants of the formulas—we have thirty-two in the formula of Whitehead, and a different constant in the formula of Peek.

I think a careful investigation should be made into these constants, because Farwell found that these characteristic constants in the corona are distinctly different for positive and negative corona.

Then it has just been mentioned, that the a-c. corona for high frequency is different from the a-c. corona for low frequency, or d-c. corona; indeed, you can make experiments, and if you use d-c. corona and introduce only a little spark gap of a mm., or half a mm., then the visual phenomenon of the corona is entirely changed and the characteristics also are very much changed. So far as I understand Townsend and Watson, they always used spark gaps in connection with the corona, and through these spark gaps the nature of the visual corona is entirely changed; for instance, in a d-c. corona with the spark gap, the positive wire is surrounded by a uniform glow and the rest of the tube is dark. If a spark gap is introduced, however, the whole corona is filled with streams of light, which are separated from each other, and in some cases they are very uniform and the whole tube glows uniformly.

Corona assumes quite a different character, for instance, in the case of hydrogen. Experiments have been made in our laboratory on corona in hydrogen and other gases, and the characteristics between positive and negative corona are entirely different. They do not resemble each other—one is a continuous and the other is a discontinuous corona, and the negative corona appears in the form of beads, while the positive corona is uniform. In this case, the difference between positive and negative corona in hydrogen, is so great that the hydrogen corona tube can be used as a rectifier. We have been able to rectify voltages up to 10,000, and there is no reason why we should not be able to rectify 100,000 volts.

John B. Taylor: Can the method of determining corona formation by listening for sound in a telephone receiver be used when working with continuous voltage?

F. W. Peek Jr.: Some years ago we rectified by corona in air. A full description of this is given in an Institute discussion.

J. B. Whitehead: I think all of the speakers have agreed that our instrument has some promise as a standard. That was our chief object. Our feeling is also quite pronounced that it will also be a working standard, but we are quite satisfied at this time to find such a unanimity of feeling that there is here the possibility, at least, of an ultimate standard of high voltage.

As to the cone shaped wire mentioned first by Mr. Chubb and last by Dr. Lloyd. The cone shaped wire, in giving the direct scale, has this one difficulty—that the presence of corona causes a slight elevation of temperature. This slight elevation of temperature means that corona will appear at a lower voltage, so, consequently, if you use the cone shaped wire, even supposing you hit the actual voltage immediately by seeing the point along the length of the wire at which it comes out, that position will change almost at once. Corona on a vertical wire, is often seen to walk up the wire, owing to this cause, hence the difficulty of securing anything like permanence in the graded diameter.

As to the determination of peak factors, the general conditions under which our oscillograms were taken are described in the paper. A third decimal place has slipped in, as a result of taking an average of several values. I agree with Mr. Chubb that it is not possible to measure peak factors to the third decimal place. However, the gradual variation of the peak factor as described in the paper was quite obvious in our determinations, taken over a wide range. The comment is quite proper. The weakest point in the determination of maximum value readings of voltage from the low-tension side, is the oscillogram.

The transformer which we used was constructed before the engineers who are interested in the possibilities of the tertiary coil were quite as certain as to the accuracy attainable, as they are now. Having consulted them, they agree that the design of the transformer that we have, as regards the tertiary coil, could be greatly improved. My comments on that point are not intended in any sense to depreciate the present day value of the tertiary coil, as a means of measurement.

As regards the humidity inside of the tube, if you allow the air in a corona tube to expand very rapidly through an orifice, you will undoubtedly get cooling as you will everywhere in the rapid expansion of air, and you will also have condensation of moisture. In our experiments, this matter is readily taken care of by providing a large opening for the air and letting it out so slowly that you do not get appreciable cooling and condensation. By providing large enough openings, the air can be changed very readily, and you can get as uniform a distribution of temperature as you please. The temperature is measured with a thermometer inside. So far as we have been able to observe we have not found any indications that this is a serious difficulty—indeed, we have not observed it as a difficulty at all, we have never found anything other than a slow change of one or two degrees throughout the course of a full run.

The centering of the wire is purely a mechanical process. We have suitable templates for the inner tube of the voltmeter, as shown in the diagram, and these templates can be adjusted through the side hole which is large enough to get your hand in, and by looking into the side hole at right angles and shifting the template, it is easy to determine the centering. The final centering is done in the instruments we described at the ends. The holes through the insulators are large enough to give us quite three or four mm. in any direction, and this is found to meet the situation.

Mr. Craighead raises the question about ionization. Some of my earlier experiments convinced me at least, although not every one, that the normal ionization in the air has no effect on the beginning of corona. These experiments included the location of radio-active substances in the neighborhood, illuminating the wire for ultra-violet light, and other well known sources of ionization, so that there was no lowering of corona voltage.

On opening the corona voltmeter after prolonged use, there is very decided evidence of ozone. We have never been able to detect, however, any variation from the calculated values of corona.

With reference to Prof. Kunz's very interesting description of the use of the elevation of pressure as corona detector I hope he will present the results of his studies in that direction, so that we may have a complete account of them. I would like to call attention, however, to the fact that in the use of the corona voltmeter by which we read pressures to one-quarter of an mm.,—of course, we could read them more closely, but that is quite sufficient to give an accuracy of less than one-half per cent—we have never detected any increase in pressure due to the presence of corona. That does not mean Prof. Kunz has not found the increase of pressure, but we are working on the threshold appearance of corona where the increase of pressure is very small. It is very small because we have quite a large volume of air in the corona voltmeter, and it is only the initial appearance of corona; consequently there is a generation of but very few ions, considered with reference to the number of molecules in the whole volume of the system. The use of elevation of pressure as the result of corona would seem to me to be subject to this very limitation that he speaks of in the resulting temperature. Certainly we have found that if we carry the voltage above the corona-forming voltage, five or ten per cent above, so as to get a large corona, changes in temperature are immediately obvious, and consequently they would introduce error.

Prof. Kunz, I am sure, will be interested to hear that we have carried out some d-c. experiments during the past year, in which we have been able to get negative corona without the appearance of beads, and I believe that the negative corona without the appearance of the beads and localized spots is simply a question of constancy of circuit conditions and of clean surface. That is our conclusion. If you allow negative corona to remain any time, after awhile it will form into these beads, but there is no doubt that negative corona can be obtained without the localized sparks.

As to Mr. Taylor's question—the sound given out by the corona is not the note corresponding to the frequency of the circuit, it is entirely due, in my opinion, to indiscriminate snapping sparks over the minute irregularities of the surface of the wire, irregularities which cannot be gotten rid of, although we polish it to a very high degree. Therefore, although we have not before us, the account of our experiments on the sound of d-c. corona, I feel sure that the sound could be used there also.

Since the experiments reported in the paper, we have compared the corona voltmeter with the sphere-gap, as shown by Fig. 1. The upper solid curve is the calculated corona curve, using the formula of my work, namely 32, for the first constant, or 0.518 for the second. The long dash upper line is the curve of corona voltage as taken from Mr. Peek's formula, namely, 31 for the first, and the second constant is 0.54. The curves are plotted between kilovolts per centimeter at the surface of the wire, and the range of atmospheric change, affecting the whole range of the abscissa, is 10 or 15 cm. below atmosphere, to 45 or 50 cm. above atmosphere, so that this is a rather wide range of air

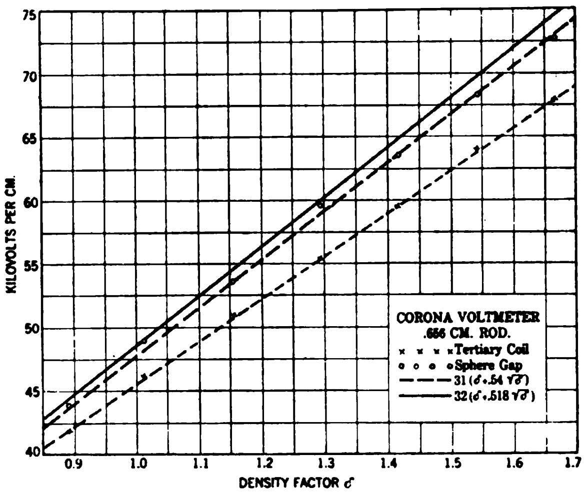


FIG. 1

density, and therefore the difference between Mr. Peek's constant and my own appears somewhat intensified.

Now, then, the lowest curve with the cross marks gives the observations on the tertiary coil of the transformer,

The tables shown in the paper give the accuracy with which the low-tension reading can be repeated, and the circles with the dots represent the sphere gap readings, all these measurements being taken on a 12.5-cm. sphere gap. The readings were taken as follows: We would set the pressure and gradually raise the voltage until corona appeared with the spark gap in parallel with the corona tube, set to a value which we knew was too great for spark-over. Keeping the pressure in the tube constant we would repeat over and over again the corona observation, closing the sphere gap by 1/100 mm. each time. Finally we came to a voltage value in which the sphere gap would let go just before we had the corona.

The interesting point about the curve, it seems to me, is that it shows that the calibration of the spark gap and Mr. Peek's corona values, are of course, coincident because they are based on the same standards and methods of measurement. The falling of the tertiary coil observations below these is entirely due to the construction of the tertiary coil. The variation of the spark-gap determination from the calculated curve would not ordinarily be considered great. I call attention to the irregularities of the gap readings as compared with those of the corona, as referred to their respective curves.

Presented at the 33d Annual Convention of the American Institute of Electrical Engineers, Cleveland, O., June 29, 1916.

THEORY OF PARALLEL GROUNDED WIRES AND PRODUCTION OF HIGH FREQUENCIES IN TRANSMISSION LINES

BY E. E. F. CREIGHTON

ABSTRACT OF PAPER

The overhead grounded wire is used for three purposes: lightning protection, mechanical support for towers, and a test circuit. The functions of the grounded wire are subdivided into at least four categories: First, the vertical grounded wire; second, the lightning rod extending above the ground; third the electrostatic induction in the horizontally situated wires, and fourth, electromagnetic induction.

The vertical wire prevents splitting of the poles. The lightning rod is of mooted desirability. The electrostatic induction for a given cloud on wires under various conditions is worked out in this paper. There is given also the protective values of overhead grounded wires in different positions and in different numbers. The effects of electromagnetic inductions have been taken into account. Theory is given to show that the grounded wire introduces into the main wave of induced lightning surge a superposed high frequency of electromagnetic induction.

The several factors to be taken into account in the process of determining the protective value of a grounded wire are as follows:

1. Strength of electric field in the neighborhood of the line wires.
2. The direction of the gathering charge in the cloud, that is the path of the discharge relative to the line, parallel or perpendicular to the line before it turns vertically downward to the earth.
3. The screening effect obtained by the use of several wires, with and without grounded wires.
4. The initial momentary potential induced on a wire at the instant the cloud discharges to earth.
5. An instant after the lightning discharge has taken place, the sudden increase in capacitance between the power wire and the adjacent parallel grounded wire.
6. The effect of the number and location of parallel grounded wires.
7. The effect of electromagnetic induction between the horizontal part of the grounded wire and the parallel power wires, in which the energy of the lightning charge on the grounded wire is more or less transferred to the power wire, instead of being dissipated in the earth. High frequencies are produced in this transformation.
8. The gradual transference of the charge which travels along the power wire to the successive sections of the grounded wire and its dissipation in the earth.

A cloud charge is chosen of such value as to produce corona potential on a No. 000 B. & S. wire, strung at a height of 1000 cm. (33 ft.) above the surface of the earth. This storm cloud is used as a standard in all cases for comparison. The induced voltage on any wire by lightning is directly proportional to the height of the wire above the earth. The induced quantity is not quite proportional due to the variations in the capacitance of the wire at different heights. For heights between 30 and 60 ft. (9.1 and 18.2 m.), however the quantity can be considered as approximately proportional to the height.

The quantity induced on the wire is only slightly affected by the diameter of the wire. This leads to the conclusion that a small grounded wire is nearly as effective as a more expensive large one.

The theory is given to show that even on a non-grounded circuit a charge can be induced by a cloud and produce practically the same potentials as when the circuit is grounded. The only exception is that of circuits of short length.

The instantaneous value of induced potential on a circuit is independent of the number of wires used. Using a greater number of wires reduces the quantity per wire but does not decrease the instantaneous value of the potential at the instant the cloud discharges to earth. Even the grounded wire may take the full potential and give no relief at the first instant. Whether it does or not depends upon how quickly the discharge takes place from cloud to earth, and how frequently along the line the grounded wire is earthed. There is, however, a screening of electrical energy by increasing the number of power wires. In other words, each surge has less energy although it has not initially less potential.

There is given a table of the reduction of quantity per wire as the wires increase in number from one to seven.

The two factors in the electrostatic protection of the overhead grounded wire are screening and increase of capacitance of line wires. The presence of the grounded wire reduces the quantity induced on each of the power wires and incidentally after the cloud discharges to earth the grounded wire takes over part of the charge from the power wires and in taking it the capacitance of each power wire is increased. Therefore, with the same quantity of electricity the potential is reduced by this increase in capacitance.

The protection afforded by one parallel grounded wire can be expressed as a very simple equation. The protection for each power wire can be calculated entirely independent of how many there are.

The general equation to express the protection afforded by two parallel grounded wires is more complex but if the two grounded wires are placed far apart their protective values can, with only a small error, be calculated independently.

As the charge runs to earth on the grounded wire at the instant the cloud discharges, it induces on the line wire by electromagnetic induction a considerable voltage in the usual conditions of the overhead grounded wire with low resistance in the earth connections and from which part of the protection afforded by the grounded wire is lost by the fact that the energy oscillates in the ground circuit and is transferred to the power wire.

The natural frequency of this wave train is found by multiplying 183,000 miles (300,000 km.) per second by the number of earth connections per mile of grounded wire. The frequency is usually over a million cycles per second.

Traveling waves are more or less absorbed as they pass each successive loop of the grounded wire, according to the value of the resistance of earth connection. In any case an endeavor should be made to have the resistance in the earth connection somewhere near the critical damping value. This prevents initial oscillations in the ground circuit and also increases the rate of absorption of a traveling wave.

A slight amount of high frequency is produced in a circuit by transposition of power wires. This may be of the order of 2 per cent to 5 per cent of the main voltage.

The general deductions for practical use taken from the theory given are as follows: From a theoretical standpoint a single grounded wire should be placed as near as practicable to the power wire in order to get the greatest electrostatic protection. The grounded wires are a little more effective when placed above a power wire than when placed below it.

In installing overhead grounded wires the greatest advantage can be obtained by keeping the overhead grounded wires as far apart as possible, that is to say, installed, as far as practicable on opposite sides of the power wires. The protective value of the second wire will then have its full maximum possible value. Also from the electromagnetic standpoint, the two wires should be placed, so far as practicable, on opposite sides of a power wire in order to reduce to a minimum the transfer of surge energy to the power wire.

The most practicable condition of protection by four grounded wires is to use the four wires in a rectangular formation which gives the widest separation. Naturally two will be above the power wires and the other two will be either below or at each side about on a level with the two lowest power wires. The mechanical conditions of installation will dictate where these wires will be hung and it is necessary to follow the rule to make the distances between the several grounded wires as great as the conditions will permit and still keep the grounded wires as near a power wire as safe mechanical clearance will justify.

I—Introduction

THE OBJECT of this paper is several-fold; primarily it is an endeavor to place the practise of the use of overhead grounded wires on a firmer engineering footing and to discuss the conditions of line construction which cause and suppress high-frequency surges. The desire is to present the material so that the conditions of installation may be made to give the greatest degree of protection with a minimum of undesirable reaction and lowest cost.

In the mathematical analysis there is no so-called higher mathematics. The difficulties involved are due simply to the extremely long simultaneous algebraic equations. It is a matter of labor more than skill. The basis of this analytical work was given by Maxwell, Kelvin and Heavyside and their familiar notation is used. Since most engineers of power systems are too occupied with other problems to juggle involved logarithmic equations, all this analysis is separated from the main body of the paper and is given only as a means of checking up the writer's conclusions. In most cases the analysis of the value of a grounded wire reduces to very simple formulas, due to the cancellation of many factors in the long, involved equations.

Many operating engineers have noted high potentials across choke coils of low inductance and other phenomena, which point directly to the presence of extremely high frequencies in traveling waves on the line. An endeavor has been made to analyze the possible sources of high frequency. There are at least four of these sources.

The earliest use of the overhead grounded wire is somewhat hidden in obscurity, due to the fact that the engineers of that date were not prolific in writing up their engineering feats. The earliest application of parallel grounded wires that the writer has been able to get track of was made by Mr. C. C. Chesney on the original polyphase transmission plant at Housatonic, Mass. in 1891. It seems that the next plant to use it was the Montreal Light, Heat and Power Co. transmitting power from Shambley Falls to Montreal. The overhead grounded wire gradually found its way into practise by reason of the strong endorsements of a number of engineers, notably among whom was Dr. C. P. Steinmetz. The use of overhead grounded wire was a mooted problem among engineers over a period of many years.

II—Analysis of the Uses of the Overhead Grounded Wire

The first question to settle in discussing the overhead grounded wire is its purpose. Its primary use is of course for protection against lightning and it is recognized also as a strengthening support between towers. Mr. J. Lawson has recently stated that the grounded wire on a wooden pole line is used also as a means of testing for defective insulators. The three recognized uses then are: lightning protection, mechanical support for towers and poles, and a test circuit. The use which is of interest in the following discussion is solely that as a protector against electrical and magnetic disturbances in the surrounding atmosphere.

Even as a protector against lightning the function of the grounded wires may be subdivided into at least four categories: First, the vertical grounding wire, second, a lightning rod extending above the line, third, electrostatic induction in the horizontally situated wires, and fourth, electromagnetic induction.

III—First Category—Protection Against the Splitting of Poles by the Vertical Conductor which at One End Is Buried in the Earth and Runs the Height of the Pole

This part of the grounded wire system has been used from early times in telegraph construction quite independent of the horizontal grounded wire which parallels the power wire, and is still standard practise for telephone and telegraph circuits. Every fifth wooden pole is protected this way. As such, this vertical grounding wire is a protection not against electrostatic induction or electromagnetic induction, but against the damaging effect on wooden poles of a direct bolt of lightning. This vertical grounding wire performs the same function when used in combination with the horizontal wire and at the same time it is an essential part of the horizontal wire in protecting against induction by acting as an earthing contact to the horizontal wire. How frequently along the line these vertical earthing wires should be used is a question of importance to be discussed as the subject is developed.

IV—Second Category—A Lightning Conductor Extending Above the Top of the Pole or Tower Is Designed to Act as an Electrode to the Bolt from the Cloud

The value of this rod lies in the possibility of its greater height keeping the arc flame from being blown between the phases of the power wires, which would cause a short circuit. Used as such, it has nothing to do with the electrostatic induction and functions only in cases of direct stroke on the line. To the writer's knowledge its value has never been definitely determined by calculations, experimentation, or use. Its use has not been very great. The extremely intense electric force and potential gradient in the path of the direct stroke of lightning brings the value of the lightning rod into question. Even if the rod is high enough to keep the ionized flame away from the power wires it must yet be determined if the intensity of electric field, induced on the power wires adjacent to the lower end of this lightning rod, is not great enough to cause a side flash from the rod to the power wires, on account of the so-called isolated capacitance of the power wires. With a power wire supported on an insulator having a grounded metal pin it seems safe to hazard a guess that there will be a side flash which would either puncture the insulator or cause a flash around the skirts. The puncture distance is of the order of one inch only, and the flashover distance is of the order of one foot (30.4 cm.) Furthermore, the equivalent sphere gap of this flashover distance, due to the effect known as creepage spark over the surface of the insulator, is only of the order of a few inches at best.

When a wooden cross-arm is used and when the power wires are highly insulated by a string of many suspension disks the chances of side-flash are greatly reduced and consequently the lightning rod comes into the realm where its practicability and use are worthy of consideration and debate.

An endeavor is here made to enumerate the elemental factors involved. There are two conditions to be avoided:

First, to keep conducting arc vapors of the direct lightning stroke away from the power wires.

Second, to prevent a bolt from striking midway between poles. Cases are known where such strokes have melted the wires in two, even where the line was yet under construction and grounded at some distance from the point of the lightning stroke.

Who is to say how far down on the lightning rod the crater of the arc will extend? Taking Dr. C. P. Steinmetz' estimate of 10,000 amperes for the average current in a lightning discharge, will the crater, during its brief life, extend below the point of the rod? The heated gases will tend to rise. The heavier the wind the more rapid is the arc flame broken up and cooled. Perhaps some of the many photographs of lightning may throw some light on this problem.

The protection against direct bolts striking the wire between poles may be determined roughly by the following methods: First, for a wire supported on pin-type insulators on wooden poles, the wire may be assumed roughly to follow the arc of a circle, the center of which may be determined. It may be assumed that if the lightning strikes well into this imaginary sector the chances of its turning and reaching the pole are rather remote. Second, if a lightning rod is used or the wires are underhung by suspension insulators, the chances of a lightning stroke reaching the wire rather than the tower or lightning rod are very much lessened. Fig. 1 is drawn on the basis of making the distances from the tip of the tower and the nearest point on the wire equal. The higher the rod or tower above the line, the less the chance of a stroke reaching the line wire, other things being equal. The expression, "other things being equal" is intended to take into account the fact that a lightning discharge does not necessarily take the shortest path to the nearest object, be it earth or an adjacent cloud. The location of the electric stress depends primarily on the accidental location of condensation of moisture in the atmosphere. Otherwise, if there is no free electricity given off in the atmosphere, the discharge will take place over the shortest path between electrodes.

While this method is admittedly crude, it is the only one available to give a comparison of the immunity of different constructions. By its use some idea can be gained of the advantages of lightning rods and the underhung construction. The evident dangers from a stroke reaching the line is that of burning the wire in two and letting it fall to the ground.

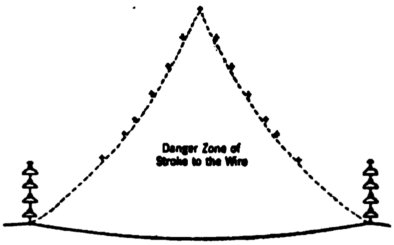


FIG. 1

If lightning gets inside the danger zone shown it is more likely to strike the wire than the tower. The curve is drawn on the basis of equal distances between the insulator and the wire. Direct strokes on the wire may fuse it in two.

With a string of six disks and the midpoint of a 500-foot span of wire 30 feet below the top of the tower the peak of the sector is 1050 feet above the midpoint of the span. With a pin-type insulator, a span of 100 feet and a sag of 2 feet, the peak of the sector is 650 feet above the midpoint of the span of wire. A 6-foot lightning rod added to the latter case lowers the peak of the sector to 160 feet and bands inward as shown in the above figure.

Should a lightning rod be sharp pointed? The early work done by Dr. Steinmetz on corona of needle points and later the work of Mr. F. W. Peek and others on corona would seem to indicate that the sharp end would have no particular value. Induced potentials of corona value often occur during storms. The formation of corona gives immediately the equivalent of a blunt end. The relief of the atmosphere by the discharge of corona is apparently too local and of such a small part of the volume of the electrostatic field of the atmosphere above the line to decrease appreciably the energy of a lightning stroke.

These questions are still in the speculative field and must be left, as refinements, to be cleared up by later work. The rest of the subject is of more importance at present and a solution is more definitely in sight.

V—General Problems of the Parallel Grounded Wire

There are several factors to be taken into account in the process of determining the protective value of the grounded wire.

1. Strength of electric field in the neighborhood of the line wires.

2. The direction of the gathering charge in the cloud, that is, the path of the discharge relative to the line, parallel or perpendicular to the line before it turns vertically downward to the earth.

3. The screening effect obtained by the use of several wires, with and without grounded wires.

4. The initial momentary potential induced on a wire at the instant the cloud discharges to earth.

5. An instant after the lightning discharge has taken place, the sudden increase in capacitance between the power wire and the adjacent parallel grounded wire.

6. The effect of the number and location of parallel grounded wires.

7. The effect of electromagnetic induction between the horizontal part of the grounded wire and the parallel power wires, in which the energy of the lightning charge on the grounded wire is more or less transferred to the power wire, instead of being dissipated in the earth. High frequencies are produced in this transformation.

8. The gradual transference of the charge which travels along the power wire to the successive sections of the grounded wire and its dissipation in the earth.

VI—Getting a Reasonable Mathematical Cloud

In the mathematical analysis of the electrostatic phenomena only the simplest forms,—such as cylinders, spheres, ellipses,—lend themselves to a practicable solution. The limitless variations in the forms of storm clouds make it impossible to select a form which might be considered the average for a thundercloud. Therefore it is necessary to turn from the cloud to the local electric field near the earth which is, after all, the center of interest. At the surface of the earth all forms of clouds give one common characteristic, namely a fairly uniform, perpendicular directed electric force over a limited area. It is assumed at present that the surface of the earth is smooth. In making the mathematical analysis we are, therefore, privileged to choose any form of cloud that gives this uniformity of field near the earth. Since we are to study first the electrostatic induction on overhead wires it is natural to choose, as a matter of simplification, a cylindrical cloud parallel to the line. In the early study, lengths of wire only one centimeter long will be dealt with and therefore over many centimeters any sort of a cloud can be considered cylindrical.

In any cylindrical conductor from which a charge of electricity emanates there is a central point where all the lines of force would meet if they were extended everywhere through the surface of the cylinder. Mathematically this point is well-known as the inverse point of a circle. Electrically it is better described as the apex of charge. The apex of charge is that point which, if all the charge were concentrated there, would give the same effect as it does distributed over the surface.

It is recognized that a cloud is not a good conductor but due to its mobility to the movement of electricity by brush discharge, it is assumed that the cloud will act like a cylinder of equal dimensions. Since this does not affect the distribution of field near the surface of the earth it seems a permissible assumption to make and is a great convenience in making calculations. (Fig. 2)

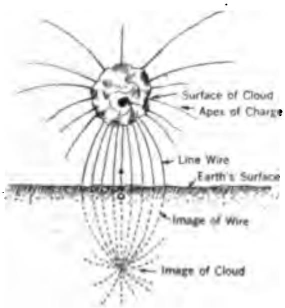


FIG. 2

Cloud of cylindrical cross-section, its electric field, its image, and a line wire in the field.

The apex of charge of the cloud will be found and calculations will be made assuming that the charge of the cloud is concentrated along this apex of charge as if it were a conducting wire parallel to the line wires.

VII—Choice of the Height of a Cloud

In absolute measure, the first effect of an increase in the height of a cloud would tend to decrease the electric force, and consequently electric induction, on overhead wires. An increase in the total charge on the cloud increases the quantity induced on the line wires. All we can say at present is that actual clouds will cause more or less severe induction on the overhead wires and let it rest at that. The object we have in view is to choose a height and dimensions of a cloud such as to give a uniform field in the neighborhood of the power wires. If the apex of the cloud is a few times as high as the line wires, it is found sufficient. A height of 55,000 cm. is chosen, however, for the position of the apex of the charge of the cloud. This value will be retained as a standard of reference for all future calculations.

VIII—Choice of a Given Charge on a Cloud for Use in Making Comparative Calculations of Protection Which May Be Expeced from Parallel Grounded Wires—and Other Data

A reasonable cloud charge is chosen arbitrarily as one which will induce a charge on a single overhead wire of corona intensity. It is found that such a cloud charge with its apex at 55,000 cm. height can be made to give very mild intensities of charge or potential gradients in the cloud itself, and such a cloud seems satisfactory enough as a basis of comparing induced charges on line wires.

All calculations are made in the absolute system of units. Anomalously, the practical system is impracticable.

An overhead wire of a usual radius of 0.5 cm. (about 3/8 in. in diameter, approximately No. 000 B. & S.) will have a critical corona gradient of potential at its surface when the charge is about 25 statcoulombs per centimeter length of wire (0.001342 coulomb per mile.*) Placing this wire at a height of 1000 cm. above the surface of the earth calls for a charge of 5700 statcoulombs per centimeter length of the assumed cylindrical cloud, to bring the grounded wire to the condition of corona. In all future calculations this constant cloud charge will be used.

One other assumed dimension is made, namely 10,000 cm. from the apex of charge in the cloud to the lower surface of the cloud. The assumed and calculated factors are given in the following list:

Apex of charge of the cloud, 55,000 cm. (1804 ft.) above earth.

Radial distance apex to surfaces, 10,000 cm. (328 ft.)

Height of wire used as standard of comparison, 1000 cm. above the surface of the earth (33 ft.)

Quantity of electricity induced on this line wire, 25 statcoulombs per centimeter length of wire (0.001342 coulomb per mile).

Quantity of electricity in the cloud, 5700 statcoulombs per centimeter length of the cylindrical cloud (0.306 coulomb per mile).

Potential at the surface of the cloud, 26,224 statvolts (7,867,200 volts).

Potential gradient at the lower surface of the cloud, 1.254 statvolts per centimeter of vertical distance (376.2 volts per centimeter). The gradient to produce corona is nearly 100 times as great, *i. e.* 30,000 volts per centimeter. Expressed in inches and feet, the potential gradient is 956 volts per inch and 11,472 volts per ft.

The field intensity at the surface of the earth is 0.4147 dyne, and correspondingly the potential gradient is 0.4147 statvolts per centimeter. (124.4 volts per centimeter = 3800 volts per ft.)

---

*$f = \frac{2q}{r} q = \frac{fr}{2} = \frac{100 \times 1/2}{2} = 25$

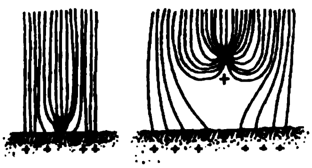
Dielectric displacement at the surface of the cloud is 0.1 statcoulomb per square centimeter of cross-section of the field.

Dielectric displacement at the surface of the earth directly under the cloud is 0.033 statcoulomb per square centimeter of earth surface.

NOTE: The undisturbed field intensity, potential gradient, and dielectric displacement at a height above the surface of the earth corresponding to line wire heights are sensibly the same as the values given above for the surface of the earth. Therefore, over the range of height corresponding to the usual height of a line wire the potential may be obtained, theroetically, by calculating the product of the height and potential gradient (V = centimeter height $\times$ 0.4147). The general relations are shown in Fig. 2. The calculations are made by equations (1) and (2) in the mathematical section.

IX—THE INDUCED CHARGE ON A SINGLE WIRE AT VARIOUS HEIGHTS FROM THE EARTH

The value of induced charge, initally at zero potential, is the second step in the determination of the voltage on the line which will suddenly appear when the cloud discharges to earth and sets free the bound charge on the line. We have just noted in the previous paragraph that the inducing potential is proportional to the height above the earth. The induced quantity at increasing heights does not, however, follow in direct proportion due to the change in capacitance of the wire.



FIGS. 3 and 4

Illustration of the cross-section of the electric field in the neighborhood of a wire, Fig. 3 on the ground and Fig. 4 in the air. The latter gathers in the field from each side nearly in proportion to its height.

Above a height of 1000 cm. (33 ft.) the increase in the quantity of electricity induced is almost a linear relation to the height of the line. This law holds up to and somewhat beyond 4000 cm. At less heights than 100 cm. the charge falls off more rapidly on a slightly curved line. The actual values are given in Table I, 3d column. These quantities are obtained by a solution of equation.

$$V_1 = 0 = \left(4.6 \log_{10} \frac{m_{11}}{r_1} \right) q_1 - \left(4.6 \log_{10} \frac{m_{c1}}{r_{c1}} \right) q_c$$

Whence—

$$q_1 = \left(\log_{10} \frac{m_{c1}}{r_{c1}} \frac{r_1}{m_{11}} \right) q_c$$

At 1000 cm. high, we have assumed a charge of 25 statcoulombs per centimeter length of the wire. At 2000 cm. high the induction would be 46.4 statcoulombs per centimeter length of wire, using the same inducing charge in the storm cloud. At 4000 cm. high, the wire would have induced on it 85.7 statcoulombs per centimeter length of it. Fourteen different heights are given in Table I, which also gives the quantity on the wire as a fraction of the total charge in the cloud. For example, at 1000 cm., the charge on the wire is 0.00439 part of the charge in the cloud.

There is given also in the table the total width of electric field that is gathered in by the wire. For example, the wire at 1000 cm. (33 ft.) gathers in the field from each side for a distance of 379 cm. (12.4 ft.), making a total width of 758 cm. (24.9 ft.). This electric field would normally go straight to the earth but due to the presence of the grounded wire is drawn toward the wire and a large part of it passes through the horizontal plane of the wire and is looped back up as is shown in Fig. 4.

At a height of 2000 cm. (65.6 ft.) the overhead grounded wire draws a field in from each side from a distance of 704 cm. (23.1 ft.).

A more satisfactory analysis of what takes place when a grounded wire is raised to different heights above the earth is shown in the two sketches, Figs. 3 and 4, which depict values taken from the table.

If a bare wire is lying on the ground (Fig. 3), it will take an electric charge which is proportional to about half its superficial area. The earth itself has a charge of 0.033 statcoulomb per square centimeter due to the charge of the cloud. Therefore, the charge on the wire lying on the ground will be of this order. When the wire is raised off the surface of the earth, as is shown in Fig. 4, a few of the lines near the wire which before found an easier path to the earth, now find a shorter path by bending around to the wire. The lines of force just beyond this width find a more desirable path to the ground than to the wire but due to the removal of part of the electric field directly underneath the wire these lines are bent under the wire in their path to earth.

The width of field drawn into the wire is obtained by dividing the charge emanating from the wire by the number of statcoulombs of displacement per square centimeter, due to the cloud.

Table I gives the heights of wire, fraction of the cloud charge which ends on the wire, quantity statcoulombs per centimeter length of wire, percentage of same referred to a wire at 1000 cm. height, the width of the field drawn into the wire at the height given, atmospheric quantity is 0.033 statcoulombs per centimeter and the potential gradient is 0.4147 statvolt per centimeter.

TABLE I.

Height of wire dia. 1 cm.	Part of cloud charge on wire	Stat-co lombs quantity per cm. length of wire	Per cent of quantity at height of wire of 1000 cm.	Width of field picked up by wire, cm.	Atmospheric potential at height given	
					Statvolts	Kilovolts
100 cm.	0.000633	3.610	14.4	119.5	41.47	12.44
200 cm.	0.001085	6.180	24.7	187.5	82.94	24.882
400 cm.	0.00196	11.164	44.6	338.8	165.88	49.764
800 cm.	0.00360	20.535	82.1	623.0	331.76	99.528
1000 cm.	0.00438	25.000	100.	758	414.7	124.4
1100 cm.	0.00476	27.170	108.7	824	456.17	136.85
1200 cm.	0.00514	29.277	117.1	888.	497.64	149.29
1600 cm.	0.00663	37.821	151.3	1148	663.52	199.056
2000 cm.	0.00815	46.422	185.7	1410	829.4	248.82
2400 cm.	0.00950	54.169	216.7	1642	995.28	298.58
2800 cm.	0.01090	62.200	248.8	1887	1161.16	348.348
3200 cm.	0.01235	70.516	282.1	2140	1327.04	398.112
3600 cm.	0.01370	78.092	312.4	2370	1492.92	447.876
4000 cm.	0.01502	85.668	342.7	2600	1658.8	497.64

X—The Induced Charge on a Single Overhead Wire as Affected by Its Size

As a convenient size for reference a diameter of one cm. for the overhead wire has been chosen and on this is induced 25 statcoulombs per centimeter length of wire (0.001342 coulomb per mile).

The first step will be to reduce the size of wire. As a rough approximation, take one strand of a seven-stranded cable and let us assume an equivalent diameter of one-third which is a radius of 1/6 cm. This wire will have induced on it by the storm cloud 22.1 statcoulombs which is 88 per cent of the quantity induced on the wire of one cm. diameter. The reduction then in the weight of the wire approximately to 1/7 has reduced the quantity of electricity drawn in by the overhead grounded wire by only 12 per cent. This is a good illustration of the slight effect that the size of the overhead wire has in gathering in the electric field. The same statement is true for sizes of wire larger than the one of diameter of one cm. If the weight of the wire is increased four times, that is to say, with an increase in the diameter from one cm. to two cm. the quantity of electricity terminating on the wire increases only 10 per cent. If the weight of the wire is increased sixteen times, which corresponds to an increase in the diameter from one cm. to 4 cm., the quantity of electricity terminating on this wire from the same storm cloud will be only 20 per cent greater if the weight of the wire is increased 64 times, which corresponds to an increase in the diameter from one cm. to eight cm., the quantity of electricity terminating on this wire will be only 33.6 per cent greater.

We may conclude from these data that calculations of electrostatic induction made for a wire of 0.5 cm. radius will give approximations for all other wires of usual practise.

INDUCING A CHARGE ON AN OVERHEAD WIRE WHICH IS NOT GROUNDED

From experiences in the laboratory in electrostatic induction such as the electrophorus, where it is necessary to ground the metal plate while it is near the charged wax plate in order to get it to take a charge, it is sometimes erroneously assumed that it is necessary to have an overhead wire grounded somewhere in order likewise to get it to take a charge from cloud induction. Contrary to this assumption, it may be stated that, in general, a system with a non-grounded neutral and absolutely no leakage over the insulators charges up with about the same quantity under the storm cloud as a system with a grounded neutral. The exceptional case is the short length of circuit.

Laboratory experience may give inadequate conceptions of the conditions outdoors and the local characteristic of a cloud lightning. It is not a question of how many square miles the storm cloud covers but only what extent of electrostatic field between cloud and earth is relieved by the lightning stroke. We are accustomed to seeing the visible part of the streak a mile or so long only. If the streak in the cloud is parallel to the transmission line, relief over a corresponding length is given to the charge induced on the line wires. But the transmission wires extend miles beyond this influence and it is the capacitance of wire to ground in the extended lengths not directly under the influence of the storm cloud which allows a non-grounded wire to take an induced charge.

Fig. 5 shows a short length of wire not extending beyond the field of the cloud. The wire takes the potential of the air at the same height. The corresponding d-c. stress is thrown on the insulation of the apparatus until the lightning stroke takes place. After the lightning stroke there is no charge on the line, and the potential of the line wire returns to normal without the presence of the usual traveling waves. For the traveling wave there has been substituted a d-c. stress over a period of time depending on the rapidity of formation of the storm cloud. Leakage over the insulators will enter, of course, to give the line more or less of a charge. There will be a momentary oscillation between line and apparatus.

Now turning to the more usual condition of a non-grounded circuit, Fig. 6 shows how the cloud induces a charge under it without leakage to ground. The large part of the line not under the cloud acts as a condenser of large capacitance which absorbs

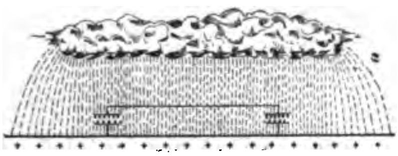


FIG. 5

Illustration of a short line under a long cloud. This line can become charged by leakage to ground only.

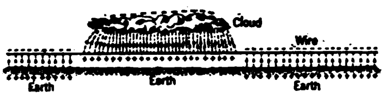


FIG. 6

Illustration of a long line under a short cloud. This line can become charged without any leakage of current to ground, that is to say, without any grounding.

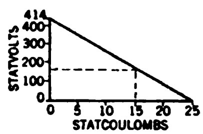


FIG. 7

The relations between induced quantity and potential on a non-grounded line wire. [000 B. & S. wire, 1000 cm. (33 ft.) high and a field of 0.414 statvolt per cm. (potential gradient.)]

the relatively small quantity induced by the cloud without causing much rise in line potential. $[V = Q \div C]$ The relations between the induced quantity and potential on the line wire are somewhat unusual. When the quantity is zero the induced potential (by the assumed cloud) is 414.7 statvolts. On the other hand, when the potential is zero, that is to say, the wire is grounded, the quantity is 25 statcoulombs. The intermediate conditions are shown by the straight line in Fig. 7.

$$V + 16.6q = 414.7$$

For different relative lengths of line under and not under the cloud the following conditions hold: If there is one mile under the cloud and nine miles of line not under, the potential of the wire will be 41.47 statvolts, $[1 \div (9 + 1)]414.7$. The quantity will then be $0.9 \times 25 = 22.5$ statcoulombs.

If, again, the relative lengths are two miles and 98 miles, the induced potential will be 2 per cent of 414.7 = 8.3 statvolts and the induced quantity will be 98 per cent of 25 = 24.5 statcoulombs.

Now, when the cloud discharge takes place there are two traveling waves, namely, the wave due to the concentrated charge under the cloud, and the wave due to the distributed charge throughout the rest of line and coils of the apparatus. These waves move in opposite directions and, since they are of opposite signs of electricity, as the concentrated wave passes through the distributed wave it will lose its potential in proportion to the cancellation of quantity.

It should be noted that the distributed charge has a quantity located down in the coils of generators and transformers depending on the local capacitance of the coils to the earth. After the cloud discharge, this lightning is inside the apparatus and must get out. In so doing it must bump into the inductance of each adjacent coil and be reflected more or less. Incidentally, this is a source of high-frequency oscillations. An attempt is made to represent these conditions in Fig. 8.

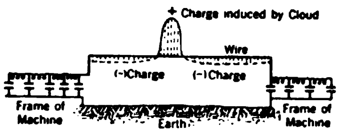


FIG. 8

The shaded parts on the overhead line shows the location of the two separated charges. The coils and condensers at the end of the line represent the conditions in a generator or transformer. Each coil is charged as a condenser by the lightning cloud.

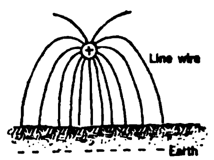


FIG. 9

The field of the induced charge on a line wire at the instant after the storm cloud discharges to earth.

FUNDAMENTAL LAW OF INSTANTANEOUS POTENTIAL AND QUANTITY IN CASES OF INDUCTION

It is purposed to show the simple method of obtaining the potential after the lightning discharge has turned free the previously bound charge on the line. To do this the movement of electricity in the cloud at the beginning and during the discharge of the lightning will not be considered now, but will be the subject of a later paragraph. As a further simplification the wire will be assumed grounded through either a resistance or inductance, so that its potential may be considered zero during the period of electrostatic induction.

At 1000 cm. up from the surface of the earth, the chosen cloud produces 414.7 statvolts (124,410 volts). A grounded No. 000 wire (one cm. diameter) at this height will take a charge of 25 statcoulombs by electrostatic induction. When the cloud discharges, the field which extends between wire and cloud will suddenly flop over (with more or less oscillation according to the nature of the lightning bolt) and appear as a field between wire and ground. The bound charge has been shown already in Fig. 4. The freed charge is shown in Fig. 9.

The potential will be given by the equation $V = Q \div C$ where Q is the quantity per unit length and C is the corresponding capacitance between wire and ground per unit length.

The object of this paragraph is to point out that to obtain the final potential rise of the wire it is unnecessary to calculate either the induced quantity or the capacitance of the wire. The potential of the wire immediately after the cloud discharge is the same as existed at this height with no wire present, namely 414.7 statvolts (124,410 volts).

This is a fundamental law and applies equally well to any number of overhead wires. It will be shown later that the addition of every wire on a pole reduces the quantity of electricity induced on each wire but it does not reduce the instantaneous potential of the freed charge. If a second wire is placed at a height of 1100 cm. (100 cm. above the first wire) the instantaneous potential after the lightning discharge is found by multiplying the undisturbed potential gradient in the atmosphere by the height of the wire; thus, 1100 cm. $\times$ 0.4146 statvolts per centimeter gives 456 statvolts (136,800 volts). The first wire again assumes a potential of 414.7 statvolts.

SCREENING OF ENERGY INDUCED BY THE USE OF SEVERAL PARALLEL WIRES ON THE SAME POLE

It has just been stated in a fundamental law that the presence of several wires does not decrease the instantaneous potential at cloud discharge although there is a decrease in quantity per wire due to the presence of several wires. (Nothing is being said at present of grounded wires.) The several wires produce a screening of quantity without a useful effect on the resultant instantaneously induced potential. There is, however, a useful screening effect of energy in the surge.

For example, with one wire alone the induced quantity is 25 statcoulombs per centimeter length of wire. The instantaneous potential of the electric wave is 414.7 statvolts and the instantaneous electrostatic energy is 5180 statjoules or ergs per centimeter. Placing a second wire of the same diameter and at the same height but spaced 100 centimeters reduces the quantity on the first wire from 25 statcoulombs to 18.36 statcoulombs per centimeter. The energy is thereby reduced to a corresponding amount (73.4 per cent), that is, to 3805 statjoules per centimeter. There is less energy in the wave on each wire to be dissipated. However, the total quantity is increased from 25 to 36.72 statcoulombs per centimeter and the total energy from 5180 to 7610 statjoules. The quantity and energy are equally divided between the two

① one wire (overhead). Electric field constant.
q-25 statcoulombs on a No. 000 wire

①	②						
q-18.36	18.36	Quantity total-36.7					
③	①	②					
q-15.70	13.65	15.70	Total-45, Average-15				
⑤	③	①	②	④			
q-13.4	10.6	9.94	10.6	13.4	Total-57.94, Av.-11.59		
⑦	⑤	③	①	②	④	⑥	
q-12.42	9.44	8.21	8.09	8.21	9.44	12.42	
				Total-68.23,- Av.-9.75			

FIG. 10

Induced charges on line wires by a constant electric field. Wires are No. 000 and spaced 100 cm. (39.4 in.) horizontally. Five groups separately, each group 1000 cm. (33 ft.) above the surface of the earth. Groups; 1 wire, 2 wires, 3 wires, 5 wires, and 7 wires. All quantities are given in statcoulombs per cm. length of wire.

parallel wires because they are the same size and at the same height.

In conclusion: Increasing the number of parallel wires decreases the energy in the surge per wire without decreasing the initial instantaneous potential. The closer the wires to each other, the greater the reduction in energy. As a limit, the reduction in energy, even if the wires are so close as to touch is a little less than inversely proportional to the number of wires. For example, two wires cannot reduce the energy to quite half of what would be induced on one. At the other extreme, when parallel wires are far enough apart to be outside each others fields they exert no screening effect on each other.

The numerical values above (Fig. 10) are calculated by equations (**5**), (**6**), (**7**), (**8**), and (**9**) (mathematical section). The general equations are given in equations (**12**) and (**13**).

For No. 000 wires in a vertical plane, 100 cm. spacing, the quantities induced are given in the following list. The central wire is always numbered 1, and the even numbers are assigned to the right and symmetrically placed wires to the left are assigned the next odd number, thus, (3) (1) (2)...

Wire one only q_1 = 25 statcoulombs per centimeter length of wire. Two wires $q_1 = q_2$ = 18.36.

The last diagram with four wires grouped around one wire shows an average reduction in quantity from 25 to 10.8 statcoulombs per centimeter which gives a reduction in surge energy to 43 per cent average per wire, other lightning conditions being equal. The equations for this group are (**14**), (**15**), (**16**) and (**17**) in the mathematical section.

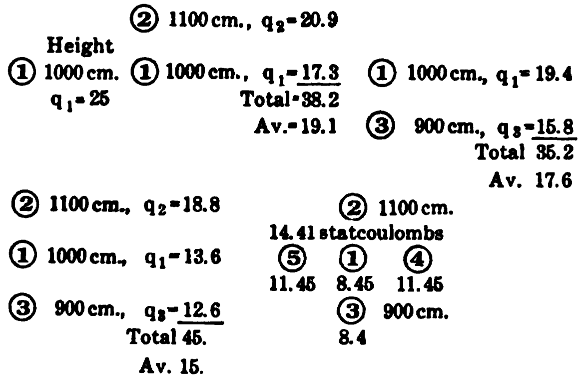


FIG. 11

Induced charges on line wires by a constant electric field. The five groups are to be considered separately. Sire of wire No. 000, spacing 100 cm. Quantities induced at the given heights as given above. All quantities are given in statcoulombs per cm. length of wire.

USE OF A PARALLEL GROUNDED WIRE. SCREENING AND INCREASE OF CAPACITANCE OF LINE WIRES

The grounded wire produces no more screening effect than a power wire in its place. Also it may not, at the first instant of cloud discharge, reduce the potential induced on a power wire, except at the pole where the vertical riser from ground is connected to the parallel ground wire. If the lightning stroke were absolutely instantaneous, or if the distance from the induced charge to the grounding pole were great the parallel grounded wire would rise to the potential it would have if it were not grounded. Since the lightning bolt requires time to form, some of the quantity set free on the parallel grounded wire will have time to pass down the vertical connection to ground and immediately becomes the seat of a charge induced by the charge on an adjacent parallel power wire.

The three stages are shown in Fig. 12.

The grounded wire increases the capacitance of the power wire and thereby reduces its potential without in any way reducing its charge. The capacitance to earth of the one wire alone at 1000 cm. height is 0.0603 statfarad per centimeter (10.78 millimicrofarads per mile). The capacitance of the same wire to the combined surface of the earth and the parallel grounded wire, 100 cm. separation, is 0.0693 statfarad per centimeter. Therefore, the reduction in potential due to increase of capacitance alone should be to 87 per cent. The quantity, by screening, was reduced from 25 to 18.3 statcoulombs (73.4 per cent). The total reduction in potential will be the product 87 per cent × 73.4 per cent = 63.8 per cent. Subtracting this from 100 per cent gives 36.2 per cent, a factor which may be called the protection afforded by the ground wire. In other words, it means that with a given cloud and no parallel grounded wire the potential of a power wire would rise instantaneously to 414.7 statvolts but with the ground wire in place the same cloud discharge will cause a rise of only 264.7 statvolts. This is a voltage ratio of 63.8 per cent, or a protection of 36.2 per cent of the potential which would have existed without the guard wire.

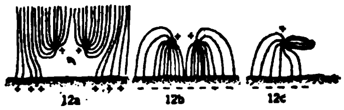


FIG. 12

Showing three stages of charge on one power wire and one parallel grounded wire (the right one). 12-a is the condition of induction before the cloud discharges to earth (not to the line). 12-b is the condition at the instant the cloud is discharged. 12-c. is the condition as soon as the charge on the grounded wire can pass to earth. The ground wire then takes an induced charge from the power wire and thereby increases the latter's capacitance.

PROTECTION AFFORDED BY ONE PARALLEL GROUNDED WIRE

In the previous work two steps were taken in the calculations simply to show the two theoretical factors involved, namely screening and increased capacitance. By treating the equations symbolically most of the factors cancel out in the two steps, leaving a very simple formula which gives the protection in one calculation.

Taking first the case of two wires in a horizontal plane, one a grounded wire, the

$$\frac{\text{Potential protected}}{\text{Potential unprotected}} = \frac{a - b}{a}$$

where $a = 4.6 \log_{10} \left(\frac{2 \times \text{height of gr. wire}}{\text{radius of grounded wire}} \right)$

$$b = 4.6 \log_{10} \left(\frac{\sqrt{(2\ \text{height})^2 + (\text{spacing})^2}}{\text{spacing}} \right)$$

and the protection $= \frac{b}{a}$

The symbolic solution is shown in equations (**18**) to (**27**) inclusive.

The equation shows that the protection decreases as the distance between the wires in the horizontal plane increases in accordance with the logarithm of a ratio. For a No. 000 wire one cm. in diameter and 1000 cm. (33 ft.) high, the factor a = 16.6. Various values of b are given as follows: For 50 cm. (19.7 in.) spacing from the grounded wire the factor b = 7.38 and the protection is 44.5 per cent. For 100 cm. (39.4 in.) spacing, b = 6, and the protection is 36.3 per cent. For 200 cm. (78.7 in.) spacing, b = 4.6 and the protection has fallen to 27.7 per cent. At 500 cm. (197 in.) spacing, half the height, b = 2.83 and the protection is 17 per cent. Lastly at a spacing equal to the height, viz. 1000 cm. (33 ft.), b = 1.61 and the protection is 9.7 per cent.

The protection is entirely independent of the size of the power wire. This is due to the fact that as the power wire is increased in size it has induced on it a greater quantity, but this is compensated by an equally greater capacitance to the earth and grounded wire. This is proven mathematically in the symbolical equations (**18**) to (**28**).

There is another simple relation. So long as there is but one grounded wire, the equation just given applies individually to any number of wires in a horizontal plane. Each calculation is made quite independently. The equation does not apply for two or more parallel grounded wires.

PROTECTION OF WIRES STRUNG IN A VERTICAL PLANE

The ratio of potentials (protected to unprotected) depends on the relative height of the grounded wire and power wire. For example, if the power wire (No. 2) is hung 100 cm. (39.4 in.) under the grounded wire, then due to the height alone the ratio of potentials will be decreased by the ratio of heights, 900 cm. ÷ 1000 cm. = 0.9. The factor previously designated by the symbol b will also change somewhat. Thus,

$$b' = 4.6 \log_{10} \left(\frac{(2 \times \text{height of grounded wire}) - \text{spacing}}{\text{spacing}} \right)$$

This equation for b' applies when the grounded wire is above the power wire. If the contrary condition is true, then the "spacing" given in the numerator is to be added instead of subtracted. The potential ratio for vertically situated wires is:

$$\text{Ratio} = \frac{\text{Pot. protected}}{\text{Pot. unprotected}} = \frac{a - b'}{a} \frac{h_2}{h_1} \qquad \textbf{(28a)}$$

Where h_1 is the height of the grounded wire and h_2 the height of any power wire strung in the vertical plane beneath.

Examples: Parallel grounded wire No. 000 (1 cm. diameter) at a height of 1000 cm. (33 ft.). Power wire, of any diameter, at 900 cm. directly underneath,

$b' = 5.89$ and the ratio

$$\frac{\text{Pot. protected}}{\text{Pot. unprotected}} = \frac{16.6 - 5.89}{16.6} \frac{900}{1000} = 58\%$$

With the power wire 100 cm. above the grounded wire, $b' = 6.085$ and the ratio

$$\frac{\text{Pot. protected}}{\text{Pot. unprotected}} = \frac{16.6 - 6.085}{16.6} \frac{1100}{1000} = 69.7\%$$

Exchanging positions of the power wire and grounded wire $a = 16.78$, $b' = 6.085$, and the ratio

$$\frac{\text{Pot. protected}}{\text{Pot. unprotected}} = \frac{16.78 - 6.085}{16.78} \frac{1000}{1100} = 57.9\%$$

Now keeping the grounded wire above, raise the power wire to double the height, viz. 2000 cm. (66 ft.) and double the spacing to 200 cm. (78.7 in.), the factor a = 18, $b' = 6.085$ again, and the

$$\frac{\text{Pot. protected}}{\text{Pot. unprotected}} = \frac{18 - 6.085}{18} \frac{2000}{2200} = 60.2\%$$

For a second power wire hung 200 cm. (78.7 in.) under the first power wire, $b' = 4.6$, and the ratio

$$\frac{\text{Pot. protected}}{\text{Pot. unprotected}} = \frac{18 - 4.6}{18} \frac{1800}{2200} = 60.9\%$$

For the third phase wire hung 200 cm. (78.7 in.) below the second wire, $b' = 3.69$ and the ratio

$$\frac{\text{Pot. protected}}{\text{Pot. unprotected}} = \frac{18 - 3.69}{18} \frac{1600}{2200} = 57.8\%$$

Subtracting each of the above ratios from 100% gives the degree of protection.

Attention is drawn to the greater protection given to the lower wire as compared to the one just above it. There are two factors involved which are antagonistic. First, the protection decreases as the distance from the grounded wire to the power wire beneath is increased. Second, the protection is increased as the power wire is lower, due to the ratio of the heights.

The foregoing figures are approximately the same as obtained in the usual practise. A grounded wire ⅜ in. in diameter is not much less than one cm. Towers are about 60 ft. high and spacings about six ft. Only one parallel grounded wire is usual even with two power circuits. The number of power wires has no effect on the protection against potential but, as shown previously, decreases the energy in the surge on each wire.

The single grounded wire is not usually directly over the three-phase circuit but this makes relatively little difference in the results. To give the factor b for wires in a horizontal plane and b' for wires in a vertical plane a general value, needs only the use of the well-known equation for the coefficient of quantity, thus

$$b_1 = 4.6 \log_{10} \frac{m_{21}}{r_{21}}$$

where m_{21} is the distance of the image of the power wire to the grounded wire and r_{21} is the spacing between the wires.

The laws for obtaining the best protection possible with a single grounded wire expressed in a practical form are: (1) string the power wires as near the earth as practicable; (2) string the grounded wire above but as near to the upper power wire as safe mechanical spacing permits.

PROTECTION AFFORDED BY TWO PARALLEL GROUNDED WIRES

It may be said immediately, without mathematical analysis, that the degree of protection afforded by two grounded wires depends on where the two wires are placed relative to each other. If they should, in the one extreme, be placed side by side, the added protection by the second wire would be very slight. If, on the other hand, they are placed on the opposite sides of a power wire their protection together is nearly as great as the values calculated separately and then combined.

The protection given by two grounded wires with one power wire anywhere between them, and all wires situated in the same horizontal plane is

$$\text{protection} = \frac{b + f}{c + d}$$

where the coefficients b, f, c and d are given by equations (**38**), (**39**), (**40**), and (**41**) respectively. (Mathematical section).

For example, wires No. 000, one cm. diameter, height = 1000 cm. (33 ft.) and spacing 100 cm. The central wire No. 1 is the power wire. Its coefficient a is not involved because the protection is independent of the size of the power wire. Coefficient $b = f = 6$, $c = 16.6$, and $d = 4.6$

$$\text{Protection} = \frac{6 + 6}{16.6 + 4.6} = \frac{12}{21.2} = 56.8 \text{ per cent.}$$

The potential ratio = 1 − 56.8 per cent = 43.2 per cent.

The potential ratio of one grounded wire and one power wire, previously calculated, was 63.7 per cent. Assuming, somewhat erroneously, that the real value combined is the product of the separate values, gives $63.7 \times 63.7 = 40.6$ per cent. This is 2.6 per cent too small but roughly approximate.

If the two grounded wires are not on opposite sides of the power wire the error of such an assumption will be materially greater.

Before pursuing further the value of the use of several parallel grounded wires it is desirable first to consider other fundamental relations in connection with electromagnetic induction which must be taken into account in deciding on the location of multiple grounded wires.

THE REACTION FROM THE LOOP OF THE GROUNDED WIRE BOTH ELECTROSTATIC AND ELECTROMAGNETIC

So far it has been assumed that the charge on the overhead wire at the instant of release by the cloud discharging to earth, passes harmlessly to earth without attending phenomena of interest. This is true, it would seem, only under exceptional conditions. This freed electric charge represents a definite energy. This energy must be either dissipated or transferred to some other circuit, since there is no way of preserving it intact in the grounded wire loop either as electrostatic or electromagnetic energy.

Each loop forms a distributed capacitance and double return circuit, Fig. 13, and shown in equivalent circuit in Fig. 14. Unless the ohmic resistance in the loop is equal to or greater than the critical damping resistance an oscillation will follow the initial discharge to earth of the freed charge. As a matter of fact, the resistance, especially of metal towers, is but of small

FIG. 13
Distributed charge and loop circuit to ground of a grounded wire at the instant its induced charge is freed.

FIG. 14
The equivalent circuit and the discharge of a grounded loop.

fraction of the critical damping value. Many oscillations will therefore take place.

So much for the charge induced by the cloud. The same statements apply to the charge induced on the parallel grounded wire by the charge on the power wire as shown in Fig. 12. c.

The value of this induced charge, already calculated for a steady condition, will overshoot Fig. 15. Momentarily it is possible to get nearly double the steady value.

For the present, the assumption is made that the length of line wire is no greater than the length of the inducing cloud. This is done for the sake of simplicity. It avoids the consideration of the traveling wave. On this assumption the charge which is freed on the power wire remains stationary except for local disturbances which come from the discharge of the grounded wire to earth.

Due to the electrostatic effect alone, the surge potential on the power wire drops from its initial value and oscillates across its final value. For example, for the two wires at 100 cm. separation both in the same horizontal plane and one grounded, the potential drops on the power wire from + 414.7 statvolts to + 195 statvolts and only after several oscillations does it reach its final stationary value of +264 statvolts. This oscillation takes place while the oscillation in Fig. 15 is active.

The electromagnetic effects must also be considered. The surges in the grounded wire are free to move with a velocity nearly equal to that of light. A considerable value of current will be reached. Rings of magnetism emanating from the grounded wire cut the parallel power wire and induce therein electromotive forces which are proportional to the mutual inductance between the power wire and grounded wire, and to the rate of change of current, $e = M\frac{di}{dt}$.

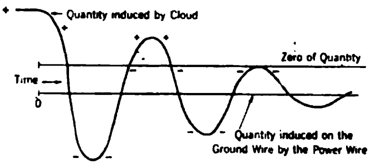


FIG. 15

The oscillation of the quantity on the grounded wire from the steady positive value at the instant it was released by the cloud discharge to the later negative value induced by the adjacent positively charged power wire.

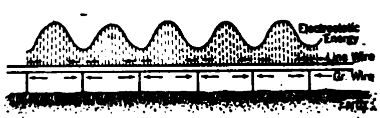


FIG. 16

The grounded wire loop is shown below the power wire. Currents are represented by arrows. The resulting humps in the electrostatic energy are depicted above the power wire.

The surge current in the parallel grounded wire will rise to its greatest value at the pole or tower where it is connected to ground by the vertical riser. The current will be zero at the center of the span. (Reason from conditions of Fig. 4).

The effect of the first half-cycle of surge current is to produce a hump of electrostatic energy midway between towers in the power wire. An attempt to depict this condition is shown in Fig. 16. As a result the main wave, only a part of which is shown in Fig. 16, will be broken up in crests, superposed on the energy induced by the direct action of the storm cloud. These crests are in fact a superposed higher frequency on a single impulse. The frequency is immediately obtainable from the distance between grounding points of the grounded wire. This distance is a wave length, as shown in Fig. 15. If there are ten towers to the mile and the velocity of the traveling wave is 183,000 miles per second the frequency will be 10 × 183,000 =

1,830,000 cycles per second. With 50 grounding points per mile the frequency is 9 million cycles per second. We have all been puzzled at times to account for the high-frequency effects of lightning in transmission circuits. Small inductances give remarkable choking effects at times. The foregoing theory has not yet had the test given by experimental evidence but it would seem to be one of the several possible causes of high frequency induced in a transmission line.

XIV—Self-Inductance, Natural Frequency, Maximum Current, Critical Resistance of the Grounded Wire and the Mutual Inductance with the Power Wire

On the assumption that the current in the part of the circuit which closes through the earth can be treated as an imaginary wire, an image at a depth under the surface of the earth equal to the height of the actual grounded wire above the surface of the earth, the self-inductance is 428 micro-henries for a length of overhead wire of 500 ft. (11,720 cm.) The capacitance of the grounded wire has already been found and from the combination of its inductance and capacitance its natural frequency is 640,000 cycles per second.

The maximum current of discharge is 569 amperes. The critical resistance which would just damp out oscillations is 370 ohms.

The mutual inductance between the grounded wire and the power wire is 179.8 micro-henries.

In these data it should be again noted that the distance between the earthing points of the grounded wire is 1000 ft. (23440 cm.) and is somewhat greater than is usual in practise. The effect of lesser distance between grounded points will be considered later.

These data show that with the usual resistance to ground at a tower of the order of 5 to 20 ohms, a great many oscillations will take place in this circuit before the energy will be absorbed in the resistance, since the critical damping resistance is 370 ohms. Since the mutual inductance is 42. 4 per cent of the self-inductance, a considerable percentage of this oscillation will be transferred to the power wire.

XV—Data on the Transfer of the Oscillating Surge on the Grounded Wire to the Power Wire

It is assumed now that the transmission wires are many times longer than the induced charge on the wires. Traveling waves will therefore follow the release of the induced charge. The primary of the circuit (the grounded wire loop) contains inductance, capacitance, and resistance. The secondary, which is the power wire, contains inductance and capacitance. From this standpoint we should use the corresponding mathematical equation but it should be noted that the capacitance of the power wire is a distributed capacitance and that as soon as a part of the charge is transferred to the power wire it does not oscillate in conjunction with the grounded loop, but the induced charge is transmitted along the power wire as a traveling wave. Since this energy is lost, in the mutual operation of the primary and secondary, the problem is similar to a secondary circuit containing a considerable resistance which absorbs energy. If these two problems give different results, it will be necessary subsequently to choose the one which more nearly fits the actual conditions.

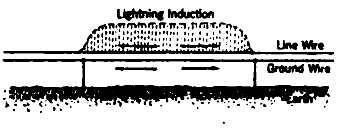


FIG. 17

Conditions of induced charges on the power wire and grounded wire at the instant of cloud discharge. Also the resulting currents.

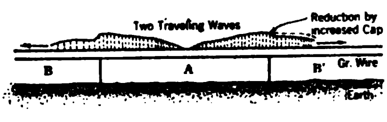


FIG. 18

The same charge as shown in Fig. 17 after it has turned into two oppositely directed traveling waves. Note the decrease in potential as each arrives at the adjacent ground loops *B* and *B'*.

Solving this problem as though the two circuits both contained concentrated inductance and capacitance without resistance, it is found that the voltage induced in the secondary is 51.6 per cent of the voltage in the primary. The initial voltage in the grounded wire, acting as primary, is 105,000 volts. Therefore there would be transferred to the line on this basis a surge which has an initial voltage of 54,000 volts and a frequency somewhat over 600,000 cycles per second. The transference of energy from the local grounded wire circuit to the power wire would very quickly exhaust the supply contained in the original surge. In round numbers the wave train would run 54 kv. first peak, 27 kv. second peak, 18 kv. third peak, 9 kv. fourth peak, 4 kv. fifth peak, etc.

On the basis of using a formula for a concentrated resistance in the secondary of these coupled circuits the results will be as follows:

To get a conception of the relations of the local oscillation in the loop of the grounded wire and the main traveling wave in a power wire, let us assume that the grounded wire is earthed only at the limits of the clouds influence.

At the instant of release, when the cloud discharges to earth, the charges on both wires start to spread simultaneously and similarly in both directions, Fig. 17. At the midway point both wires reach zero potential at approximately the same instant Fig. 18. The traveling wave on the power wire has now split into two parts and is gradually passing beyond the locality of the charged loop of the grounded wire. The grounded wire *A* has produced no decrease in potential of the power wire. When the surges on the power wire reach the adjacent grounded loops, *B* and B^1, they have their potential decreased by the added capacitance of these uncharged grounded wires.

The surge in the grounded loop continues to oscillate locally and by mutual induction, transfers a fraction of its energy to

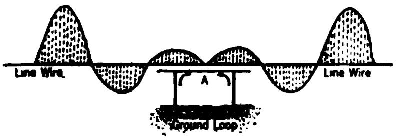


FIG. 19

Showing the tail put on to the main lightning surge by the transfer of surge energy from the grounded loop to the power wire by electromagnetic induction. The resistance of the grounded loop is less than the critical value.

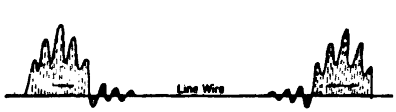


FIG. 20

Superposed higher oscillation on a traveling wave produced by the oscillations in a grounded loop. This effect occurs when the initially induced charge covers several grounding points.

the power wire. This transferred energy cannot add directly to the main traveling wave on the power wire because the main wave has passed beyond the influence of the grounded loop, *A*. The grounded loop *A* can do nothing more than put an attenuating tail on the main wave and make of it thereby a wave train (assuming for the present purpose that the cloud discharge has caused a simple impulse). This wave train is shown in Fig. 19.

If the induced charge of the cloud covers several grounded loops the two traveling waves should be a combination of Figs. 16 and 19, as represented in Fig. 20.

From these results we see another defect of the overhead grounded wire, namely that after it absorbs its part of the surge energy from the cloud it returns this energy to the power wire in the form of a wave train. According to the local conditions this wave train may be either superposed on the charge induced directly by the cloud on the power wire or it may follow immediately on the heels of this traveling wave, or both simultaneously. Although the voltages of this wave train are condiserably attenuated, the wave train may do harm to insulation. Should the coils of apparatus in any part have a natural frequency corresponding to that of the wave trains, the energy of this entire wave train may be concentrated again in this local resonant point, and consequently the potential may rise to extremely high values. This resonant condition would not occur, however, if the grounded wire had not produced the wave train.

From this standpoint, therefore, it is desirable to have a resistance in the earth connections of the grounded wire which approaches the critical damping resistance. Since there are two earth connections in this circuit this resistance should be approximately 185 ohms each.

The objection to the higher resistance in the earth connection

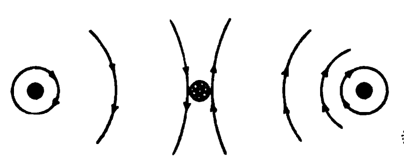


FIG. 21
A grounded wire placed on each side of a power wire so as to reduce the mutual inductance to zero.

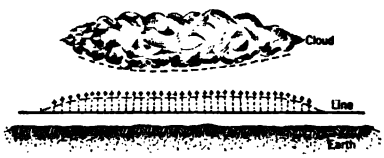


FIG. 22
Stationary induced charge on the line before the cloud discharges.

may be found when analysis is made of the conditions of potential during a direct stroke. If, however, it is conceded that a direct stroke will invariably cause side flashes to the power wires in spite of the value of the earth resistance, this objection to the higher resistance of the grounded wire will not be valid.

In placing a parallel grounded wire, the object should be to increase the electrostatic protection and decrease the electromagnetic induction of the ground wire surge which is transferred back to the power wires. Raising the grounded wire high above the power wires decreases the electromagnetic induction but unfortunately decreases also the electrostatic protection.

A better method of reducing the electromagnetic induction is to employ two grounded wires and place them symmetrically on each side of a power wire or group of power wires. Such a condition of zero electromagnetic induction is shown in Fig. 21.

As a third means of reducing the transfer of surge energy from the grounded wire to the power wire, the use of critical damping resistance in the grounded loop has already been mentioned.

XVI—Movements of Induced Charges on Line Wires Coincident with the Movements of Charges in a Cloud

So far the assumption has been made that the electrostatic charge on a line starts from a stationary condition at the instant a lightning bolt takes place between the cloud and earth. A stationary charge first collects gradually under the storm cloud. This induced charge is distributed along the line over a distance somewhat greater than the length of cloud, Fig. 22. Coincident with the discharge to earth there is also a collection of the accumulated charge on the line towards one point. This point has been called the bolt peak and is the point on the line nearest to the point on the earth struck by the cloud discharge. In the usual thunder cloud the quantity of electricity in the vertical discharge from the cloud has been gathered from some distance horizontally in the cloud and therefore there will be a corresponding movement of the electrostatic charge on the line as represented in Fig. 23. This preliminary shifting of the charges on the power wires and grounded wires will cause some loss of energy by induction in the grounded loop. If the charge traveling on the line wires can be retarded by means of choke coils, especially those which absorb high-frequency energy, it may be possible to materially decrease the peak of potential on the line wire. This is still an indeterminate condition which should be decided by experimental data on the rapidity of movement and the quantity of electricity which would be concentrated by this particular effect of the lightning discharge. On the side of the retardation by inductance it is evident that only a limited amount of concentrated reactance is permissible on the line.

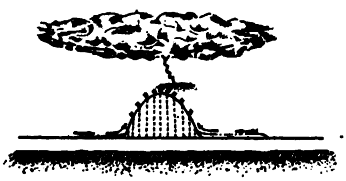


Fig. 23

Concentration of charge on the line at the instant of cloud discharge and coincident with the corresponding movements of charge in the cloud.

If these reactances in the power wires are staggered they will become a help in reducing the potentials of lightning by breaking up the waves. Such a possible effect is shown in Fig. 24 for two parallel wires in which the charge on one is retarded behind the charge on the other and therefore the capacitance of the adjacent wire becomes available in absorbing the charges electrostatically, thereby reducing the potential. Reflections take place at each coil, which again give time for the absorption of the surge energy on the line by the parallel grounded wire. The more the charges can be absorbed on the line the less the amount to reach the apparatus in the stations.

The best type of high-frequency absorbing reactance is the one with distributed resistance between turns. A partially conducting cement is used which serves both as a mechanical support and as an electrical resistance, Fig. 25. As the surge potential piles up on each turn of the coil it forces current through the distributed resistance between turns. Thereby the recoil from stored magnetism is avoided and a part of the surge energy is transformed into heat energy. The steeper the wave front

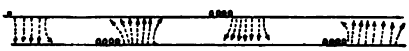


FIG. 24

Illustration of a method of breaking up a traveling wave by retardation, reflection, and absorption by specially designed choke coils placed in staggered position in the three-phase wires. A traveling wave meets the absorber choke coil and three things take place, namely, it is partially absorbed by the shunting resistance from turn to turn, it is partially reflected by the inductance, and it is partially transferred to the adjacent wire by dielectric displacement (as indicated by the arrows). This displaced charge is divided into two parts and one part travels in the opposite direction to the original wave. Thereby a traveling wave is broken up into many parts and dissipated.

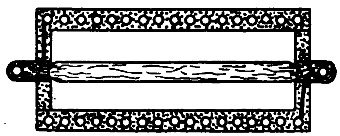


FIG. 25—ABSORBED TYPE OF CHOKE COIL

A choke coil made of bare wires cast in a semi-conducting cement. This gives a distributed leakage which is more effective than shunting the entire coil with a simple resistance. Every turn as it chokes back the surge and raises the potential of it, causes an absorption of its energy by forcing the current through the shunting resistance.

and the higher the frequency the more efficient is the absorption of surge energy. In other words, the more severe the surge, the more it is forced through the resistance.

XVII—THE ABSORPTION OF THE TRAVELING WAVES BY THE SUCCESSIVE LOOPS OF THE GROUNDED WIRE

We have just discussed an objectionable feature of the grounded wire in producing a wave train on the power wire and we now come to a condition which is more favorable to the grounded wire. Lightning impulses and all the succeeding traveling waves trains which pass along the power wire must have their electromagnetism looped into every successive grounded wire loop. Thereby each of these grounded loops will have transferred to it a fraction of the energy of the traveling wave and this energy will be more or less absorbed according to the value of the ohmic resistance in the grounded loop. Again, we come to the desirability of having a comparatively high resistance in the grounded loop. This resistance should either be in the earth connection or inserted in series in a wire circuit. In this way the grounded wire will serve as an absorber of traveling waves and should give efficient absorption in all cases except where the induced lightning is near a station and has only a short distance to travel.

If there is no appreciable absorption of energy in the grounded loop, the effect of the grounded loop will be to break up the main traveling impulse into a long wave train of a wave length corresponding to the length of the grounded loop. Thereby a single impulse from a cloud will be transformed into a long train of waves at very high frequency.

XVIII—The Frequency of the Lightning Bolt

So far the assumption is made that the cloud discharge does not oscillate between the cloud and earth. Prof. Elihu Thomson has shown that some parts of the path of discharge in the cloud itself have too much resistance in their paths to permit of a free oscillation. Mr. De Blois' records on an oscillograph (A. I. E. E. Transactions, Vol. XXXIII, 1914, p. 519) have shown this effect. There is, however, low resistance in the main path of the lightning discharge and therefore a possibility of local oscillations between the ends of this conducting streak. Since the length of the conducting streak is comparatively short, its frequency, if it exists, is relatively high, perhaps of the order of 200,000 cycles to a million cycles per second.

Any such oscillation will induce a corresponding oscillation on the transmission line, and will be added to the natural oscillations already discussed. It should be noted that any oscillation induced by an oscillation of a cloud discharge will add surge energy to the power wires at each alternation. The original quantity induced on the line cannot return to the starting point when once freed by the initial action of the cloud discharge. The initial charge takes the form of two traveling waves and there is not much more argument in favor of their return with the oscillation of the cloud discharge than there is that a rifle bullet will return to a gun by the force of the air which rushes into the muzzle after the bullet passes out. The traveling wave, like the rifle bullet, possesses dynamic energy which keeps it traveling once it is set in motion along the line wires.

So each succeeding oscillation of a cloud discharge will start a new oscillation on the line and will thereby produce a wave train which has a greater energy than the original induced charge.

XIX—The Effect of the Combination of Lightning Voltage and Power Voltage at the Instant the Bound Charge is Set Free on the Line

At the instant the cloud discharges to earth these two sets of voltages both appear on the line. The power voltage at one instant has one phase positive, another phase negative, and the third phase at zero potential. If the lightning potential is positive the corresponding quantities of electricity will combine or cancel, leaving an inequality in the voltage of the traveling waves which depart from this point. This subject has been discussed in a previous article by the writer and is of especial interest in the subject of the arcing ground suppressor. It is another factor which adds complication to any exact calculations of what actually takes place during and subsequent to a lightning discharge. This phenomenon may produce a material decrease in the surge potential by causing waves to travel in the three phases one ahead of the other, the stronger holding the weaker one back by electromagnetic induction. As a result it is possible that equally induced charges on the three phases, which have equal tendencies initially to oscillate towards earth may be thrown out of relative location on the longitudinal length of the circuit and thereby produce line to line surges.

XX—High Frequency Produced in Apparatus by Transposition of Power Wires

Transpositions of power wires are made with two purposes, at least, in view, namely, first to decrease the induction on parallel lines, and second to prevent shifting of the neutral of the circuit. Our present interest is centered in the second purpose.

If the power wires are hung in a vertical plane the lowest wire will have the greatest capacitance to earth, and the highest wire the least. If there are no transpositions of the phase wires there is a tendency to shift the neutral from the center of the three-phase triangle. If the neutral of the circuit is grounded, this shifting tendency will produce a current at the neutral connection to earth. The current passing to earth will be such as to satisfy the unbalanced capacitances of the phase wires.

If the neutral is not grounded the tendency to shift will cause an actual shifting of the neutral throughout the system. The shifted point will be permanent.

A single phase simplifies the illustration, Fig. 26. To get the direction of shift of the neutral, without mathematical analysis make the capacitance of the lower wire many times greater than the upper wire. Practically this can be done by closing the disconnecting switch on the lower wire and leaving the other disconnecting switch open. As a result the transformer gives the effect of being grounded by the lower wire. The capacitance of

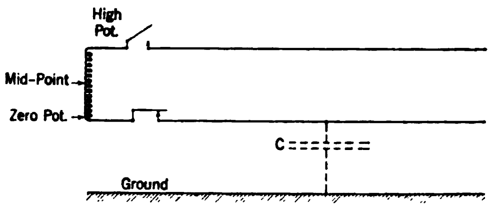


FIG. 26

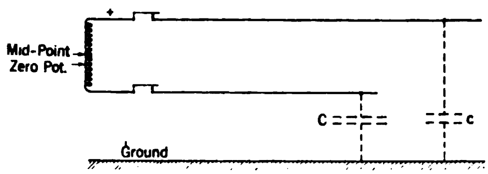


FIG. 27

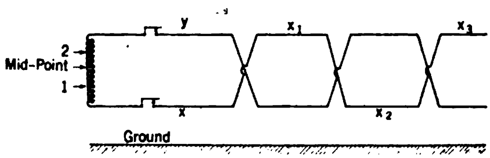


FIG. 28

the lower wire is so great as compared to the capacitance of the coils of the transformer that the potential of the connected side is reduced sensibly to zero.

Now, if the upper line wire is connected to the transformer, the two sides will be more nearly balanced but the lower wire will still have the greater capacitance and therefore the neutral will remain shifted from the midpoint of the transformer coils as indicated in Fig. 27.

Incidentally it might be noted in passing that the arcing at the switch contact in opening on one line wire alone causes rapid shifting of potential in the transformer at every break of the arc. If the length of line is such as to resonate with the natural frequency of the transformer coils, and especially if the transformer coils are not designed to break up the surges into several different frequencies, it is possible to get local resonance in the transformer coils. Such resonance will produce high voltages.

Our problem is the production of high frequencies, especially at the time of switching, not by arcing, but by the transposition of the phases along the line. Fig. 28 shows a transformer being closed on a transposed line. In the first section wire x is the lower one and the neutral of the transformer will be shifted from the midpoint M to a point 1. As the traveling wave runs along the second section the circuit becomes unbalanced on the opposite side and the neutral shifts across the midpoint to a point 2. There is a sudden shift for every section the traveling wave

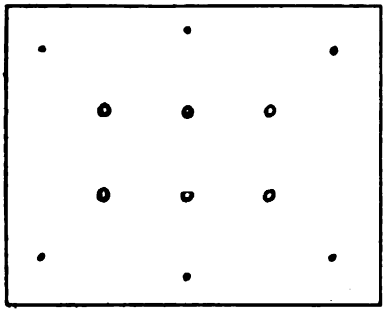


FIG. 29

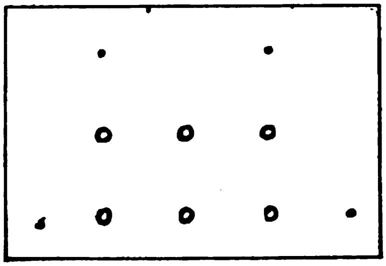


FIG. 30

passes, which throws a high frequency into the transformer windings. The frequency (neglecting higher harmonics) can be found by dividing the velocity of light by twice the number of miles per transposition. For example, if the line is transposed every five miles, the frequency produced by closing a switch on to this dead line will be 18,300 cycles per second.

$$\left[\text{(183,000 miles per second)} \div 2 \times 5 = 18{,}300 \right]$$

At 60 cycles or any frequency low as compared to the natural frequency of the line the successive sections of transposition cancel the unbalanced currents and as a result there will be no shifting of the neutral. There can be no such cancellation for a traveling wave because the charging currents do not flow to the several sections simultaneously, but successively.

The degree of unbalancing depends upon the relation of the capacitance of the coils of the transformer to the difference in capacitances of the line wires. As an example, the following data are used: Two line wires No. 000 (one cm. diameter) are vertically hung and transposed every five miles. The upper wire is 66 ft. high (2000 cm.) and the lower wire 40 ft. high (1210 cm.) The capacitance of the upper wire to earth is 10.2 milli-mf. per mile (0.0557 statfarad per cm.) and of the lower wire 10.55 milli-mf. per mile (0.0590 statfarad per cm.)

If the quantities emanating from each wire are assumed to be equal, the potential of the upper wire will be 7 per cent greater than the lower wire. If, on the other hand, the potentials are assumed to be equal the quantity on the lower wire will be 5 per cent greater than the quantity on the upper wire. If the neutral of the circuit is not grounded both the charges and the potentials will change somewhat. The voltage of the upper wire will differ by less than 7 per cent from the lower wire. Since this difference is so small it is hardly worth while to make careful calculations. We may assume approximately that the shifting of neutral is about 4 per cent of the potential of one wire. It is evident that such a slight variation in potential even at high frequencies can do no harm to transformer coils except perhaps in the rare case of resonance between the coils and this high frequency.

General Survey of Protection by Overhead Grounded Wire

It is impossible to make definite recommendations which will cover all conditions of transmission circuits. There is much territory where lightning is not prevalent and therefore the expense of the overhead wire may well be avoided. There are also cases where spurs of circuits are carried out to small consumers where the financial returns do not warrant the expense. If such a circuit, when damaged, can be made to free itself from the main circuit without a general interruption, the use of a grounded wire can be questioned. There may be still another case where, theoretically at least, the overhead wire may not be necessary. This condition will occur when the insulation of the transmission line is so high that an induced stroke cannot flash over the insulators. In other words, the insulators cannot be flashed over except by a direct stroke. With the suspension-type insulators and the tower carried well above the insulators the parallel grounded wire would then be of no particular value. What the dielectric strength of such an insulator must be is not known.

In the majority of transmission circuits, however, the problem is rather of the nature of how many overhead grounded wires to use and where to place them to get the greatest advantage. Certain mechanical conditions will limit the freedom of choice of location. For example, with the usual suspension type of construction it may be unwise to install overhead grounded wires in the same horizontal plane as the power wires, due to the chances of grounding by side swinging. At any rate, the wider tower would be materially more expensive. Under such conditions the overhead wires would naturally be strung either above or below.

In the case, however, of pin-type construction the grounded wires may be placed laterally as well as above the power wires.

Various locations of grounded wires are shown in Figs. 29, 30, 31, 32, and 33.

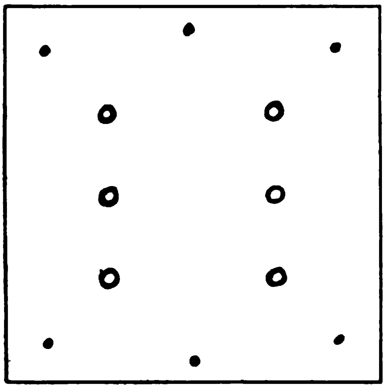


FIG. 31

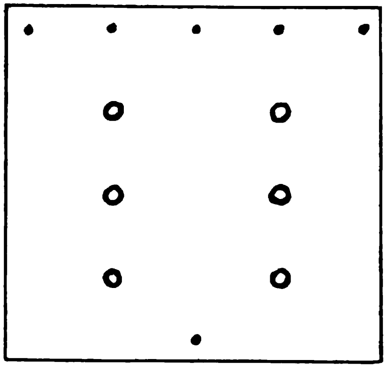


FIG. 32

Fig. 29 shows two parallel circuits of six wires arranged in horizontal formation and six grounded wires separated as widely as possible from each other and yet as near to the power wires as mechanical clearance will permit. The grounded wires are arranged in pairs symmetrically so as to decrease the electromagnetic induction. The two outside lower wires might be raised to the same position as the corresponding one in Fig. 30 without making much difference in the protective value, or the two upper outside wires might be lowered on each side without making a very great difference in the protection. Mechanical conditions of support will be the criterion. The simple rule is to space the overhead grounded wires as far from each other as convenient, but as near to the power wires as is safe.

Fig. 30 shows a desirable location for four grounded wires on the same type of circuit as Fig. 29.

Fig. 31 shows a distribution of six grounded wires for two three-phase circuits verticallyhung. In some cases it maybe desirable to keep the grounded wires within the same width as the two circuits.

Fig. 32 shows another disposition of the six grounded wires which is not so good from the electromagnetic standpoint but which is somewhat better from an electrostatic standpoint. It has already been shown that the lower wires of the vertically hung circuits are greatly protected by their lesser height above earth and therefore they do not need the presence of grounded wires as much as the upper power wires.

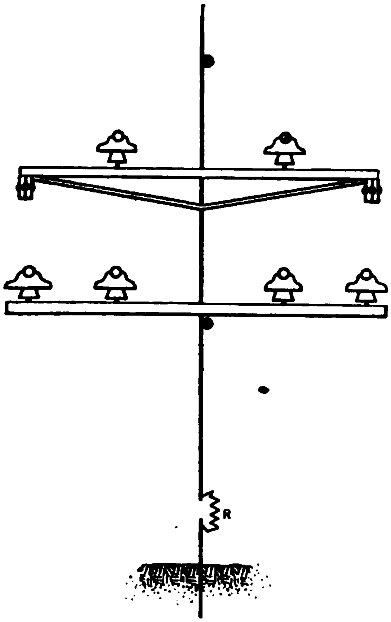


FIG. 33

Fig. 33 shows a desirable distribution of four grounded wires where non-grounded pins on the insulators are used. To preserve the insulation afforded by the wooden cross-arm the metallic connections of the laterally grounded wires are carried free of the cross-arm, in fact, long metal braces might be used in this case. At one point in the circuit is shown a series resistance to bring the total resistance in the grounded loop up to a value at least equal to one-fifth of the critical damping resistance.

From an electrical standpoint grounded wires of small diameter can be used. From a mechanical standpoint the size of the wire is dictated by the length of span. From calculation of loading of the wire under sleety conditions the practise calls for about a 3/8-in. (9.5 mm.) stranded Siemens-Martin steel wire for a span of 600 ft. (182 m.), ¼-in. (6.3 mm.) for a span of about 250 ft. (76 m.), and the ordinary telegraph wire for spans of about 100 ft. (30. m.).

The cost of the ⅜-in. (9.5 mm.) steel wire will vary according to the cost of the metal and the cost of stringing, being usually somewhat greater than $100 per mile rather than less, although $100 per mile is a convenient figure to use for comparisons. The total cost of electrical circuits, including the towers, varies from $2000 to $12,000 per mile. Each overhead grounded wire adds to the cost from 5 per cent to 1 per cent of the cost of a line. Since the use of several grounded wires gives such a large percentage of protection against lightning strokes in most cases they are justified. If line protection could be made so thorough as to do away with large installations of steam auxiliaries in local substations the cost of parallel grounded wires would drop immediately to a relatively insignificant figure.

MATHEMATICAL EQUATIONS

Following are the general equations for a single overhead wire and a parallel cylindrical storm cloud:

$$V_1 = \left(4.6 \log_{10} \frac{m_{11}}{r_1}\right) q_1 + \left(4.6 \log_{10} \frac{m_{c1}}{r_{c1}}\right) q_c \qquad (1)$$

$$V_c = \left(4.6 \log_{10} \frac{m_{1c}}{r_{1c}}\right) q_1 + \left(4.6 \log_{10} \frac{m_{cc}}{r_c}\right) q_c \qquad (2)$$

Where V_1 = potential of the wire

V_c = potential of the cloud at its surface

q_1 = statcoulombs per cm. of length of wire

q_c = statcoulombs per cm. of length of cloud

m_{11} = distance in cm. from the image of wire 1 to the surface of wire 1 = 2000 cm.

r_1 = radius of wire 1 = .5 cm.

m_{c1} = m_{1c} = distance from the image of the cloud to wire 1 = 56,000 cm.

r_{c1} = r_{1c} = distance from the apex of charge in the cloud to wire 1 = 54,000 cm.

m_{cc} = distance from the image of the cloud to the surface of the cloud = 100,000 cm.

r_c = distance from the apex of the cloud charge to the lower surface of the cloud = 10,000 cm.

On substituting these values, equations 3 and 4 are obtained:

$$V_1 = 16.6\, q_1 + .0727\, q_c = 0, \qquad q_c = 5700 \qquad (3)$$

$$V_c = .0727\, q_1 + 4.6\, q_c = V_c \qquad V_c = 26{,}200 \qquad (4)$$

For two parallel wires in a horizontal plane, both grounded, the quantities are found from the following relations where 414.7 is the potential of the undisturbed field at 1000 cm. above the earth.

$$V_1 = 0 = 16.6\,q_1 + 6.0\,q_2 - 414.7 \qquad (5)$$
$$V_2 = 0 = 6.0\,q_1 + 16.6\,q_2 - 414.7 \qquad (6)$$
$$q_1 = q_2 = 18.36 \text{ statcoulombs per centimeter} \qquad (7)$$

$$\text{Electrostatic energy} = \frac{1}{2}\,q_1\,V_1 = \frac{1}{2} \times 18.36 \times 414.7$$
$$= 3805 \text{ statjoules per cm.} \qquad (8)$$

For comparison of one of two wires to one wire alone:

$$\text{(One wire only) Energy} = \frac{1}{2} \times 25 \times 414.7$$
$$= 5180 \text{ statjoules per cm.} \qquad (9)$$

Capacitance of one of two wires to ground = 0.0443 statfarad per cm. **(10)**

Capacitance of one wire to ground = 0.0603 statfarad per cm **(11)**

The general relations of potential in statvolts and quantity in statcoulombs per cm. length of wire are given below:

$$V_1 = \left(4.6 \log_{10} \frac{m_{11}}{r_1}\right) q_1 + \left(4.6 \log_{10} \frac{m_{21}}{r_{21}}\right) q_2$$
$$- (\text{gradient} \times \text{height } (1)) \qquad (12)$$

$$V_2 = \left(4.6 \log_{10} \frac{m_{12}}{r_{12}}\right) q_1 + \left(4.6 \log_{10} \frac{m_{22}}{r_2}\right) q_2$$
$$- (\text{gradient} \times \text{height } (2)) \qquad (13)$$

Notation is similar to that of equations **1** and **2**. The second wire is No. 2 and the effect of the cloud is simplified to the expression, " gradient × height of wire."

The equations for induced quantity on 5 wires (4 grouped around one, height of 1000 cm., spacing 100 cm., see Fig. 11 in text) are as follows:

$$V_1 = 0 = 16.6\,q_1 + 12.0\,q_2 + 6.1\,q_3 + 5.9\,q_5 - 414.7 \qquad (14)$$
$$V_2 = 0 = 6.0\,q_1 + 21.2\,q_2 + 5.4\,q_3 + 5.2\,q_5 - 414.7 \qquad (15)$$
$$V_3 = 0 = 6.1\,q_1 + 10.8\,q_2 + 16.76\,q_3 + 4.6\,q_5 - 455.8 \qquad (16)$$
$$V_5 = 0 = 5.9\,q_1 + 10.4\,q_2 + 4.6\,q_3 + 16.36\,q_5 - 373.0 \qquad (17)$$
$$q_1 = 8.45,\ q_2 = q_4 = 11.45,\ q_3 = 14.4, \text{ and } q_5 = 8.4.$$

To get the protection and potential ratio due to the use of a parallel grounded wire:

Symbolical solution for potential ratios of two wires in a horizontal plane, one of which is a parallel grounded wire. The initial induction is given by equations **12** and **13**, or simplified:

$$V_1 = 0 = a\,q_1 + b\,q_2 - \text{(gradient} \times \text{height of wires)} \qquad \textbf{(18)}$$

$$V_2 = 0 = b\,q_1 + d\,q_2 - \text{(gradient} \times \text{height of wires)} \qquad \textbf{(19)}$$

Let k be the undisturbed potential at the height of the wires

Then

$$q_1 = \frac{d - b}{ad - b^2}\,k, \qquad q_2 = \frac{a - b}{ad - b^2}\,k \qquad \textbf{(20)}$$

After the cloud discharges the charge on wire 1, the grounded wire, will pass to earth and wire 1 will take an induced charge q^1.

$$V_1 = 0 = -\,a\,q' + b\,q_2 \quad \text{whence } q' = \frac{b}{a}\,q_2 \qquad \textbf{(21)}$$

Substituting this in the new equation for the potential of wire 2

$$V_2 = -\,b\,q' + d\,q_2 = \left(d - \frac{b^2}{a}\right) q_2 \qquad \textbf{(22)}$$

Substituting the value of quantity on wire 2 from equation **20** gives for the potential of the power wire:

$$V_2 = \frac{ad - b^2}{a} \quad \frac{a - b}{ad - b^2}\,k = \frac{a-b}{a}\,k \qquad \textbf{(23)}$$

The potential of wire 2 without protection of wire 1 is

$$V_2' = k, \text{ therefore} \qquad \textbf{(24)}$$

$$\frac{V_2 \text{ protected}}{V_2' \text{ unprotected}} = \frac{a - b}{a} \qquad \textbf{(25)}$$

In which these coefficients are the same as given in equations **12** and **13**

$$a = 4.6 \log_{10} \frac{m_{11}}{r_1} \text{ and } b = 4.6 \log_{10} \frac{m_{12}}{r_{12}} \qquad \textbf{(26) and (27)}$$

$$d = 4.6 \log_{10} \frac{m_{22}}{r_2} \qquad \textbf{(28)}$$

The protection is independent of the coefficient (d) which depends on the size of the power wire.

If the grounded wire is above the power wire the ratio would be decreased in proportion to the percentage of height, then

$$\frac{V_2 \text{ protected}}{V_2' \text{ unprotected}} = \frac{a - b}{a} \times \frac{\text{height of power wire}}{\text{height of gr. wire}} \qquad \textbf{(28a)}$$

If, on the other hand, the grounded wire is below, the fraction containing the heights is inverted.

Protection afforded by two grounded wires with a power wire symmetrically placed cetween them, all three wires in a horizontal plane. The outside wires, No. 2 and 3, will have equal quantities of electricity induced on them. The general equations are:

$$V_1 = a\, q_1 + b\, q_2 + b\, q_3 + k \tag{29}$$

$$V_2 = b\, q_1 + c\, q_2 + d\, q_3 + k \tag{30}$$

With the wires at zero potential and the cloud charge negative,

$$V_1 = 0 = a\, q_1 + 2\, b\, q_2 - k \tag{31}$$

$$V_2 = 0 = b\, q_1 + (c + d)\, q_2 - k \tag{32}$$

$$q_1 = \frac{c + d - 2b}{a\,(c + d) - 2b^2}\, k \tag{33}$$

Immediately after the lightning discharges

$$V_2 = 0 = b\, q_1 - (c + d)\, q', \quad q' = \frac{b}{c + d}\, q_1 \tag{34}$$

$$V_1 = a\, q_1 + 2\, b\, q' = \frac{a\,(c + d) + 2b^2}{c + d}\, q_1$$

$$= \left(1 - \frac{2\, b}{c + d}\right) k \tag{35}$$

As before (k) disappears in the potential ratio which becomes

$$\left(1 - \frac{2b}{c + d}\right)$$

$$\text{The protection} = \frac{2\, b}{c + d} \tag{36}$$

If instead ,of taking the two grounded wires equally spaced from the power wire, they should have been unequally spaced, then $2b$ becomes two separate factors, say $(b + f)$, and the protection from two parallel grounded wires becomes

$$\text{protection} = \frac{b + f}{c + d} \qquad (37)$$

$$\text{Where } b = 4.6 \log_{10} \frac{m_{21}}{r_{21}}, \quad \left\{ \begin{array}{l} m_{21} = \text{image 2 to wire 1} \\ r_{21} = \text{spacing wires 2 and 1} \end{array} \right\} \qquad (38)$$

$$f = 4.6 \log_{10} \frac{m_{31}}{r_{31}}, \quad \left\{ \begin{array}{l} m_{31} = \text{image 3 to wire 1} \\ r_{31} = \text{spacing wires 3 and 1} \end{array} \right\} \qquad (39)$$

$$c = 4.6 \log_{10} \frac{m_{22}}{r_2}, \quad \left\{ \begin{array}{l} m_{22} = \text{image 2 to wire 2} \\ r_2 = \text{radius} \end{array} \right\} \qquad (40)$$

$$d = 4.6 \log_{10} \frac{m_{32}}{r_{32}}, \quad \left\{ \begin{array}{l} m_{32} = \text{image 3 to wire 2} \\ r_{32} = \text{spacing wires 3 and 2} \end{array} \right\} \qquad (41)$$

Since the grounded wires are assumed to be the same diameter and the same height $\dfrac{m_{22}}{r_2} = \dfrac{m_{33}}{r_3}$.

Discussion on "Theory of Parallel Grounded Wires and Production of High Frequency in Transmission Lines" (Creighton), Cleveland, Ohio, June 29, 1916.

Harold S. Osborne: In considering any circuit which uses the ground as part of the electric circuit, we are forced to take account of a factor which in the present state of the art is to a considerable extent unknown, that is the property of the ground itself. The ground is not a perfect conductor, and in a great many instances in which the ground is used as a part of the circuit, the effect of the resistance of the ground is very considerable.

In dealing with currents of a few hundred or a few thousand cycles, we have found that as to electrostatic effects, the resistance of the ground usually has but slight effect. The determination of what the equivalent level of the ground is, is sometimes difficult. For example, a row of trees may have a considerable electrostatic effect, and would be very difficult to take account of in mathematical work. In electromagnetic effects, the resistance of the ground is, for currents of the frequencies of which I have spoken, ordinarily very considerable. We have found in some cases that a grounded circuit produces the same effect as though the return current were concentrated at a point a thousand feet below the surface of the earth, and in some cases a considerably greater distance, and I would be very much interested if Mr. Creighton can give us any information regarding the effects of the ground at these very high frequencies which he is discussing.

The other point I had in mind is an effect of the use of overhead grounded wires of which the author does not speak—the overhead grounded wires not only tend to protect the power lines from induced charges from clouds, but also tend to protect the circuits paralleling the power lines from charges induced by the power circuit. This effect is very considerable in some cases, and I am sure that telephone engineers should be pleased that Mr. Creighton is advocating their more extended use.

N. S. Diamant: I think it is well in connection with this paper to call attention to the advantages of investigating graphically electrostatic effects of ground wires, at least in the simple cases; the advantage of the graphical method is its simplicity and especially the fact that it gives a picture of the electrostatic stresses existing in the space near the ground and transmission wires.

From the nature of the subject, I think it is a serious defect not to have included in the paper references to previous work and to detailed mathematical and graphical solutions. The fundamentals on which the treatment of the subject is based are given in the monumental works of Maxwell. However, without going to original sources it would have added greatly to the value and usefulness of the paper to have a few references; even if the author used no references whatsoever, it would not have been as difficult for him to look up some, as it will be for any reader who may desire further details.

As Mr. Creighton has emphasized there are important assumptions to be made which are not unassailable and on which differences of opinion may exist. The results of this paper depend on these assumptions which Mr. Creighton has so clearly brought out. Now, references, no matter how incomplete, would have allowed us to compare some of the author's assumptions and results with those of others.

John B. Taylor: I must confess to being somewhat confused in following this paper, through the use of some of the terms. For instance, when we are discussing periods of time as brief as a millionth of a second, what is the interpretation to be put on such words as "instantly" and "suddenly." I judge Mr. Creighton wants us to assume that a charge accumulates in a cloud gradually through moisture condensation or other atmospheric condition, and that equally gradually the ground wire and the conductors of the line accumulate charges by induction from the cloud. Then "suddenly" without regard to time, it is assumed that the charge on the cloud, disappears in a lightning stroke, leaving the charge on ground wire to oscillate at its own natural period as determined by the conditions of the circuit,—distance between earth connection and the inductance and capacity involved.

A different state of affairs seems more consistent with his estimated length of lightning stroke as one mile. How is it possible to be rid of the charge on the cloud through a stroke a mile long in a time negligible compared with the time of oscillation in the overhead ground-wire circuit, which is given, in a 500-foot span, in the order of two million cycles per second.

The transfer of the cloud charge over a mile will take, in round figures, ten times as long as for the overhead wire charge to reach earth through the connection provided at 500-foot intervals. From this the release of the induced charge on the ground wire should follow the cloud discharge and be practically a periodic, instead of setting up oscillations of the order of millions of cycles.

In discussing the early use of overhead ground wires, Mr. Creighton may have overlooked the long established practise of the American Telephone & Telegraph Company. The "zero" wire on the tops of the poles served for lightning protection, mechanical stability, and convenience in testing. Mr. Creighton points out that a small wire is almost as effective as a large wire, as regards its electrostatic effect, but mechanical strength and ability to discharge heavy strokes without fusing are important factors. In some early installations poor material and flimsy construction gave more trouble than was prevented. There was a time when ground wires were in disfavor, but they have come into favor again, only after recognition of the need for good mechanical construction.

John B. Whitehead: It is interesting to remember that ever since the days of Benjamin Franklin, scientists, physicists and engineers have studied lightning phenomena, but no satisfactory explanation or theory has resulted. It is impossible, of course, to control the conditions in the natural case, and hence experience is limited to inadequate laboratory studies. Therefore it seems to me that it is quite proper to build up assumptions which come as near to actual conditions as our existing theories indicate, and then to compare the results following from them with the natural case.

Several years ago a paper was read before the Institute by Mr. J. P. Jackson, in which he made an effort to plot the equipotential surfaces of a transmission line with ground wires upon the towers. The surface of zero or ground potential, was shown to have different shapes in accordance with the different positions of the ground wire. The whole question reverts of course to Faraday's original proposition. which has been justified by experience in a hundred ways, that if you want to protect anything from lightning or from electrostatic influences surround it by a grounded cage. The grounded wire is simply a small approach to that condition, and therefore taking the conditions Mr. Creighton outlined in his abstract, it is perfectly natural that the nearer you put a grounded wire to the transmission wire just so much more nearly do you give it a grounded screen.

I question the correctness of one of the conclusions, namely that the grounded wire placed below the power wire should give it approximately as much protection as when the grounded wire is placed above it. Naturally, there would be some, but I think the difference should be quite considerable for all but the smallest distances of separation. Otherwise, the conclusions are in accord with the conception that the grounded wire, is simply an approximation to a grounded cage.

The author questions whether a lightning rod should be pointed, since when the corona starts from a point it is equivalent to making the wire blunt ended. My conception of the point of the lightning rod is that it gradually dissipates the charge as the potential rises by the discharge from its points, and consequently tends to keep down the potential. I should, therefore, question whether a blunt point would serve so well as a sharp point.

L. W. Chubb: The author speaks of the peaking of the charge, illustrated in Fig. 8, causing a displaced negative charge which forces a charge in the windings of the apparatus in an undesirable way. I understand that this menace only exists for the ungrounded system.

E. E. F. Creighton: Yes.

L. W. Chubb: Mr. Taylor has called attention to the relative time constants of the short line sections and the long lightning path, precluding the possibility of propagated wave trains and the more probable existence of sloping wave fronts. This is, I think, an important point and the analysis of lightning phenomena should be made assuming only factors of the proper order of magnitude.

In Fig. 14 Mr. Creighton has shown the parallel ground wire divided into short sections by the grounding wires, and each having an electrostatic capacitance to ground. At the time of discharge from cloud the freed charge in each section will divide and pass out the grounding wires as shown. The currents in the adjacent sections will induce in the power line traveling waves in opposite directions, which will result in standing waves. If the induced waves in the power line are nearly in phase there will be a rather complete cancellation of the waves and a falling off in amplitude along the line as it passes outside of the influence of the cloud. This cancelling effect and the damping in the circuits would seem to be enough to limit the wave trains beyond the influence of the cloud to a rather insignificant amplitude. There is also some doubt in my mind whether the released charge in the section of the ground wire will oscillate, because the capacitance is not concentrated as shown in the figure. The section has distributed capacitance and inductance. If the distributed constants of the section of the ground wire do prevent the propagation of wave trains in the power line, the standing waves will not exist and the bad after effects of the ground wire would be reduced to a very sloping wave front of much less amplitude than if the ground wire were not present.

In several places in the paper the author, in pointing out the inductive effects of the ground wire on the power wire, speaks of the sudden change in capacitance to the line. Capacitance is an invariable physical constant and I cannot see how a change in capacitance takes place during the transient.

E. E. F. Creighton: I am unable to give Mr. Osborne any experimental information on the distribution of high-frequency currents in the ground. I am glad Mr. Osborne added another use of the overhead grounded wires which I had overlooked.

Referring to Mr. Diamant's request for a bibliography, I have to confess that I did not make one and in fact did not attempt to look up all the references. The mathematical equations, as originally given by Maxwell and Heavyside are available to those who have the volumes. These I have not referred to for many years. The work by Heavyside will be found in one of his two volumes of "Electrical Papers."

Referring to Mr. Taylor's comments—I endeavored to simplify this matter by considering only one variable at a time. The neglected factors are, I believe, stated in the foot note. The words "instantly" and "suddenly" then refer in an indefinite way to the period of time corresponding to the length of charge in the constants of a circuit. In reading the paper it should be kept in mind that in the beginning all factors that could be set aside were neglected and subsequently each one of these was considered, although they were not all combined, as it would make the subject too complex.

Referring to Dr. Whitehead's skepticism on the protection given by an under-hung wire—I can only recommend to him that he make the calculation to be convinced.

Referring to the last paragraph in Mr. Chubb's discussion—it is impossible to come to any definite understanding because of the several different definitions given for capacitance. If one defines capacitance as the quantity per unit difference of potential, then Mr. Chubb's conception of the invariable physical constants will hold only when there are two electrodes, namely one positive and one negative. We often think of capacitance as certain dimensions, as is always true in a single condenser but when there are three or more electrodes then capacitance is determined not only by the physical relations but also by the relative potentials of the conductors. I have worked out many examples to prove this statement. The calculations are too long to include in this discussion. This paper was shortened more than 50 per cent by curtailing the mathematical work and calculations. I can hardly hope to have deleted this material judiciously in every case although I hope I have put enough mathematical work at the end of the paper to suffice for the understanding of the equations used.

Presented at the 33d Annual Convention of the American Institute of Electrical Engineers, Cleveland, O., June 30, 1916.

SUGGESTIONS FOR ELECTRICAL RESEARCH IN ENGINEERING COLLEGES

BY V. KARAPETOFF

ABSTRACT OF PAPER

The primary object of the paper is to present a list of topics in electrical engineering suitable for thesis, research, and advanced study. A plea is made for systematic research, each college specializing year after year in only a few topics for advanced investigation. The author suggests that the Educational Committee of the Institute become a central place for information and a stimulus in applied electrical research, cooperating with engineering colleges and with individual inventors and investigators.

Various types of investigations are enumerated, such as invention, experimental study, theoretical study, library search, and compilation of data. Some advice is given the young investigator as to how to proceed in the most efficient way and to avoid a disappointment.

"WHAT topic shall I choose for my required thesis?" This is a question that will sound familiar to a teacher in electrical engineering. Sometimes the students puts the question in this way: "I have some spare time and should like to do research work; what would you suggest for a subject?" Again, once in a while a young practising engineer writes that he does not wish to become " rusty " and asks that a subject be suggested for systematic study in the evenings. Truth forbids the statement that such inquiries come often enough to be burdensome; nevertheless the writer found it convenient some years ago to compile " A List of Electrical Subjects for Thesis, Research and Advanced Study," as a ready reference in answering such inquiries. This list was privately printed in 1909 and has been used since by a number of the author's colleagues in various engineering colleges.*

A revised and augmented list is now offered to the profession in the hope that it may prove useful and stimulating to students,

*For a similar list of topics in mechanical engineering see H. Wade Hibbard, "Thesis Directions for Students," Proceedings of the Society for the Promotion of Engineering Education, Vol. 21 (1913) p. 129.

to teachers, and to engineers who are interested in research, invention, and advanced study in electrical engineering.

The author also recommends that the Educational Committee of the Institute revise this list from time to time and keep it up to date, soliciting additional suggestions from various technical committees, from prominent practising engineers and from teachers. In this manner the Educational Committee would in time become a source of information and stimulus for organized electrical research.

Anyone who follows European electrical periodicals will agree that this country is behind Germany and England in the invention of new types of electrical machinery and apparatus, in the discovery of new electrical phenomena, and in the development of working theories and numerical relations needed in our profession. Whatever the causes of our backwardness, we must find a remedy for it, and the most important first step is to systematize and organize research.

The American Institute of Electrical Engineers has not limited itself in the past merely to recording the progress of the art and the opinions of its members. Through its committees and representatives the Institute has participated in the solution of a number of important national and international problems, and it has never failed to take an active interest in activities by which it was able to render important service to the profession and to the nation.

The promotion of organized research in engineering and the encouragement of young men to train themselves in the art of invention is at present an important national problem, if we are to rank with the leading European nations and to be independent of them in times of need. The author has emphasized elsewhere more in detail the importance of *systematic* research and of encouraging the art of invention among young engineers.* The national engineering societies are naturally called upon to lead in this movement, and the American Institute of Electrical Engineers ought to do its share. In fact, one of the principal objects of the Institute, according to its

*See his paper entitled "What has Engineering Education contributed to Scientific Progress and Invention," presented at the second Pan-American Scientific Congress in Washington, D. C., on Dec. 31, 1915, and published in the Bulletin of the Society for the Promotion of Engineering Education, April 1916, p. 597. See also J. A. Fleming, "Organization of Scientific Research," *The Electrician*, (London), Feb. 18, 1916.

constitution, is "the advancement of the theory and practise of electrical engineering and of the allied arts and sciences."

The Educational Committee of the Institute could well carry on this work if some of its members were selected with this purpose in view, and if it could arrange for cooperation with the other technical committees. This would be a distinct field of activity closely connected with the rest of the work of the Institute, and at a safe distance from the work of special educational societies, especially the Society for the Promotion of Engineering Education. This new activity of the Educational Committee of the Institute might be carried on as follows:

1. The Educational Committee could announce in the PROCEEDINGS and by letter to the electrical departments of the technical schools in North, Central, and South America that it is prepared to assist the students and young engineers by suggesting topics for research, invention, and advanced or special study.

2. The Educational Committee could regularly collect and publish suggestions as to timely topics for research from the technical committees of the Institute, from manufacturing and operating concerns, testing laboratories, consulting engineers, prominent scholars, etc.

3. The Educational Committee could collect information as to the facilities for research available in different schools, and the problems already solved or under investigation. The principal schools might be induced to conduct certain researches in cooperation, rather than to duplicate work. Each school ought to specialize in research along a few definite lines year after year, in accordance with the facilities available and the relation to the local industries. In this manner valuable results could be achieved, whereas now the attempts are mostly sporadic, leading nowhere.*

4. The principal results of research might be published regularly in abstract in the PROCEEDINGS, and thus made of general use, where now they are simply filed in college libraries.

*Perhaps the most instructive case of systematic research carried on through many years was that at the Elektrotechnisches Institut in Karlsruhe, under the inspired guidance of the late Engelbert Arnold (1856-1911). As a result of this work we have several volumes of the most accurate and useful information on dynamo-electric machinery and numerous valuable inventions; while scores of Arnold's former students all over the world, are prominent as inventors, investigators, designers, and scholars. In this country Professor Harris J. Ryan with his students has carried on investigations on dielectric stresses for years with splendid results.

5. The Educational Committee from time to time should publish in the PROCEEDINGS a brief account of the most important progress in apparatus, methods of measurement, mathematical relations, etc. In these accounts emphasis should be placed upon the method of attack, logical reasoning, patience of the inventor or the investigator, the importance of a clear knowledge of physics, mathematics, mechanics, and chemistry, and in general all such facts as may encourage young investigators and help them in their own research.

6. The Institute might announce each year one or more prizes and medals for the best improvement in apparatus, measurement of some difficult quantity, the best theoretical investigation, etc. These prizes need not be over $50 to $100 each, and the money can be easily appropriated out of the general expense fund of the Institute. Prizes might also be announced for the solution of definite problems of special importance in manufacturing and manufacturers might be induced to furnish money for them.

7. The Institute could help both the electrical industry and the colleges by inducing larger electrical concerns to maintain industrial scholarships in engineering colleges that are prepared for the work. Such scholarships have proved very useful in chemical industry, and in the manufacture of cement, steel, etc.

8. The Institute might pave the way and lend its influence towards the foundation of a National Institute for Electrical Research, or even a National Institute for Engineering Research, similar to some existing institutes for medical research.

GENERAL REMARKS

1. The list furnished is by no means complete or exhaustive and is primarily intended to be suggestive. It would of course be out of the question to write out in detail the purpose and the program of every possible investigation in electrical engineering. The important preliminaries to almost any bit of research are to find out the present status of the problem, to formulate what is needed, and to devise the means for carrying on the investigation. Having selected a general topic the student should make a search in the literature of the subject, consult his instructors, and if necessary take the matter up with outside specialists.

2. The topics are suggested in general terms only, because it is not supposed that a beginner would use the list. If neither the student nor his teachers know anything about the present

status of a certain topic, it is hardly likely or even advisable that the student should take it for his thesis. He needs an elementary text-book on the subject. If, however, at least one of them knows something about the particular topic, its mention in the list will be sufficiently suggestive, and will recall to his mind certain definite problems to be investigated, and he will know where to go for some first-hand information on the subject.

3. Each technical college will find it more effective and more useful from an educational point of view to induce successive students to continue each other's investigations for a term of years until definite results have been achieved. The college can then afford to invest a considerable sum of money in apparatus and will develop real experts among its faculty who supervise this research. With a proper selection of a few topics this policy would in a few years lead to the formation of a valuable specialized experiment station.

4. As far as possible, only subjects of vital interest have been selected for the list, although the author does not believe that the immediate applicability of the results is of prime importance. What counts is the ability to size up a situation; to obtain the necessary information; to concentrate one's whole attention and interest on a problem, and to get definite results. Facts and relations that are of no practical use today, may become very important presently.

5. Much valuable work can be accomplished by colleges and their advanced students through exercising a wise foresight as to future developments in the electrical industry. Often manufacturers feel disinclined to experiment on subjects whose commercial usefulness seems remote, and here is where a college can blaze the way, clear the situation, perform the first preliminary experiments and bring the results to the attention of those who may continue the work on a larger scale and with more accurate means.

6. A résumé of the present situation is needed in most of the important topics for research. Sometimes a student without much imagination but with plenty of patience may be utilized for this preliminary work; he may thus become a useful contributor to the solution of a problem where he would have failed if allowed to undertake an original investigation. It is earnestly urged that students and others interested in the progress of our profession do more of this kind of work, describing in a connected and critical manner what has been done, how it was done, where the information is to be found, and what remains to be done.

Such information freely published in magazines and transactions would not only serve as a powerful stimulus for research, but would relieve able investigators and inventors of a great burden.

PRINCIPAL TYPES OF INVESTIGATIONS

(a) *Invention or improvement* in apparatus, in connections, in materials, in methods of manufacture, etc. If possible, always take an investigation of this kind, because the progress of engineering art depends essentially upon invention.

(b) *Search in the patent records of the United States and foreign countries* with the view of determining the state of the art in a particular subject or branch of industry. Such a search often saves a great amount of labor, expense, and bitter disappointment later on. Moreover, a thorough knowledge of the combinations and means used by other inventors sometimes suggests one of the remaining combinations not covered by patents, or an improvement in the preceding inventions. If students and young engineers would do more of this class of work and less promiscuous inventing, we would have fewer annoying and disappointed inventors, and more inventions of real value.

(c) *An experimental investigation* of some device or group of devices, a material, a process, etc., to determine the effect of certain factors, for future guidance.

(d) *A theoretical investigation* of some relationship or phenomenon, with the view to explaining or generalizing certain observed facts; also to predict performance, to enable the designer to proportion a piece of apparatus, to avoid some harmful effect in operation, or to take fuller advantage of some beneficial effect.

(e) *Compilative* or semi-compilative work, such as systematization of notation or nomenclature; comparison of theories, experiments or data of various investigators: unification and simplification of procedure in design or in other computations; preparation of tables, curves, formulas, etc., for a particular purpose; bilbiography of a given topic, etc.

ADVICE TO THE YOUNG INVESTIGATOR

1. One who hopes to succeed in invention or research must possess persistence, accuracy, imagination, resourcefulness, good general education (so as to borrow methods from other branches of science) and in addition some special knowledge or skill directly pertaining to his problem. It may be experimental skill, dexterity with tools, mathematical ability, knowledge of foreign languages,

etc. Often an attempted research ends in failure not because of alleged external difficulties but because the student selected the wrong kind of problem; for instance, one requiring experimental ability, when his strong point is library research. An insufficient knowledge of the fundamentals of one's profession often results in a failure in research, though it is sometimes difficult to convince the student of the connection between the two.

2. Before taking up a piece of special research ask yourself if the same time could not be more profitably spent in a study of some more general topic in electrical engineering. For example, would you spend, say, half a year in experimental research of the effect of wave-form of the applied voltage upon the core loss in a transformer, or would it be more useful for yourself to put the same time in a study of books and articles on transformers in general, their theory, construction, design, connections, etc.? This question no one but yourself can answer.

3. Remember that in practically every case you expect to continue the work of others; therefore be particularly careful to find out what has been done, avoid duplication, and give due credit to the preceding investigators. The literature search may be properly begun with the "Science Abstracts," Part B, Electrical Engineering. In some cases Part A, Physics, must also be consulted. The corresponding German publication "*Fortschritte der Elektrotechnik*" is also excellent and perhaps more systematic; in addition to abstracts and periodicals it contains new books and patent specifications. The well known "Engineering Index," and the card catalogues arranged by topics and found in the Engineering Societies Library in New York, in Carnegie Library in Pittsburgh and in large college libraries are also great helps. The indexes to the leading electrical magazines and transactions should also be consulted.

4. When planning some research or invention try to think of it in the light of the past and future development of the subject, and not as a detached little investigation of your own. This means that you must connect your work with that of former investigators, and present your results in definite form so that the following investigators can connect them with their work and profit by your labors.

5. There are problems on which no one is working, either because the situation is premature, or because others became discouraged through lack of results. There is an advantage in working on such a problem. Should you succeed, your credit

and recognition will be so much greater. On the other hand, you are much safer working on a problem already staked out by others, where you are merely developing a detail. Some prefer exploring the wilderness, others keep near to beaten paths.

6. Almost any problem mentioned in the following list may be made as short and elementary or as long and thorough as is desired, from a superficial undergraduate thesis finished in a few weeks, to an expert's deep research carried on devotedly through a long series of years. Do not "bite off more than you can chew," but whatever you decide to do, do it well.

7. Do not try to maintain secrecy regarding your work, but try to draw into it and to interest in your problem as many other able persons as you can. Both you and they will be benefited thereby. Consider yourself to be but a thief's apprentice who is learning how to steal nature's secrets, but is not actually doing it yet.

8. Having made a patentable invention or obtained a patent do not try to hold it for an exorbitant price. Dispose of it on the basis of a reasonable sum down and a moderate royalty per year or per piece sold. If you have a real inventor's stuff in you, you will make many more important and lucrative inventions. Dispose of your first effort as soon as possible; it will be an encouragement for your further work.

Electric Generators and Motors

Output Coefficients. Theoretical justification and limitations of the D^2L formula.

Values of flux density, ampere-conductors per centimeter of periphery, and current density in actual machines.

General study of the best utilization of active iron and copper.

Elements of cost of machinery.

Heating and Ventilation of Machinery. Flow of heat along and across laminations, along copper conductors, across slot insulation, through thick field coils, etc.

Heat transfer between various surfaces and the air, stationary and in motion.

Temperature distribution in a given machine, and bettering its performance by more effective cooling.

Forced ventilation.

Cleaning and cooling of the air.

Rating for intermittent service.

Commutation in Direct-Current Machines. Actual phenomena of commutation with and without interpoles, by means of oscillograph.

Commutation on a device imitating an actual armature coil.

Interpoles, effect of their width and saturation; inductive shunts.

Effect of compensating windings on performance.
Study of brushes.
Proposed formulas and theories of commutation, a critical review of.
Approximate methods of integration of the differential equations of commutation.

Mechanical Construction and Stresses in High-Speed Machinery. Support of armature coils; dovetail stresses; vibration of shaft; stray currents in shafts; fastening of field coils; high-speed commutator; stresses in stationary frame; eccentric rotor.

Armature Reaction and Inductance. Armature reaction in d-c. machines.
Armature reaction in polyphase and in single-phase alternators.
Proposed methods for compounding alternators.
Exact theory of armature reaction and practical approximations.
Leakage inductance of windings, and the separation of slot leakage, end-connection leakage, etc.
Theoretical predetermination of leakage inductance.
Transient condition during short-circuit.
Hunting.

Polyphase Induction Motor. Proposed methods for speed regulation.
Performance characteristics and circle diagram above synchronism.
Predetermination of power factor from design data.
Magnetic leakage and its components.
Exact circle diagrams of performance.
Magnetizing effect of distributed windings.
Experimental separation of losses.
Methods for accurate determination of slip.

Single-Phase Induction Motor. Proposed methods of starting.
Rating of the same frame for one, two, and three-phase windings.
Design of a single-phase induction motor.
Experimental and theoretical investigation of the elliptical revolving field.
Circle diagram of a single-phase induction motor.

Single-Phase and Polyphase Commutator Motors. History of development.
Classification of types.
Means employed for improvement of commutation.
Performance diagrams of the principal types of commutator motors.
Comparison from the point of view of speed-torque characteristics.
Comparison from the point of view of commutation.
Experimental study of a commutator motor.
General principles of design.
Complete design of a single-phase railway motor.
Design and construction of a working model, imitating the electrical relations in a commutator motor.
Phase adjusters for improving power factor.

General Design. Factors to be considered in the design of a new line of machines.
Critical comparison of procedure used by various authors.
M. m. f. required for the active layer.
Design of a line of small machines for manufacture in large quantities.

Layout of a factory for production of a given line of electrical machinery.

Improvements in Methods of Testing. Critical study of methods for measuring temperature, core loss and the separation of hysteresis from eddy current.

Measurement of friction and windage.

Resistance measurements.

Methods of loading a machine by means of circulating power (pumping back methods).

Measurement of speed, slip and acceleration.

Load losses in single-phase alternators.

Special Types of Electrical Machinery. Homopolar generator, reduction of brush friction, increase in speed.

Constant-current machine for operating large arc projectors.

Train-lighting generator driven from car-axle.

Automobile starting motor and lighting generator.

Magnetos for ignition.

Synchronous motor with high starting torque.

Electric variable-speed drive for automobiles.

High-frequency alternator for radio work.

Motor-generator set for intermittent load with energy stored in a fly-wheel, such as are used in steel mill and mine-hoist work.

Combination of an induction motor and a polyphase commutator motor.

Motor-converter consisting of an induction motor and a d-c. generator with inter-connected windings. Permutator or a converter with stationary field and armature and revolving brushes. Thury high-tension d-c. constant-current machine.

Battery boosters and counter e. m. f. sets.

TRANSFORMERS

Leakage Reactance. Experimental investigation of the influence of arrangement and shape of coils.

Theoretical formulas derived from the equations of electromagnetic field.

Influence of unequal distribution of current in large conductors.

Internal vs. external reactance for safety of large systems during short-circuits.

Economic Relations. The best distribution of losses for a given service.

Amount of copper and iron as a function of relative prices of these materials.

Best values of flux and current density.

Influence of Wave-form. Effect upon the voltage drop, upon the iron loss, and upon the stresses in dielectrics.

Temperature Rise. Theory of conduction of heat; experimental data; influence of various factors; safe temperature rise with various materials; devices for forced cooling.

Artificial load for heat run.

Extrapolation of heating and cooling curves.

Connections. Comparison of delta and Y-connections under normal and abnormal conditions.

Analysis of currents and voltages in *T* and in *V* connections.
Doubling the frequency by means of two transformers.
Electrostatic Stresses and potential gradient in and around bushings, terminals, between coils, etc.
Extra stresses due to transient conditions.
See also the section on Dielectrics.

Power Plant Design and Economics

Standardization of electrical equipment for smaller plants.
Elements of first cost and of operating expenses.
Rational methods of charging for energy.
Forms and blanks for accounting.
Safety appliances, emergency devices, labor-saving apparatus.
Parallel operation of power plants.
Division of load between a steam and a water power plant.
Uses of storage battery.
Automatic substations.

Transmission Lines and Cables

Mechanical stresses in towers and in conductors; influence of temperature.
Skin effect in copper covered and steel wire and in stranded cable.
Interference between power and telephone lines; theory, calculation of induced currents, experimental investigation, methods for reducing interference; the general problem of transposition.
Locating faults with the line energized or dead.
Protection against grounds and short-circuits, sectionalization, relays.
Actual experience with lightning and possible conclusions.
Various types of protection against lightning.
Theory of the ground wire.
Current and voltage relations in lines with distributed properties.
Standing and traveling waves; surges and protection against them.
Experimental mechanical apparatus imitating electric waves.
Transient electric phenomena studied experimentally and theoretically.
Kelvin's law of economy and its various practical applications.
Computation of electrostatic capacity and stresses of cables.
Reduction of capacity in telephone cables.
Propagation of signals in submarine cables.

Electric Traction

General Projects. Design of a high-speed underground road for a large American city.
Design of an elevated road for local and express trains.
Electrification of a large steam railroad center.
Electrification of a mountain division of a steam railroad.
Gasoline-electric and straight gasoline cars for light traffic.
Storage-battery car.
Trackless trolley car.
Competition of the motor bus and of the " jitney " with city, suburban, and interurban railways.

The electric truck.
The electric passenger vehicle.
The dual power car.
Electric traction of boats on a ship canal.
Design and organization of repair shops for a large electric-railway system.

Track, Trolley, Signals. Standardization of the materials, and of the methods of operation and maintenance.
Rail corrugation.
Continuous rail, electric welding, thermit welding.
Bond testers.
Stray currents and prevention of electrolysis.
Overhead construction in various classes of service.
Mechanical stresses in trolley wire, in messenger cables, and in the supporting structures; the problem of support on curves.
The surface-contact system.
Sectionalization of trolley circuits in freight yards, in large passenger terminals, etc.
Automatic switching.
Automatic signals.
The problem of safe and quick dispatching of high-speed roads.

Rolling Stock. Quick and accurate predetermination of time-speed curves.
Design of an apparatus for automatic tracing of time-speed curves.
Resistance to motion of single cars and trains.
Special equipment of an electric car or locomotive for various tests and experiments.
Single-phase locomotive with an electro-dynamic converter or with a mercury-vapor rectifier.
The possibilities and limitations of high-tension direct-current traction.
Recuperation of power on electric roads.
Control of high voltages or of heavy currents in an electric locomotive.
Various types of drive; gears, side-rods, direct drive.
Electrically controlled air brakes for high-speed roads.

ELECTRIC LIGHTING*

Light sources: proposed standards; new types of electric lamps; position and shape of filaments, temperature of operation; color characteristics, and effects; design for special purposes; operating mechanisms.

Lighting accessories; optical properties of diffusing and reflecting media; globes, shades, and reflectors for special purposes; "daylight" glass; means for eliminating glare.

Visual photometry; sensibility of photometers; size of photometric field; errors due to instruments; errors due to operator; effect of color sensibility of observer; recording devices; calibrating devices; integrating photometers; flicker photometers; standardization of absorbing solutions; means for eliminating color differences; standardization of conditions of measurement.

*Contributed by Professor F. K. Richtmyer.

Physical photometry: the selenium cell; the photoelectric cell; the bolometer; the thermopile; absorbing solutions; photographic methods; other chemical methods; new methods.

Studies in illumination: Survey and criticism of present conditions in various types interiors, in streets, etc.; intensity and type of illumination necessary for various purposes; eye fatigue and visual acuity as dependent on intensity of illumination, color, and system used; design of systems of illumination; illumination calculations.

Terminology of illuminating engineering.

Relation of art, architecture, physiology, and psychology to illuminating engineering.

Application of Electric Motors*

Industries. Agriculture, automobile, bakeries, boiler works, bottling works, box factories, breweries, brick factories, broom factories, building construction, candy factories, carpet and rug factories, cement, clothing, corn mills, cotton mills, cotton oil seed mills, creameries, dairies, dye works, flour mills, foundries, freight handling, glass factories, glove factories, hardware manufacture, harness factories, ice machines, irrigation, knitting factories, laundries, lumber mills, machine shops, paper box factories, paper and pulp mills, piano factories, pipe mills, planing mills, porcelain factories, railways, refrigeration, rubber industry, shoe factories, shoe repairing, soap factories, spice factories, steel mills, stone quarries, stove factories, sugar industry, tanneries, textile mills, tile factories, tobacco factories, trunk factories, wagon factories, wall paper factories, woodworking factories, woolen and worsted mills.

Classes of Service. Air compressors, blowers, coal cutters, concrete mixers, conveyors, cranes, crushers, dental appliances, dredges, elevators, exhausters, fans, hoists, ice cream freezers, lime kilns, locks, pumps, printing presses, rock drills, sewing machines, ship propulsion, towing machinery, turn-tables, vacuum cleaners, vehicles, washing machines.

Measuring Instruments and Methods

General. Study of characteristics, errors, cost of manufacture, etc. of a given type of meter.

Development of a new type to meet competition in price or to avoid infringing certain patented features.

Design of a complete calibrating equipment for a manufacturing concern, an operating company, a testing laboratory, a college, etc.

Special instruments, such as a double tariff meter, a maximum-demand indicator, a volt-ampere meter, an automatic synchronizer, a phase displacement meter; instruments, for recording rapidly-fluctuating currents and voltages, etc.

Instrument transformers. Design, methods of calibration, errors, exact theory, vector diagrams, etc.

Extra-Accurate measurement of various quantities used in electrical engineering, viz., current, voltage, power, resistance, inductance,

*Contributed by Mr. D. B. Rushmore.

capacity, speed, acceleration, slip torque, magnetic properties, dielectric properties.

Analysis of methods, errors, applicability in various cases, new devices and new diagrams of connections.

Magnetic Measurements. Measurement of permeability, core loss and retentivity.

Effect of composition and treatment of steel upon its magnetic properties.

Heusler alloys.

Experimental investigation of distribution of a magnetic field, using an analogous condition of flow of heat or electricity through metal, or flow of water.

Detection of flaws in rails by a magnetic method.

Relays. Overload, underload, and reverse load; over or under-voltage, high and low frequency, low power factor.

Merz-Price and similar selective arrangements.

Time characteristics, instantaneous, definite time, inverse time, etc.

Relays for regulating voltage of generators, batteries, feeders, etc.

Regulation of power factor, frequency, speed, etc. by means of relays.

Relays for submarine telegraphy.

Radio Transmission*

Methods for producing damped oscillations for transmission purposes.

Methods for producing damped oscillations of particularly constant amplitude for laboratory measurement purposes.

Methods for producing undamped or continuous oscillations for transmission purposes.

Study of radio detectors.

Study of radio amplifiers.

Study of the " beats " receiver and methods for producing oscillations for the same.

Comparison of " tikker " and " beats " receiver for the reception of undamped waves.

Advantages and disadvantages of using the " beats " receiver for damped waves.

Directive radio communication. Study of the variation of signal intensity with varying wave lengths. Methods of modulating the antenna current for radio-telephony.

Design of a compact portable decremeter.

Study of radio measuring instruments.

Design and construction of portable radio sets.

Design and construction of radio apparatus suitable for instruction and demonstration.

Modern theories of propagation of electromagnetic waves (without mathematics).

Experimental determination of " radiation resistance."

Mathematical theory of radio transmission.

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*Contributed by Mr. C. W. Ballard.

Dielectrics

Experimental study of various insulating materials under various conditions of service.
Theory of dielectric stresses in two dimensions by means of conjugate functions.
Experimental investigation of distribution of an electrostatic field using an analogous condition of flow of heat or electricity through metal, or flow of water.
Surface resistivity.
Design of high-tension insulators, bushings, transformer insulation, etc.
Reliability of spark gaps of various shapes.
Measurement of extra-high voltages.
Design and construction of a transformer for testing purposes.
Study of insulating oils; development of a practical and reliable test.
Compressed gas as electric insulation.

Miscellaneous Problems

Agriculture, electricity in.
Amplifiers for weak currents and voltages.
Arc phenomena.
Automobile starting, lighting, ignition.
Atmospheric electricity, oscillograph study by means of an antenna.
Circuit breakers.
Electromagnets.
Farm lighting and power.
Fixation of atmospheric nitrogen.
Fuses.
Heating and cooking; heat accumulators; high-resistivity alloys; temperature control· insulation.
Magnetic separation of iron ores.
Marine applications of electricity; electric drive of an ocean steamer.
Pictures, transmission of, by electricity.
Precipitation of suspended matter; smoke abatement.
Rectifiers, aluminum, cathode ray, mercury, revolving, vibrating contact.
Safety rules, standardization rules, and standard specifications of various associations in this country and abroad; a critical comparison.
Submarine signaling.
Thermo-electricity, generation directly from fuel.
Telegraphy, rapid, multiplex, submarine with alternating currents.
Telephone apparatus for the deaf.
Telephone transmitters of great power; sensitive telephone receivers and relays, phantom circuits.
Water purification by electricity.
Welding, electric.

APPENDIX

In connection with the suggestion that the A. I. E. E. should encourage systematic research under the auspices of its Educational Committee, the following description of the organization and work of the Research Committee of the A. S. M. E. is given by Mr. R. J. S. Pigott, a member of the committee.

The object of the Research Committee is to promote the investigation of phenomena, operations, or results of experiments concerning fundamental laws on which engineering practise is based, and to place such data in permanent and basic form. The general committee meets at stated intervals to consider suggested research subjects and to appoint sub-committees to do the actual work of research. Generally, the chairman of the sub-committee is a member of the general committee, but not necessarily so. The present sub-committees are those on fuel oil, materials of electrical engineering, safety valves, worm gears, lubrication, clinkering of coal, steam flow meters, laboratory systems and methods; and a committee on investigation of machine tools is under consideration.

The chairman and members of the sub-committee either carry on research in their particular field, themselves, by cooperation with manufacturers, or else have the work done by an interested manufacturer. In general, the expense of the research is borne, therefore, by the interested parties and not by the society.

Up to the present time the committee has not presented any final reports, but the work on worm gearing is well under way, and also that on steam flow meters. As research work is usually lengthy, final reports in less than two or three years are not to be expected. As noted in the definition of the activities of the committee, the work may consist in some cases merely of collation of existing data and putting them in usable form, rather than of original research.

DISCUSSION ON SUGGESTIONS FOR ELECTRICAL RESEARCH IN ENGINEERING COLLEGES" (KARAPETOFF), CLEVELAND, OHIO, JUNE 30, 1916.

J. B. Whitehead: There is truth in what Prof. Karapetoff has to say about the products of research from Germany and England. I do not know that it is quite as definite as he would imply, but I have in mind the character and form of the publication of the results of research as given in the German and English periodicals; and the publications of the German and English engineering societies, I think are superior to those of our own. I would make a plea here for a more careful editing of the publications of our American research. Certainly a comparison, particularly of the German publications, with our own will, I think, indicate that there is truth in what I say, namely, that these publications are better prepared. The precautions that are taken in experimental work are better described, and more effort is made, and I suppose more careful editing accompanies the publication of the results of experiments abroad.

As regards the special fields of investigation in different universities and colleges as related to their particular equipment, I do not believe that is a practical suggestion. I think that research is a question of men and minds, more than it is of equipment and location. I do, however, believe that continuation of a particular subject that has once been started is a most prolific and valuable principle to have in mind. It is one, fortunately, which results naturally in the course of events—when a particular line of research develops and a mature student or a professor is conducting research, it is most natural that he should invoke the assistance of the younger men, and the younger men's interest is at once attracted, and so the work continues naturally. This condition obtains in many places now.

I believe that the suggestion of prizes for investigations is a very good one. We have a number of prizes in this country now for conspicuously valuable results of research, but they are, I think, usually given as rewards for completed efforts, for more mature work. I believe the offering of prizes for work done by young men, perhaps before they leave college, would be a very valuable incentive.

The suggestion of a Research Committee is not a new one. I had in my hand before I left my office, and expected to bring with me, a small pink leaflet that perhaps some of those present will remember. It was headed "Committee on Cooperative Research," and I think the date was 1903 or 1904. That leaflet sets forth a number of subjects from which in the minds of the Committee profitable results might be obtained. I was interested to find that a number of the subjects which were suggested in that comparatively short list are still to be found in Prof. Karapetoff's list.

I do not think that the list of subjects, such as given by Prof. Karapetoff, goes very far in helping the investigator on his way.

Fields for study and for investigation are not difficult to point out. I have found in my relation to this subject that it is far more important, not only to suggest the subject, but to outline the attack. It is almost always indispensable that this should be done. Obviously, an investigation cannot be attacked in any direction without a complete survey of the literature and the work which has already been done. It is not possible, however, to entrust to a young investigator a study of the literature and to leave him to work out the lines of his attack. You can point out the literature to a student and tell him where to go so that he can make a survey of the whole field, but even then he cannot digest it. His judgment is not sufficiently matured to enable him to decide which are the contributions most valuable to the particular line of attack he has in mind. I have found much to my discomfort that it is the duty of one who is attempting to inspire research work to go much further than to simply suggest the subject. It is almost invariably a case of outlining the apparatus and the equipment, and generally also ordering it.

Alan E. Flowers: I think a great many colleges have made use of lists of thesis subjects, such as are submitted here, possibly not so long, possibly more varied in some cases. Such a list has very generally been found to be very useful as a starting point, and nothing that I say later should be constiued as opposed to the idea of having such lists, but it is certainly true, as Prof. Whitehead has just said, that the most important thing is, that the list should be supplemented by personal interview and by a considerable amount of suggestion and in some cases of instruction.

I am also very much interested in the idea which is advanced in the paper, of giving prizes for research work. It has always been a matter of great regret to me that the original plan for the Edison Medal was not so arranged that the medal would be made available, in some measure at least, for worthy undergraduate theses. As I remember the conditions, there was a certain age limit, and in addition it was provided that the thesis should be entirely the work of one man. In nine theses out of ten, the thesis is the product of two workers. There are several reasons for this. One of them is the necessity in a great many cases, particularly the case of experimental theses, for two observers, and as it is out of the question for a student to hire his observer, he must have a co-worker. This provision eliminated most of the theses of any value.

I think the conditions for such prizes could readily be changed so as to greatly stimulate experimental research work in the case of the undergraduate, and I rather think that there is some need for such stimulation, because the student who conducts an experimental research thesis is greatly handicapping himself as compared with the student who conducts almost any other type of thesis. He is very sure to put in more time on the work; he is very sure to have more worry; and he is very unsure to get results that will satisfy anybody. Anything within reason that can be done to encourage and help the experimental thesis is, in my opinion, worth while doing.

I am quite sure that, however much I would object to an educational committee or a research committee defining what subjects certain places should take, there is a great good to be obtained by getting major lines started at particular places and endeavoring to make it possible to continue that line of work at that place.

The reason I object to the scheme of fastening research subjects on places, is that I believe the most important thing is to keep the door wide open for a large number of individual suggestions. Whenever we begin to use the fixed method, what might be called the autocratic method, it seems to me we are killing off the most valuable and the most useful of the possibilities, that is, the origination of ideas, the origination of subjects, the carrying on of individual work and the encouragement of originality.

Scholarships would help, to a certain extent and possibly the most useful thing would be something in the nature of industrial scholarships, made available, not for the undergraduate, but for the graduate student. The undergraduate student who shows ability in research and has originality, would be encouraged by the prize and he might then very easily be led on to the post-graduate work of great value.

I think that great good might come to the Institute from a Research Committee. I am a member of the Research Committee of the American Society of Mechanical Engineers, and I have been very greatly impressed by the possibilities of that committee's work.

I feel it would be hardly right, however, to leave this subject without saying one more word about "prizes" I mean by that, compensation. I am afraid that at the present time there has come into existence the idea that in research "virtue is its own reward." So far as I can see, the relations between compensation in research work and compensations for other kinds of work is very much to the detriment of the research worker, whether he be working in pure science or applied science. That seems to me a fundamentally wrong condition, and I think it ought not to pass unnoticed. It is not only a question of the right of the thing, but also a question of the amount of work that might be done. It is a question of the encouragement of additional work. I have long had the feeling that there ought to be some special form of compensation, besides whatever there may be in the way of salary, whatever there may be in the way of reputation, that will come to the worker for each particular thing which he brings out. I see no reason why, a research worker, who reaches results of value, and allows them to be put on the market, should not get royalties, should not have the sort of thing granted an independent invention.

The large companies ought to give serious consideration to granting some special royalty or lump payment for each invention developed by one of their workers.

C. E. Skinner: My attitude toward this subject is probably quite different from that of the man in the university, as my whole experience has been in connection with a large corporation. I have many times been asked by university men to suggest subjects for research work. I find it a very difficult thing to do, because it is hard to outline the surrounding conditions to the man undertaking the research. One does not always know the facilities at his command, and the large corporation is, as we all know, whether you are inside or outside, somewhat jealous of the information leading to new things.

I think that some of the cautions, some of the advice, given by Prof. Karapetoff are very good indeed, and I am not sure that some of his subjects, shown in the list, are not too large. I frequently tell my associates that no matter what a subject is, no matter how small it seems to be, if one goes into it completely—going into literature the first, which should always be done, going into the investigation with a view to finding out about all that can be found out about a particular thing—the subject will grow and the interest will grow.

It very often happens that the by-product of the research is of far greater value than the direct result. A research may be entirely successful when it proves that the object sought cannot be attained. It is very hard for young men, particularly, to get that viewpoint, that the proof that a certain thing cannot be done in the way he had an idea it could be done is of as much value, perhaps, as the doing of the thing he sought. It practically always transpires that in the case of doing research of that kind there are some by-products which are extremely valuable and make very good leads for further research. Having that in mind the suggestion of continuous work on a subject when once undertaken is very good.

I have been very much interested in the last year with the attempts of some of the British people in endeavoring to match up, if possible, with the German research. This war has brought home to the English, as nothing else could possibly do, the desirability of working in advance of anything they have hitherto done. I think that ought to come to us in America in the same way. We have had a stimulus here in the enormous orders for material, and we have had a stimulus in the cutting off of many materials which before the war were available, and research in industrial lines is going along at a very rapid rate. The English people feel that on account of their having a very large number of relatively small corporations, that it may not be possible for any one of these corporations to carry on the work in an entirely satisfactory way. Consequently, they are talking of a co-operative research arrangement which would take in the industrial corporation, the university, and whoever else might be interested. There is a germ of thought there for us, that some sort of co-operation is desirable.

It is not easy for the industrial corporations to line up on this matter of research, on account of the fact that most industrial corporations in this country depend for their business on the protection given by patents. Patent protection, as we all know, is a difficult enough matter as it now stands, without having the added difficulty of the suggestion proposed, that is, the research being made by the corporation, andthen the idea developed, patented by some one outside, with no control by the corporation resulting. If our business is founded on patent protection, then we must have control, and while the work of the university can be of great assistance, it is difficult to tie that up in a satisfactory way with the control that must be had by the industrial corporation.

I have stated on a number of occasions, that it was a shame to have the equipment which is possessed by many of the universities, idle three hundred and sixty out of the three hundred and sixty-five days of the year, when many companies would have been glad, if they could get possession of that equipment, to use it three hundred days in the year and make it efficient. It is too much like the farm machinery which is used, for, let us say, one week of the year, and the rest of the year it stands out in the weather. There is any quantity of such equipment in the technical universities of the country which ought to be efficiently used and used throughout the greater part of the year.

Just what arrangement can be made for accomplishing this desirable result of cooperation between the corporation, which must use the results, and the individual research worker, either undergraduate or post-graduate, I am not sure. I have worked out a few individual cases, but more with a view of training research men than any hope that the work in the school would be very productive, so far as actual researches were concerned. As a training for research men, it has proven very valuable.

F. C. Caldwell: It does seem that some kind of co-operation between the various engineering colleges where thesis work, both undergraduate and graduate, is being done, would be very desirable. We must all feel the lack of effectiveness that we experience in connection with much of this work. Along the line of what Mr. Skinner has said, we have to remember that the primary object of undergraduate research, is not the production of valuable results, but the training of men, who are largely beginners, so far as this kind of work is concerned.

What is needed is some kind of clearing house between the various institutions to help in avoiding unnecessary duplication of work. In some cases, especially with undergraduate work, recognized duplication is a good thing, on account of the checking of the results obtained. This also would be facilitated by such an arrangement.

One other point is perhaps suggested in one of Professor

Karapetoff's items, the desirability of selection of the men who are to do undergraduate research. We try to guide men who seem to have no talent for investigation, and no very great interest in it, into other kinds of thesis work. We give them a design or a compilation, and thus reserve the energy of the instructing force and the equipment for the few men who seem to give promise of really accomplishing something in the way of research and of really gaining something by the training which their work along this line will give them.

E. E. F. Creighton: I think the most valuable suggestions regarding research work were given by our President in his address at the opening of the Convention a few days ago. This whole question, especially the educational side, is of the utmost importance. There is not the slightest possibility at the present time that we can have too much research taught. More theses should be written, beginning with a student's freshman year. Progress is dependent mostly upon research and invention. The idea seems to have gone around that the inventor has an especially fine mind, that he was born clever. I think it is a misconception. There are degrees of ability shown in lawyers, mechanics, doctors, engineers, inventors, and so on. It is not a question of relative ability in these several activities, but training. Research and invention come from the suitable concomitant attitude of mind or view-point. Invention can be taught as readily and as certain of results as any of the professions. A definite course of educational work could be laid out, I believe, which would produce inventors by thousands. Most of the training in life, from infancy, is opposed to the production of inventors. It is too much to discuss at this time but, briefly put, I believe inventors would appear in numbers if everybody would give the mental attention they now apply to "What will people think of me if I do?" to "What will nature do for me if I do?"

To show the results of the attitude of mind I wish to draw a contrast. In a big organization they have their work divided into many different departments. Two of these are Sales Department and Invention or Research Department. The attitude of the mind of a salesman is such that he could not possibly invent. The attitude of mind of the inventor is such that he makes an extremely poor salesman. The salesman must always look to the attractive points, the advantageous points of the things he has to sell. These are known colloquially as the "talking points." He must so impress the purchaser. On the other hand, the research man or inventor must skim over the things that go right and he must worry himself night and day about the little things that go wrong. Start an inventor out in the sales business, and he will tell the prospective customer all the things that are wrong about the apparatus rather then the things that go right.

Before the war started, we had an organization of advanced students in industrial work, and it fell to my lot to take these students, who were all graduates of colleges, for two, three, or six months and use them in the laboratory. I have had many illuminating experiences. I got far enough in this work to be able to tell, with a fair degree of certainty, where a man came from simply by watching how he went at his work. One illustration—three men were independently given a problem, and I was unable to see them again for two days. The first man went to the University library where he combed the shelves for information on the subject. It happened to be an investigation of a new type of protective apparatus. He reported that he was sorry that he was away from the big libraries where he could consult the authorities. (Incidently there were no authorities on this subject.) The second man was of a mathematical turn, and he sat down with a pencil and got his fundamental equation started, and attempted to solve the problem by differential equations. He had landed at the point where he had an expression that he could not solve. The third man did not think about looking up published material, and tried no mathematics, but he went into the shop and commenced to make up a device to try out.

Now, of these three men, the first one was educated in Paris, and like the French, venerated the authorities in science. That was his view-point. The second man was educated in one of our best eastern colleges, where they do a great deal of still thinking and a great deal of mathematical work, and although his tastes, as I found subsequently, were such as to allow him to do experimental work, he had been trained to immobile thinking. The third man was from the good old wooly West where they have not formed the habit of looking up the subject or referring to some authority. It seems to me that "try it" is the fundamental need in all research work.

Some time ago I had the pleasure of giving some young men a chance to train themselves for invention. To help me prove my point,I found that as soon as they got the view-point of the inventor they could invent on short notice. I remember one instance, where two of them made three inventions in ten minutes. All of these inventions did not ripen into patents, but, nevertheless, they caught the view point and invented.

We often hear discouraging remarks made to young investigators stating that they are beginning to investigate before they have had any training. It is a great mistake to assume that one must be familiar with current scientific facts before beginning to investigate independently—very much book knowledge is liable to be an overwhelming handicap and a damper to one's enthusiasm. The kindergarten is the place to begin investigation and invention. The work of Mari Montesorri is one of the best illustrations of this theory. If her methods could be carried along through the grammar schools and the colleges the scientific world would move forward in leaps and bounds.

In the university world I know of one professor who, I think, has the proper view-point for training investigators. Professor

Sanford of Stanford University started his work, and is still carrying it on, in the face of a great deal of opposition. In his course in physics he took away the books from the students and gave them a lot of simple apparatus to work with and set them at it. The criticisms of his methods, especially by the engineering students, were—I can characterize them in one expression—"If I were a Faraday, I could get something out of that course." That is a great mistake. Every investigator must have a start. I have been surprised at the young fellows who have worked with me, who have made an investigation, gathered their data, and then not knowing what to do with it, have gone to some book to find out what it might mean.

As a last proof that my theory is correct, I will cite the case of the Italian janitor in our laboratory, whom I set to work on research work. He has embarrassing moments with his arithmetic and spelling, but nimble fingers and an active mind are gathering in much useful data.

D. D. Ewing: It seems to me the trend of the discussion has been mostly along the line of invention. I think that there is a great deal of research work that can be carried on in a university, that does not have anything to do with invention. Research work on subjects like the one which forms the basis of the paper following this one, "Tractive Resistances to a Motor Delivery Wagon on Different Roads and at Different Speeds," is a fair example of what I have in mind. Traffic studies relating to the transportation of passengers, the delivery of freight, the relation of traffic to schedules and car routing, and great variety of other engineering economic subjects are fruitful lines of research, the work on which can be carried on in universities as well as anywhere else. We should not get it into our heads that the only kind of research work is the research work which leads to invention.

Regarding the alignment of research work in universities and colleges, I think that that depends on whether the research work is being done for the purpose of pure research and the results which come from such research, or whether it is being done for the purpose of training young men.

I object to spoon-feeding the students. Too much alignment and guidance are not good for the student. The primary function of the university, in my opinion, is to train men and not to get definite results in research work. Such results, however, as we do get I think should be recorded where they may be available to all, and that, to me, is the crux of Prof. Karapetoff's paper. I desire to say a word regarding another line of research mentioned in Prof. Karapetoff's paper, namely, that of library researches. Such work, I believe, can be carried on in the university to better advantage than in the factories of manufacturing companies, or by engineers, or by the research men of operating companies, because of the library facilities that are available to university men. I think that one of our great difficulties, at least at Purdue

University, is to get men to do library research. The students all want to do experimental research. Prof. Flowers indicated that he had some difficulty the other way. I feel, however, there is a great field for university research along that line. As has been pointed out in the paper a resume of the various lines of thought and scientific endeavor would be very useful, and this could be carried on by the universities.

Practicing engineers could co-operate in a very helpful manner with the university research men in the suggestion of subjects which are along economic or other lines not leading to invention. I readily appreciate Dr. Skinner's statement regarding the matter of invention. I can see why the manufacturing companies would not care to have such research carried on in the universities, but, on the other hand, all those researches which do not lead to invention could be carried on in co-operation with operating companies, and I think a great deal of value would result from it. Further the research work in this country would be greatly stimulated if we had a little better cooperation between the parties interested in such work.

C. Francis Harding: I wish to bring up one or two points concerning which I am, to some extent, in opposition to the author of the paper, particularly with regard to the question of prizes. I do not believe that a monetary prize or any other prize is going to develop research men or induce them to take up research investigations in the university. I think possibly that some prestige, some honor, which might be conferred on such a man, possibly some recognition by the Institute such as the publishing of the paper, or that which the Engineering Society of Western Pennsylvania offers in connection with its thesis investigations would be far preferable to holding out a prize of $25 or $50, whatever it might be, for the man who would carry on the best research investigation.The latter would take on the form which the university degree assumes for such men who are working to get the sheepskin only, and not for the training which the sheepskin represents.

I do not believe, to take up another question treated in the paper, that it is necessary for the Institute or any other body to suggest subjects. Any live man who is connected with a university, talking half an hour with an engineer of a manufacturing company, or of a public utility corporation, can find readily a large number of subjects which are available and worthy of research investigation, and which his institution is best fitted to undertake. Such may have either a practical bearing, or possibly some value as an invention.

I feel that any action which the Institute may be able to take such as appointing a Research Committee or along any other line which will lead towards further co-operation between the universities and the men of the manufacturing companies and the utilities interested in research, will be to the mutual advantage of the student, the universities and ultimately we hope, to the manufacturing companies and the Institute as well.

N. S. Diamant: We may disagree with Prof. Karapetoff as to specific suggestions made in the paper, but I think we shall all agree that it is high time that universities raise their standards of ***scholarship*** and ***research*** and do their share along with the industrial corporations. It may not be exaggerating the importance of the subject to say that it will prove a national calamity if they do not.

Research is not something as mechanical as a glance at the paper may suggest, and in regard to it we may well refer to President Carty's address and abide by his advice and some of his suggestions.

The average standard of scholarship and research at present is very low—considering the universities all over the country—and the author seems well justified in using the expression "superficial undergraduate thesis" with emphasis on superficial.

In regard to the quantity and quality of work that has been done so far in the United States and in Europe—as I would add Switzerland, France, Belgium, etc., to the countries mentioned by the author—I am afraid both Mr. Whitehead and Prof. Karapetoff are right in their comparison—the European work in general seems to be more thorough, and to be published in a more ***scholarly form***, not only from a ***technical*** point of view but ***literary*** as well.

J. J. Carty: The distinction which I made in my paper between pure scientific research and industrial research is a distinction which I think should be borne in mind all of the time in considering questions such as these. I have frequently heard during the discussion here, the term "research," employed as though it meant but one thing. It really means two things. There is pure scientific research and industrial scientific research, and the necessity for this distinction is well illustrated when we come to discuss the ethics of publication as applied to the two cases.

Pure scientific research is conducted for the purpose of extending the boundaries of knowledge and publication is one of the goals. It is ethical to publish these results; it would be unethical not to do so.

When it comes to industrial research the ethics of the case are different. The industrial scientist is employed by a manufacturer or other client to make a scientific investigation at his expense and for his benefit. It would be unethical for the industrial scientific research worker to publish the results of his investigation until his client gives him permission to do so; that is, until the client has determined to his own satisfaction that he will not be injured by the publication.

There is no obligation whatever upon the manufacturer to give out to his competitors scientific information obtained at his expense and for his benefit. The manufacturer embodies the results of his scientific investigations in practical form and benefits the public through the improved product which he provides. Almost invariably, however, the results of industrial scientific investigation are published in due course, as a rule this publication being in the form of an issued patent, which is the method adopted by our form of government to take the place of trade secrets. I am told, however, that there is such a thing as property in trade secrets and if you will read the remarkable paper by Mr. Frederick P. Fish on "The Ethics of Trade Secrets," you will find there a great deal of interesting and curious information upon this subject.

The question as to whether our universities or technical schools should undertake industrial scientific research is a large one which is now being carefully studied by many who are interested in the subject. It is certain that if the technical schools are to carry industrial research work to the point of taking problems from the manufacturer and solving them for pay, the manufacturer will insist upon a contract with the university whereby the publication of the results will be forbidden until such time as he is protected by issued patents, or for other reasons concludes that his interests will not suffer by the publication.

I do not wish to imply that there is no place for industrial research in the universities or technical schools. This question is now being seriously studied. I hope it will be found that there will be a great deal that they can do. I hope to see spring up near the universities large industrial research laboratories and if it is found that they can be successfully associated with the universities, all the better.

In any event, as soon as our manufacturers have awakened to the importance of industrial scientific research, I believe industrial laboratories will spring up everywhere and that the universities and technical schools will find it difficult to graduate in sufficient numbers, men trained in the rigorous methods of the pure scientist to carry on the work of industrial research.

D. H. Braymer: I was interested in the remark of one of the speakers, comparing American journals with foreign journals. I think I have an explanation. It is hardest to obtain the results of research work from professors and universities themselves. It is next easiest to get it from the manufacturing companies, and it is easiest of all to get it from the research departments of the operating companies. Operating engineers interested in new developments are always glad to tell what they have done, why they have done it, and what they are going to do. I can see no reason why there should not be the same attitude toward a publication on the part of the universities and the manufacturers.

A. A. Nims: We are thinking today in terms of the nation rather than in terms of the individual. Five of the national engineering societies are just completing an important step in the preparedness program upon which the country has entered. It is, therefore, appropriate and significant that we have brought to our attention, as convincingly as Professor Karapetoff has done, another service wherein the same societies, with others, can render effective aid in furthering that larger preparedness for national co-operation of which military readiness should be an incidental phase.

Scientific research has not been regarded with that degree of respect by those who might devote their talents to it, nor has such reliance been placed upon it by those who might use its results, as has been accorded it elsewhere. The writer has a distinct recollection of the distaste and dissatisfaction with which senior thesis was regarded at the engineering college from which he graduated. The fellows looked upon thesis work as "not practical," *i. e.* unrelated to the work they expected to take up after graduation, or else themselves unfitted to accomplish results commensurate with the effort expended. Hence the majority of them considered there were other more profitable uses for their time, and since senior thesis has been made elective few take it.

The business firms that are able to maintain adequate equipments for effective research are vastly outnumbered by those who are unable, and who acquire their new technical information by accident or by appealing to some outside agency for the solution of special pressing problems. Occasional, unrelated research, inspired by sporadic inquiries, is more expensive, less effective and commands less confidence than well-organized, well-directed, continued effort. The economics of a high load-factor applies to a plant for scientific research in the same manner, though not to the same degree, that it does to a plant for producing electric energy.

With research encouraged and coordinated throughout the country, students would gradually take a different attitude toward their first encounter with such work. Inquiries on various subjects would be referred to the best authority, securing the most reliable information in the shortest time.

It is quite possible that one of the greater and more lasting benefits of the present commercial activity under limited supplies of materials may be found to lie in the fact that it opened our eyes to the incompleteness of our scientific and technical knowledge and compelled us to take systematic means to extend it. It is, therefore, greatly to be hoped that Professor Karapetoff's suggestions may lead to constructive action along the lines pointed out.

Alexander Gray: The technical press is not able to obtain original articles from the universities because the universities are not turning out good stuff. Most of the research that is started is never completed because there is a lack of men of research ability and because the men available are not properly guided. The large corporations take the best of the men and some of those that are left become teachers.

The original work done in most of our schools does not begin to compare with that done by the manufacturing companies and it is not because of lack of equipment. What we need rather is men like Kelvin of Glasgow, Thomson of Cambridge and Arnold of Karlsruhe to guide our graduate schools, but such men do not seem to develop in our universities.

One of the speakers considered it inadvisable to offer prizes for research. I have seen how two prizes offered to engineers for public speaking have set a whole senior class to work by giving direction to its thought.

Prof. Karapetoff is right when he insists on the schools limiting themselves to one or two subjects rather than spreading their energy over a large number of disconnected subjects. Only by years of work in a given field can results be obtained that are of great value, and only in this way can the work be carried on from year to year with instructors always coming and going.

Presented at the 33d Annual Convention of the American Institute of Electrical Engineers, Cleveland, O., June 30, 1916.

TRACTIVE RESISTANCES TO A MOTOR DELIVERY WAGON ON DIFFERENT ROADS AND AT DIFFERENT SPEEDS

BY A. E. KENNELLY AND O. R. SCHURIG

ABSTRACT OF PAPER

In this paper is given a complete report on an investigation of tractive resistances of urban roads to a motor delivery wagon equipped with solid rubber tires. The " tractive resistance " as used in this paper, includes still-air resistance, but does not include wind resistance and the resistances internal to the truck. The test truck is fully described with its driving mechanism and the storage battery which supplied the motive power. The investigation involved test runs over definite lengths of road, at measured truck speeds, to determine the gross battery output during these runs; and laboratory tests to determine the overall efficiency of the truck between battery terminals and rear-wheel treads at speeds and loads corresponding to the road tests. The results included in the paper are (1) overall efficiency of truck mechanism and (2) tractive resistances of a number of typical urban roads. The components of tractive resistance for a typical road are also given.

THE INVESTIGATION herein described was carried on in the Research Division of the Electrical Engineering Department, at the Massachusetts Institute of Technology, during the year 1915, under a fund contributed for researches on motor trucks.

Object of the Research. The object of this research was to determine the resistance, including air resistance, offered to an electric truck, by level urban roads of different surface varieties, at standard truck speeds not exceeding 25 km. (15.5 miles) per hour. For this purpose, the output of the storage battery on a test truck was measured, for both directions of travel, over standard road beds, at different controller speeds. From this output were deducted all the corresponding electrical and mechanical losses in the truck mechanism, as determined by laboratory tests. The remainder of the output was consequently attributed to (1) road- (2) air- and (3) wind-resistance. The wind resistance was eliminated by averaging the results for both directions of running, leaving as the final result the sum of the road and air resistances.

By "road resistance" is meant the horizontal force required to pull the truck, assumed as internally frictionless, over the horizontal road, in the absence of air. By "air resistance" is meant the horizontal force on the truck required to overcome the resistance of the air, assumed as quiescent in the absence of the truck. By "wind resistance" is meant the horizontal force on the truck necessary to overcome the resistance of the wind velocity, or that velocity of the air with respect to the ground which exists in the absence of the truck.

The Test Truck

Through the courtesy of the manufacturer, a 1000-lb. (450-kg.) worm-drive, single-reduction electric truck, or delivery wagon, was placed at the disposal of the Research Division for the purposes of the test. A picture of this truck is given in Fig. 1. Its specifications are as follow:

Load capacity 1000 lb. (450 kg.) equipped with one d-c. series motor.

Overall length of frame	4280 mm.	168½ in.
Width of frame	890 mm.	35 in.
Wheel base (*i. e.* distance between centers of front and rear wheels, when front and rear axles are parallel)	2730 mm.	107¾ in.
Wheel gage	1470 mm.	58 in.

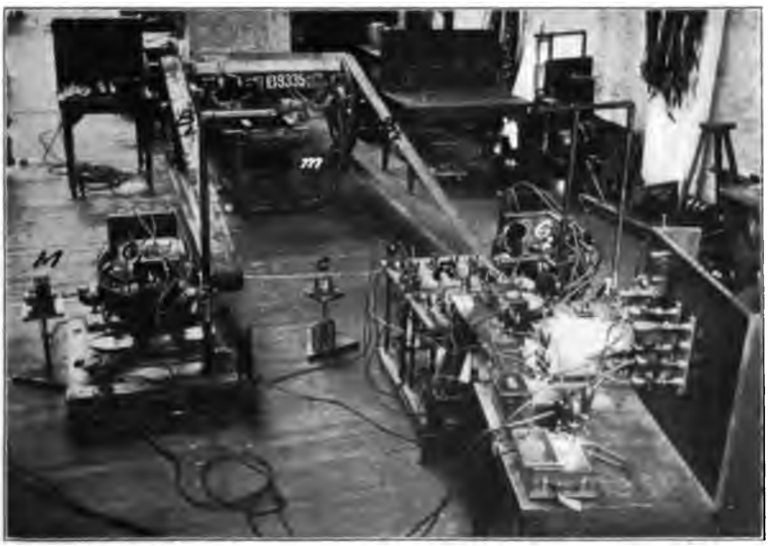
The total weight of the truck, including motor, battery and body, but without load or passengers, was 4200 lb. (1910 kg.). Each of the four wheels was equipped with one solid-rubber demountable tire (manufactured for this type of delivery wagon) rated at 36 in. by 2½ in. (91.5 cm. by 6.35 cm.), and actually measuring about 35 in. (89 cm.) tread diameter, and 2½ in. (6.35 cm.) width of base. The brakes were of the internal expanding type on each rear wheel.

A cross section of the rear wheel, showing bearings and tire, is seen in Fig. 2. Fig. 3 is a drawing of side and front elevations of the truck. This type of electric truck is commonly used for city and suburban parcel-delivery service.

The transmission system was of the shaft type, the speed reduction between motor and rear wheels being accomplished by a single worm with worm wheel, *i. e.*, the motor shaft is extended, through two universal joints, *U* (Fig. 3), which allow for spring compression due to load and impact, to the worm *W* (Fig. 4). Through *W*, the rotation is transmitted to the worm-

[KENNELLY AND SCHURIG]

FIG. 1—VIEW OF TEST TRUCK



[KENNELLY AND SCHURIG]

FIG. 8—VIEW OF TEST ARRANGEMENT FOR TRUCK EFFICIENCY

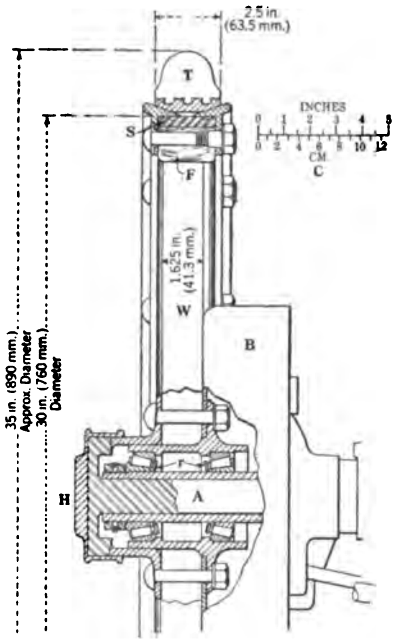


FIG. 2—CROSS-SECTION OF REAR-WHEEL BEARING WITH WHEEL AND TIRE

T demountable solid-rubber motor tire, rated at 36 in. by 2½ in. (915 mm. by 63.5 mm.)
S steel band
F bent felloe
W wheel with 12 spokes
B brake drum, containing internal-expanding brake (details not shown).
r tapered roller bearings
H hub cap
A rear-wheel axle
C approximate scale.

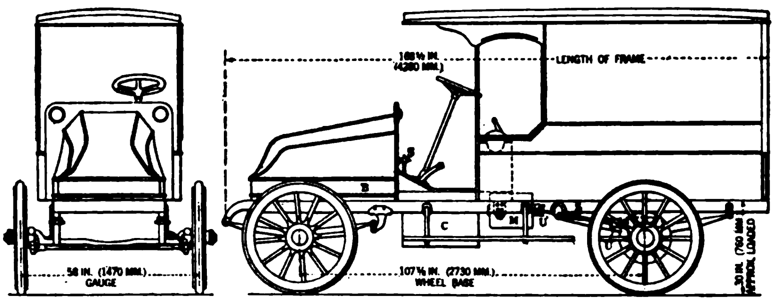


FIG. 3—SIDE AND FRONT ELEVATIONS OF TEST VEHICLE

B Battery compartment containing 45 cells
C Battery compartment containing 15 cells.
M Truck motor
UU Universal joints
S Driving shaft connecting motor and worm gear
s Speedometer

wheel *R*, (Fig. 4), which makes one revolution for every nine of the worm, or of the motor. In order to transmit the motive power to both wheels, and yet permit them to revolve at different speeds, the differential gear is provided, which consists

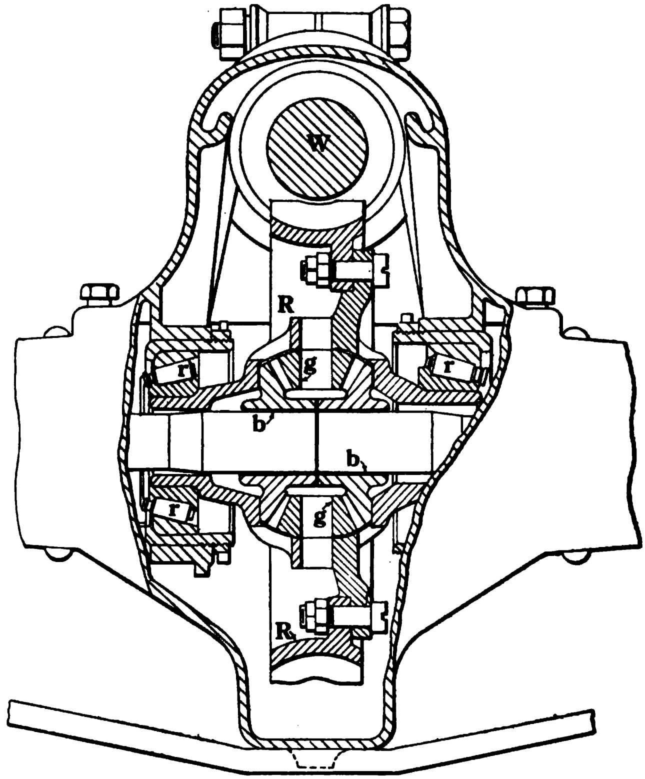


FIG. 4—SECTION THROUGH DIFFERENTIAL GEAR FOR WORM-DRIVE TRUCK

W worm
R worm wheel; ratio of worm to worm-wheel = 9:1
gg gears attached to worm-wheel *R*
bb bevel gears meshing with *gg* and connected to sections of rear-wheel shaft
rr tapered roller bearings

of the small bevel gears *gg*, capable of revolving about axes fixed to the worm wheel *R*; the small gears *gg* mesh with the two bevel gears *bb*, of which one is fixed to the right-hand section, and the other to the left-hand section of the rear axle. The corresponding shaft bearings of the roller-bearing type are *rr*.

Driving Motor and Controller. The electric motor *M*, Fig. 3, has the following specification: No. 282,666, E20, W 2, 32 amperes, 60 volt, 1200 rev. per min. The manufacturer's test data for this type of motor are given in Fig. 5.

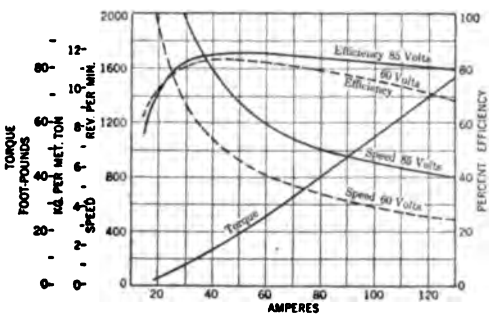


FIG. 5—MANUFACTURERS' CHARACTERISTIC CURVES FOR AUTOMOBILE MOTOR

60 volts—32 amperes—1200 rev. per min.—the two series field windings are connected in parallel with each other

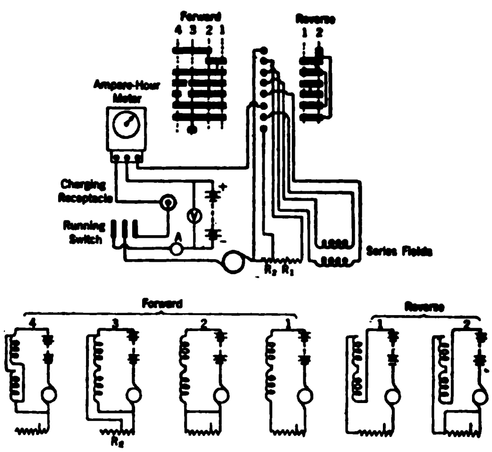


FIG. 6—DEVELOPMENT OF CONTROLLER AND DIAGRAM OF CIRCUIT CONNECTIONS

The controller is of the following description: Type S-35, Form A. It is of the drum type, having four forward and two reverse speeds.

The connection diagram of the controller and motor is given in Fig. 6.

The operation of the controller is as follows:

*Forward, point 1. Fields 1 and 2 in series, all starting resistance in series with armature and fields.

*Forward, point 2. Fields 1 and 2 in series, all starting resistance short circuited.

Forward, point 3. Fields 1 and 2 in series, but shunted by resistance R_2

Forward, point 4. Fields 1 and 2 in parallel, starting resistance not used.

Storage Battery. The battery consisted of 60 Type A-6 cells of the regular nickel-iron type, with a rated discharge capacity of 225 ampere-hours. The normal charge and discharge rate is 45 amperes, and the normal period of charge is seven hours

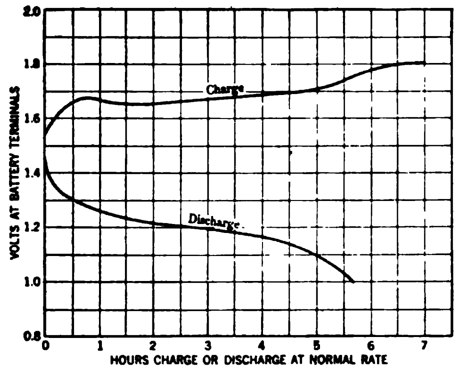


FIG. 7—MANUFACTURES' CURVES OF TERMINAL VOLTAGE PER CELL DURING CHARGE AND DISCHARGE AT NORMAL RATE FOR ALKALINE STORAGE BATTERY

at this rate. Fig. 7 gives the manufacturer's curves of terminal voltage per cell during charge and during discharge, in each case at the normal rate of 45 amperes. The average discharge voltage per cell is approximately 1.2 volts. The battery was placed in two compartments, one being 23 in. by 18 in. (58 cm. by 46 cm.) and 15 in. (38 cm.) deep with 15 cells at *C*, Fig. 3; another being 40 in. by 31 in. (102 cm. by 79 cm.) and 15 in. (38 cm.) deep, with 45 cells at *B*, (Fig. 3.)

The entire battery with solution, trays and connections, weighs approximately 1200 lb. (550 kg.)

*Reverse, point 1, same as forward point 1, except that direction of current through series fields is reversed.

Reverse, point 2, same as forward point 2, except that direction of current through series fields is reversed.

Experimental Procedure

The tests made were of two kinds; namely,

(1) Road tests, over selected measured lengths of road, at different measured truck speeds, to determine the gross battery output.

(2) Laboratory tests, to determine the overall efficiency between battery terminals and rear-wheel treads, at speeds and loads corresponding to the road tests.

Road Tests. The resistance (excluding air-resistance) offered by a level roadbed to a moving truck, depends upon

(1) The surface quality; *i. e.*, the smoothness, hardness and resilience of the road surface.

(2) The size of wheel and tire quality; *i. e.*, the dimensions, smoothness, hardness and resilience of the tire tread.

(3) The speed of the vehicle.

(4) The load or weight of the vehicle.

(5) The construction of the vehicle, *i. e.*, whether with or without springs.

In these tests variations in (2) and (5) were eliminated, by using the same vehicle and the same type and size of wheel and tire throughout, which fairly represent standard average conditions for half-ton truck service.

In order to investigate the effects of road surface quality on tractive resistance, stretches of nearly level typical urban roads were selected, with the aid of records in the Boston City Engineers office. Runs were made with the truck over each selected stretch of road, at nearly constant speed by controller, and successively in both directions for each controller point, thus covering the range of speeds afforded by the controller. The effect of load in the vehicle, upon the tractive resistance, was also tried in a few cases.

The technique of the tests was as follows: Previous to the first test of the day, the car storage battery was fully charged. The car crew consisted of one driver and two observers. The driver confined his attention to steering the car, while running at constant controller position. If the driver had to change the controller position, or apply the brakes, during the run, the run was repeated.

The first observer was stationed on the front seat, beside the driver, and noted the stop-watch times of start and finish, as well as the readings of the speedometers during the run.

The second observer was stationed in the body of the truck, and continuously took readings of voltage and current at battery terminals, by calibrated measuring instruments; these instruments being supported on cushions to minimize their vibration. The positions of these instruments in the battery circuit are indicated in Fig. 6 at *A* and *V*.

The start and finish for each stretch of road were marked off by chalk, or other clearly visible lines, drawn across the roadway. The car was always set in motion at a suitable distance behind the starting line, so as to reach approximately steady speed when this line was crossed. A stop-watch was started by the first observer at this moment. It was stopped by the same observer at the moment when the front wheels of the car crossed the finish line. The reading of the stop-watch was thus the time of the run.

The length of the run between start and finish lines was determined by means of a tape line. The runs varied in length from 400 ft. (120 m.) to 2600 ft. (790 m.)

Wherever the grades of the test stretches were not obtained from the city maps, they were measured directly, on special days, by the car observers, with surveyors' level and rod, in the regular way.

For each controller speed, the car was run three times in each direction, over the test section, in immediate succession. By this method of running in alternate directions over the same section, the effect of wind on car resistance was approximately eliminated, on the assumption that if a wind was blowing, it was uniform in velocity, and tended to exert a uniform pressure on the car, whether the latter was running with it or against it. No heavy windstorms occurred during the period selected for the tests. The arithmetical mean of the road resistances, as measured at nearly constant speeds in opposite directions, was assumed to eliminate the effect of wind velocity.

A further correction, namely that due to the change of kinetic energy inparted to the vehicle, between start and finish, became necessary, because the speed was not absolutely constant during the run; *i. e.*, a slight retardation or acceleration took place over the test stretch, in spite of the fact that the controller was not changed, that roads of uniform grade were selected, and also that the truck was started as far in advance of the mark as was practicable. The energy imparted to a truck which is accelerating includes not only that necessary to overcome its internal and external resistances, but also that definite amount of energy which is required to produce the acceleration. The latter portion of energy is known to be equal to

$$\frac{1}{2}\frac{W}{g}(v_2^2-v_1^2) \qquad \text{kg.-m.}$$

where W is the mass accelerated (kg.), v_2 and v_1 being the velocities in m. per sec. at end and at beginning of the run, respectively; g is the mean constant of acceleration due to gravity, *i.e.*, 9.81 m. per sec. This energy was subtracted from the total energy imparted to the truck. The importance of this correction and the method of its application in a typical case may be seen from Table III.

Table I contains a sample set of observations made in a particular run in alternate directions over a test section.

Laboratory Tests. In order to determine the truck-mechanism overall efficiency, from storage-battery terminals to tire treads, as already referred to, the car was taken into the Lowell laboratory, the rear wheels raised from the ground, and belted each to a load-generator. The motor was then operated through the controller, at a number of speeds, the power being delivered to the load-generators and measured over a considerable range of speeds and outputs. Fig. 8 gives a photographic view of the test arrangement. The car B-9335 is shown, with its rear axle supported on I-beams. The rear wheels are belted to two similar 5 h.p. d-c. generators G_1G_2, loaded by banks of adjustable *Ia-Ia* resistors R. Fig. 9 gives a diagram of the electrical test connections.

The speed of the rear wheels, in these laboratory tests, was measured by means of the magneto m (Fig. 8), belted to one of the wheel brake drums. It was also checked by means of the magneto M coupled to one of the load generators G_1. In order to ensure equality in speeds of the two truck wheels, under test conditions, so that the load might be equally divided between them, and that the conditions might correspond to those when the car runs on a straight path, a slip counter c was inserted between the two generator shafts, so as to indicate, by the flashing of a light, if their speeds materially differed.

The load generators were separately excited. Their output was measured by d-c. voltmeter V, and ammeters A_1A_2, Fig. 9, in their respective circuits. Separate tests were made on the load generators G_1 G_2, to determine their mechanical and electrical armature losses, under different load conditions. These

TABLE I.

SAMPLE SET OF OBSERVATIONS FOR TYPICAL TEST RUN

Run No. 19. *Length* 900 ft. (274 m.) *Gross Weight* 4710 lb. (2140 kg.) *Date* June 15, 1915.
Location = Beacon St., Brookline, Mass.
Start = (east) mark in curb at crossing of Kilsyth St., Elevation: 0
Finish = (west) " " " " Strathmore Road, " +4.3 ft. (1.31 m.)
Description = tar macadam, in good condition, surface wet.
Weather = cloudy, misty rain; wind east; temp. 60 deg. fahr. (15.5 deg. cent.)

Controller Point 1.

	1st Run						2nd Run						3rd Run					
Time	63.6 sec.			51.0 sec.			63.0 sec.			51.4 sec.			62.4 sec.			53.6 sec.		
Direction	West			East			West			East			West			East		
	Battery output		†km. per hr.	Battery output		†km. per hr.	Battery output		†km. per hr.	Battery output		†km. per hr.	Battery output		†km. per hr.	Battery output		†km. per hr.
	volts	amp.		volts	amp.		volts	amp.		volts	amp.		volts	amp.		volts	amp.	
	80	29.5	16.3	81	22.5	19.1	79	28.5	16.3	80	23.0	18.3	81	27.5	18.1	80.5	24.8	18.0
	80	30.1	15.6	81	21.5	21.1	79	29.0	15.9	80	22.5	20.1	81	28.5	16.6	80.5	24.0	18.7
	79.5	30.1	15.3	81	22.5	19.7	79	28.5	15.9	80	22.5	19.7	80	29.5	15.1	80.5	23.8	18.2
	79.5	29.5	15.6	81	23.0	19.1	79	29.5	15.9	80	22.5	19.1	80	29.5	16.1	80	24.0	19.1
	79.5	28.5	15.3	81	23.0	21.1	79.5	29.5	15.6	80	22.5	18.6	79.5	30.1	15.3	80	23.8	18.7
	79.5	29.5	15.3	81.5	22.5	18.7	79.5	29.0	15.3	81	23.8	19.7	79.5	30.8	15.3	80	23.8	18.0
	79	30.1	15.7	....	....	19.1	79.5	28.5	15.3	81	22.5	19.7	79.5	29.5	15.3	80.5	23.0	19.1
	....	....	15.3	....	....	19.1	79.5	29.0	15.6	81	22.0	....	79.5	29.5	15.3	80.5	23.0	....
	....	....	15.3	....	....	19.1	79.5	29.0	15.6	81	22.0	....	....	....	....	....	....	....
	....	....	14.7	....	....	....	78.5	29.5	15.6	81	22.0	....	....	....	....	....	....	....
	....	....	....	....	....	....	78.5	30.8	15.3	....	....	....	....	....	....	....	....	....
Averages	2360 watts		15.4 15.5*	1830 watts		19.6 19.4*	2310 watts		15.7 15.7*	1810 watts		19.3 19.2*	2350 watts		15.9 15.8*	1910 watts		18.6 18.4*

†Speedometer readings.
*Speed (km. per hr.) obtained from stop watch readings and distance measurement.

	East	West
Average battery output (watts)	2340	1850
Average speed by stop watch (km./hr.)	15.7	19.0

NOTE: Two independent speedometers were employed and read in each test; in the above table one set of speed values has been omitted. Calibration corrections have been applied to instrument readings.

losses added to the outputs, gave the total generator inputs supplied through the driving belts.

The losses in the two driving belts B_1 B_2, Fig. 8, were approximately determined by taking two successive light load tests, first with the regular heavy leather belts shown in Fig. 8, and next with special light cotton belts of negligible power loss, but of very limited transmitting capacity. The difference between the inputs, in these two tests, measured the power consumed in the leather belts; because the other losses in the two tests were the same.

The friction losses in the front wheels (about 70 watts total), were also measured by belting them to the rear wheels through light belts in special tests. No allowance was made for any possible increase in wheel-bearing friction under increased gravitational pressures; but since all the wheels had roller axle bearings, such extra friction losses were probably very small.

The sum of the load-generator outputs, the armature losses, and belt losses, was taken as the car output at rear-wheel treads, at various measured inputs.

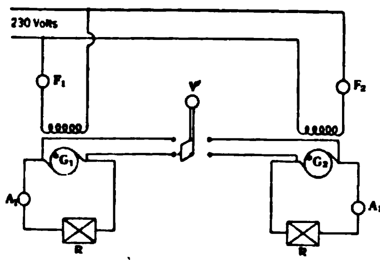


FIG. 9—DIAGRAM OF CONNECTIONS FOR DETERMINATION OF TEST TRUCK OVER-ALL EFFICIENCY BY MEANS OF LOAD GENERATORS G_1 AND G_2

*Each generator was belted to one of the rear truck-wheels

A detailed quantitative analysis of these various losses appears in the next section.

RESULTS OF TESTS

Although the primary object of this research has been a determination of tractive resistances to an electric truck, under the conditions previously defined; yet, incidentally the tests have furnished results of practical value of the overall efficiency from battery terminals to wheel treads of this type of electric car, under normal operating conditions.

Overall Efficiency of Driving Mechanism. A summary of typical data obtained in one of the laboratory tests is given in Table II. The first column gives the output in watts at the battery terminals, determined from the simultaneous readings of a calibrated voltmeter and ammeter, V, A, Fig. 6. Column II gives peripheral wheel speeds in km. per hr. and in miles

TABLE II.

DATA AND RESULTS FOR OVERALL EFFICIENCY OF TEST TRUCK

CONTROLLER ON POINT 4 FORWARD; BATTERY FULLY CHARGED.

I.	II.		III.	IV.	V.	VI.	VII.	VIII.	IX.
Battery output	Peripheral rear wheel speed		Sum of generator outputs	Losses for generators: Armature copper	Losses for generators: Stray power	Losses for generators: Belt losses	Sum of gen. outputs and losses	Equivalent truck output on road	Overall efficiency per cent
watts	km./hr.	miles/hr.	watts	watts	watts	watts	watts	watts	
1860	31.6	19.7	0	0	895	237	1132	1066	57.3
2390	25.7	16.0	872	4	645	161	1682	1616	67.6
2770	23.1	14.4	1289	11	632	130	2062	1996	72.0
3350	20.0	12.4	2001	36	529	98	2664	2598	78.5
3570	19.2	11.9	2230	50	499	90	2869	2803	78.5
3790	18.3	11.4	2420	65	471	86	3042	2976	78.5
3980	17.6	10.9	2560	80	447	77	3164	3098	77.8
4130	17.0	10.6	2656	96	427	72	3251	3185	77.2
4470	16.1	10.0	2920	132	399	65	3516	3450	77.1
4720	15.6	9.7	3090	167	377	59	3693	3627	76.8
4940	15.0	9.3	3270	204	361	56	3891	3825	77.5
5075	14.5	9.0	3317	236	341	53	3947	3881	76.5
5290	14.3	8.9	3274	262	322	50	3908	3842	72.7

per hr., derived from the voltage readings of magnetos M, m, Fig. 8. Column III gives the total generator output as determined by simultaneous readings of calibrated instruments V, A_1 and A_2, Fig. 9. Columns IV, V and VI itemize the following losses: (IV) armature copper losses (watts) in generators G_1 G_2, as obtained by resistance measurements of armatures, and from the observed armature currents (ammeters A_1 A_2, Fig. 9.); (V) stray-power losses (watts) in generators G_1 G_2, as determined from special stray-power tests, already referred to; (VI) belt losses; *i.e.*, frictions in both driving belts B_1 and B_2, as determined by special belt-loss tests, already mentioned. Column VII gives the sum of the losses in columns III, IV, V and VI. Column VIII gives the equivalent output of truck on road, as obtained by subtracting from the watts tabulated in column VII, 66 watts for average front-wheel friction, the latter as determined by the special front-wheel friction-loss test already mentioned. The last column gives the overall efficiency of the car for road runs, *i. e.*, the ratio of columns VIII and I.

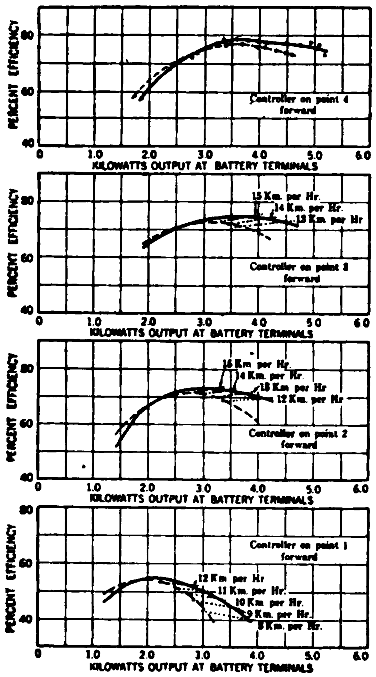


FIG. 10—CURVES OF OVERALL EFFICIENCY OF TEST TRUCK

With battery fully charged (full lines)—and with battery partially discharged (dash lines)—Dotted lines are drawn at constant rear-wheel peripheral speeds, as indicated—60 alkaline cells, type A6, were used.

Efficiency tests as elaborated in Table II were made at each controller position for forward speeds. In view of the relatively large voltage variation (see Fig. 7) of the truck battery, between full charge and partial or complete discharge, and at different current outputs, it was found necessary to perform efficiency-test runs; (1) at a fully charged battery and (2) at a partially discharged battery, (1) corresponding to high impressed voltage and (2) to a slightly lower impressed voltage. The results of the efficiency tests are shown in Fig. 10. It is seen that the condition of the battery has a considerable effect upon the results. Fig. 10 shows, besides efficiency curves at fully charged battery (full lines), and at partly discharged battery (dash lines), a number of constant speed lines (dotted). For example, the overall road efficiency of the truck at 3500 watts battery output, controller on point 2, and at a truck speed of 13 km. per hr. (8.1 miles per hr.) is 71 per cent from Fig. 10. It was for convenience in the handling of the data that the truck speed was chosen as the third factor necessary for the determination of the truck efficiency, rather than the battery terminal voltage. It should also be pointed out that none of the efficiency curves in Fig. 10 are drawn at constant battery terminal voltage, and that they are, therefore, only approximately comparable to the manufacturers' motor efficiency curves reproduced in Fig. 5. Such an approximate comparison shows that the efficiency of transmission between motor and rear-wheel treads is in the neighborhood of 90 per cent for this truck under the conditions tested. This high value may be attributed to the fact that the driving mechanism involves but a single speed reduction, between motor and rear axle, by a worm and worm wheel (Fig. 4). The maximum values of over-all efficiency, including all mechanical and electrical losses beyond the battery terminals are seen from Fig. 10 to be as follow, when an approximately fully charged battery (60 cells, type A 6)is employed.

55 per cent, controller on point 1, forward at a battery output of 2000 watts.

73 per cent, controller on point 2, forward at a battery output of 3000 watts.

75 per cent, controller on point 3, forward at a battery output of 3500 watts.

78 per cent, controller on point 4, forward at a battery output of 3700 watts.

Tractive Resistance. The complete data and results for tractive resistance are shown, for a typical test run, in Table III. In columns I and II are tabulated the controller position and the direction of run, respectively, as previously defined. The speed (average of stopwatch readings divided into measured length of run for three consecutive tests) is given in column III. Column IV contains the average battery output in watts, already referred to (See Table I). Column V contains the number of meters of rise of elevation between start and finish. The average time of run (see Table I) is shown in column VI. The truck over-all efficiency, as taken from the efficiency curves (Fig. 10), is tabulated in column VII. Columns VIII, IX and X contain the follow-

TABLE III.

TEST DATA AND RESULTS FOR RUN NO. 19

Gross weight = 2140 kg. (4710 lb.)
Length of run = 274 m. (900 ft.)
Description of Road = Tar macadam.

I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.	XIII.	XIV.
							Power losses (watts)						
Cont. pos.	Dir. of run	Speed $\frac{km.}{hr.}$	Batt. output watts	Incr. of elev. m.	Time of run sec.	Overall eff. of truck per cent	In truck	Against gravity	Due to change of kin. energy	Total	Tract. power watts	Tract. resist. $\frac{kg.}{met.ton.}$	Equiv. per cent grade
1	W	15.7	2340	+ 1.31	63.0	54.5	1063	436	−76	1423	917	10.0	1.0
2	W	18.3	2370	+ 1.31	53.9	70.0	712	510	− 9	1213	1157	10.8	1.08
3	W	19.6	2600	+ 1.31	50.4	71.0	755	546	20	1821	1279	11.2	1.12
4	W	21.8	2970	+ 1.31	45.2	75.0	743	608	80	1431	1539	12.1	1.21
1	E	19.0	1850	− 1.31	52.0	54.0	850	−529	48	369	1481	13.4	1.34
2	E	20.9	1920	− 1.31	47.4	65.5	662	−580	117	199	1721	14.2	1.42
3	E	22.4	2050	− 1.31	44.2	66.0	696	−621	118	193	1857	14.3	1.43
4	E	24.5	2500	− 1.31	40.2	69.5	763	−683	271	351	2149	15.0	1.50

TABLE IV.

TEST DATA AND RESULTS FOR LOSS OF POWER DUE TO CHANGE OF KINETIC ENERGY OF TEST TRUCK FOR RUN 19

Controller point	1		2		3		4	
Direction of run	West	East	West	East	West	East	West	East
v_2 average speed at finish $\frac{\text{km.}}{\text{hr.}}$	15.1	19.3	18.25	21.8	19.8	23.0	22.6	26.2
v_1 average speed at start $\frac{\text{km.}}{\text{hr.}}$	16.9	18.5	18.4	20.2	19.5	21.7	21.6	23.5
$v_2^2 - v_1^2$	− 58	30	− 6	67	12	58	44	134
Average time of run, sec.	63.0	52.0	53.9	47.4	50.4	44.2	45.2	40.2
Average power lost in accelerating truck, watts	− 76	48	− 9	117	20	118	80	271

ing power losses in watts: VIII in truck, as obtained from IV and VII; IX against gravity; X due to change of kinetic energy of truck between start and finish (see table IV), all of which losses are supplied by the storage battery. In column XI are tabulated the sum of the entries of columns VIII, IX and X. The difference between IV and XI gives the total tractive power, as recorded in XII. Column XIII contains the tractive resistance in kg. per metric ton as derived from XII. The last column contains the equivalent percentage of grade, since 10 kg. per metric ton is just equivalent to 1 per cent grade.

The test data and results for loss of power, due to change of kinetic energy of the truck, for a typical road test are tabulated in Table IV. The results are negative for runs in which the velocity decreased. It is seen from the magnitude of these results, that they are by no means negligible. In practically all the road tests, this item was found to be of importance.

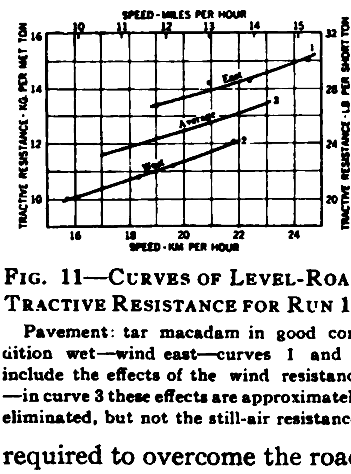


FIG. 11—CURVES OF LEVEL-ROAD TRACTIVE RESISTANCE FOR RUN 19

Pavement: tar macadam in good condition wet—wind east—curves 1 and 2 include the effects of the wind resistance—in curve 3 these effects are approximately eliminated, but not the still-air resistance.

In Fig. 11 are plotted the results for a typical test, in accordance with Table III. The ordinates of curve 3 represent the horizontal force per metric ton, and per short ton, which is required to overcome the road resistance, and still-air resistance, at constant speed on level road, with no wind blowing. Curves similar to those of Fig. 11 were plotted for each road test. A summary of the tests is represented by Figs. 12 to 18 inclusive.

Asphalt Roads, (Fig. 12.) The curves plotted in Fig. 12 apply to both sheet asphalt (*a*) and to bitulithic pavements (*b*), both defined as follow: (*a*) asphalt, consisting of (1) a foundation of hydraulic cement or concrete, (2) a binder course of broken stone and asphaltic cement (dissolved asphalt), (3) a surface layer of asphaltic cement mixed with sand; (*b*) bitulithic pavement, which may be classified as a type of asphalt-macadam pavement, built on a concrete, stone-block or macadam foundation, consisting of a mixture of broken stone, sand and asphaltic cement, proportioned and mixed before being laid. This mixture, after having been laid hot, and rolled, is covered with a coat of hot asphaltic cement and fine stone chips.

The tests showed that there was no appreciable difference between the tractive resistances of sheet asphalt and bitulithic pavements as above defined when in good condition; so that both of these pavements are represented on one and the same diagram Fig. 12. The asphalt pavement, when in good condition, offers a low resistance to vehicular traffic, on account of its smoothness and hardness. Curve (1) is seen to be almost flat, and if the still-air resistance is eliminated by an approximate formula*, a straight horizontal line, (see curve 5), results for the road resistance alone. Curves 2 and 3 are steepened by the addition of impact and vibration losses. These extra losses are due to the impacts which the truck receives as it encounters local lumps and hollows in the worn pavement. The dash-line curve

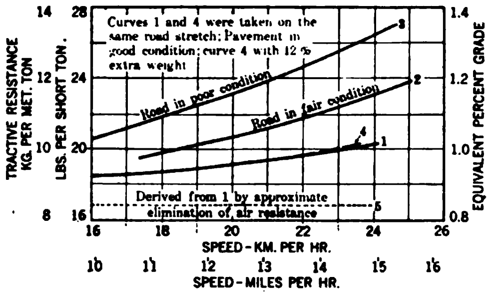


FIG. 12—TRACTIVE RESISTANCE FOR ASPHALT ROADS
Sheet asphalt and bitulithic.

was obtained when the total moving mass was increased 12 per cent, and is seen to be almost identical with curve 1.

Wood-Block Roads, (Fig. 13). The full-line curve of Fig. 13 applies to wood-block paving, which consists of rectangular

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$$*P = 0.0025\frac{A.V^2}{W} \quad \text{lb. per short ton}$$

air resistance, in which formula A is the cross-section of the car in sq. ft., V the speed of the car in miles per hr., and W the total mass in motion (in short tons); see American Handbook for Electrical Engineers, 1914, Wiley, New York, p. 1166. In metric units, the above equation takes the form

$$P = 0.0047\frac{av^2}{w} \quad \text{kg. per metric ton}$$

if a is expressed in sq. m., v in km. per hr. and w in metric tons. The area offered to the air by the test truck was approximately 14 sq. ft. (1.3 sq. m.) and the moving mass was 2.36 short tons (2.14 met. tons), except when otherwise noted.

creosoted hard-pine blocks, approximately 4 in. (10 cm.) deep, 3.5 in. (9 cm.) wide and 8 in. (20 cm.) long, placed, with the fiber vertical, and the long dimension crosswise to the street, upon a foundation of concrete with a thin layer of sand interposed between concrete and wood blocks. The curve is nearly horizontal because of the smoothness of the pavement.

Brick-Block Roads, (Fig. 13). The brick-block roads upon which tests were made, consisted of rectangular vitrified paving brick, approximately 4 in. (10 cm.) deep, 3.5 in. (9 cm.) wide, and 8.5 in. (21.5 cm.) long, laid with the length perpendicular to the curb, upon a foundation of concrete and a cushion layer of sand. The results for brick roads show nearly as low a resistance as those for the wood block, but the curve for the former is steeper, particularly for the case of a worn surface, again

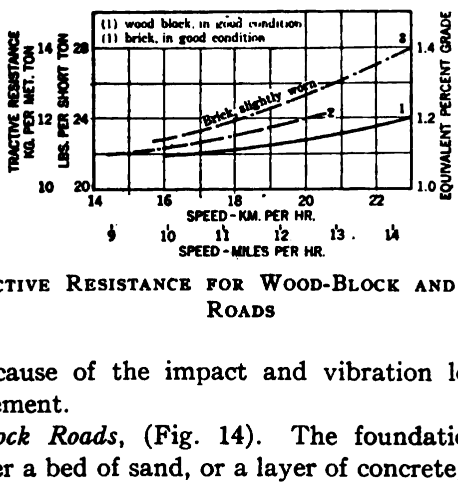

FIG. 13—TRACTIVE RESISTANCE FOR WOOD-BLOCK AND BRICK-BLOCK ROADS

probably because of the impact and vibration losses on the rougher pavement.

Granite-Block Roads, (Fig. 14). The foundation for these roads is either a bed of sand, or a layer of concrete, with a sand cushion to separate the blocks from the concrete. Average dimensions for the rectangular blocks are about 4 in. (10 cm.) wide, 11 in. (28 cm.) long and 8 in. (20 cm. deep). The joints are filled either with small pebbles and sand, or with hydraulic-cement grout. The former filler is subject to being partially washed out by precipitation, and removed by the street sweeper, and thus allows the edges of the blocks to be exposed to wear, which renders the pavement far less smooth than one with cement-filled joints. The full-line curves 1 and 2 in Fig. 14, which apply to granite-block roads with cement-filled joints, show a greater upward slope than those for the smoother brick-block, wood-block, and asphalt roads, already mentioned; while the granite-block pavements constructed with the less durable filler are seen to offer a still more rapidly increasing resistance at increasing velocities, because of the greater losses of kinetic energy due to road impact.

Macadam Roads, (Fig. 15 and 16). This type of road has a pavement consisting of several layers of broken stone, (trap rock, granite, lime stone, slate, etc.) ranging in size from about 3 in. (7.6 cm.) to about 0.5 in. (1.3 cm.) in largest dimension. The fragments of stone are held together by a binding material of which there are two general types: (1) clay, loam, sand, or finest screenings (stone dust from stone crusher), distributed

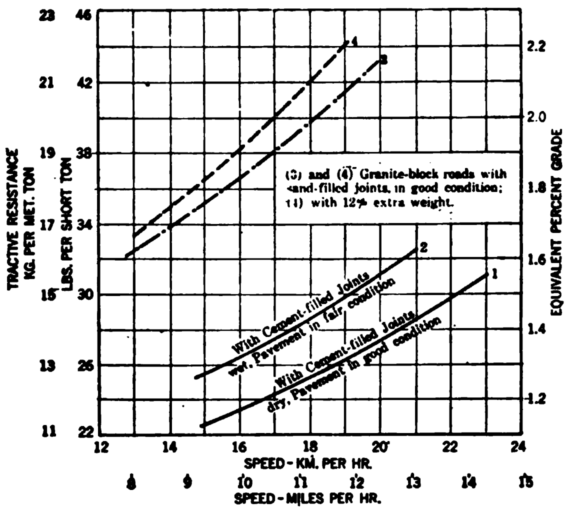

FIG. 14—TRACTIVE RESISTANCE FOR GRANITE-BLOCK ROADS

over each layer of broken stone, water being sprinkled over the surface; and (2) tar, either mixed with the broken stone before it is laid, or distributed over the broken stone, after the latter has been spread and rolled; type (1) is known as a water-bound macadam, and type (2) as tar-macadam.

Fig. 15 shows the results obtained for water-bound macadam roads, the dot-dash curves apply to the oiled pavements, full-line curves are for unoiled roads. A dusty road (curve 2), is seen to have a greater resistance than a similar one with a hard surface without dust (curve 1); while a badly worn road with holes (curve 3), shows a far higher resistance than 1 and 2, and a much more rapid rise with increasing speed, due to impact losses. Curve 4 for an oiled macadam road, though in fair condition, shows a higher resistance than a similar road unoiled. Heavy oiling increases the resistance without increasing the slope of the curve, as indicated by curve 5; this effect is probably caused by the softening of the surface and the resultant loss of power due to the depression of the surface material by the wheel tires. The combined effects of wear and oil are seen in curve 6. Curve 7, if compared with curve 5, (the two curves applying to the same road, but to different days and different total weights of moving vehicle), shows a slight increase of

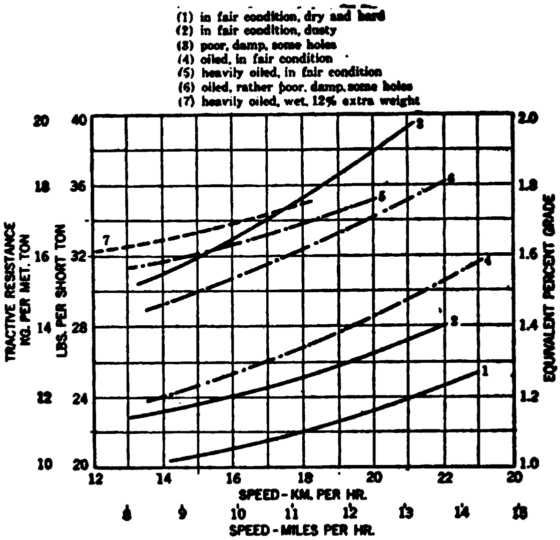

FIG. 15—TRACTIVE RESISTANCE FOR MACADAM ROADS

resistance due probably to both decreased road resilience and increased weight.

The results for tar-macadam roads, (Fig. 16) are similar to those for water-bonded macadam; *i.e.*, the effects of surface deterioration are definitely seen by comparison of curves 1, 2, 3 and 4. Curve 5 is of interest in again demonstrating that the resistance of a soft surface of low resilience is greater than that of a similar but hard road by an approximately constant amount, (see curves 5 and 1). The dash-line, curve 6, (12 per cent extra weight), is seen to follow very closely curve 2, (the two curves include data obtained on the same road under similar conditions, but with different total weights.)

Cinder and Gravel Roads (Fig. 17.) Curve 1 in Fig. 17 applies to a road with a gravel surface, in fair condition, but slightly dusty. A cinder road with a dry and hard surface in fair condition, is seen to have a slightly lower resistance, probably because of its greater resilience.

Summary for All Classes of Urban Roads Tested. Typical results for all classes of urban roads tested are summarized graphically in Fig. 18, and numerically in Table V. It appears from these summaries, and from the foregoing discussions, that

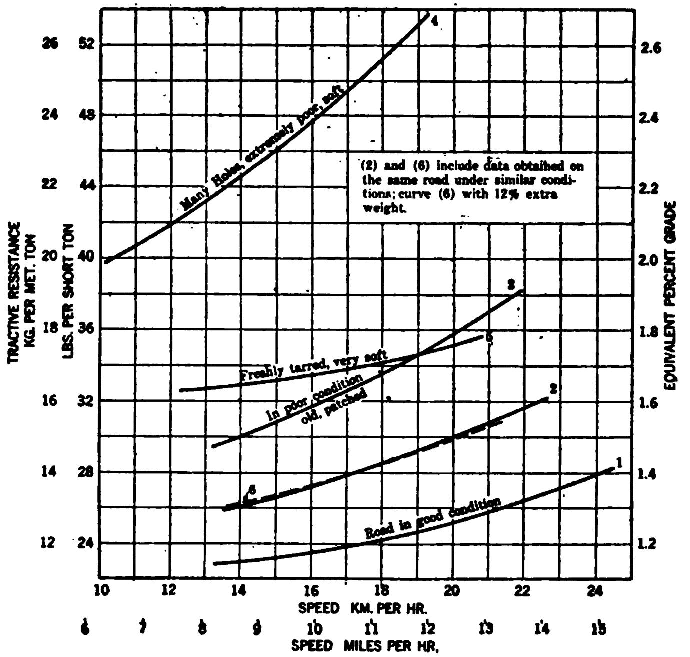

FIG. 16—TRACTIVE RESISTANCE FOR TAR-MACADAM ROADS

there are three principal elements which determine the tractive-resistance-speed curve for unit weight of a given vehicle, within the range of conditions covered by this test:

(1) A constant resistance, see curve 1, Fig. 19*, the magnitude *A* of which depends on the lack of resilience of the road surface and wheel tire material, *i.e.*, on the energy losses due to displacement of tire material and road-surface material. This constant element *A* would be encountered upon a smooth level road

*The quantitative data of Fig. 19 refer to the asphalt roads of Fig. 12.

of the particular type considered, in the absence of impact, air, and wind-resistances.

(2) An increasing resistance with increasing speed, due to

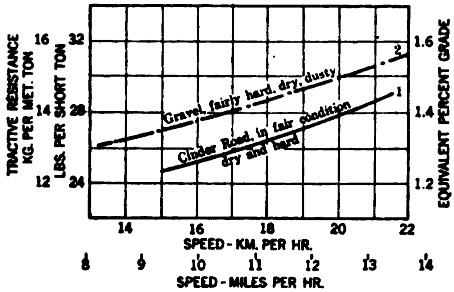

FIG. 17—TRACTIVE RESISTANCE FOR GRAVEL AND FOR CINDER ROADS

impact losses (curve 2), which results from lack of smoothness of road surface; losses of this nature are usually known to vary approximately as the second power of the velocity at impact; and

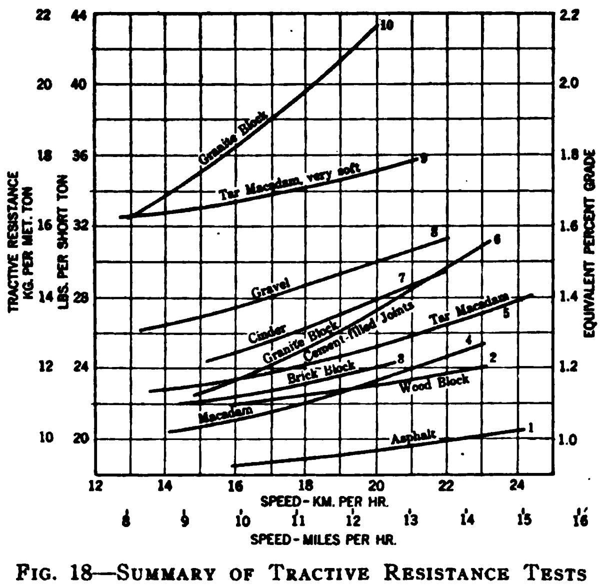

FIG. 18—SUMMARY OF TRACTIVE RESISTANCE TESTS

(3) An increasing resistance with increased speed, due to air pressure against the front of the vehicle, curve 3, which resistance is known to depend, roughly, on the second power of the speed (see above under "Asphalt Roads"). The sum of the three

TABLE V.

SUMMARY OF TRACTIVE RESISTANCES OF DIFFERENT URBAN ROADS AT DIFFERENT SPEEDS

All tractive resistances are expressed in equivalent per cent grade.

Road		Equivalent per cent grade		Per cent increase in tractive resistance from 16 to 20 km. per hr.	Comparative tractive resistance factors referred to asphalt roads	
Type	Condition	at 16 km./hr. (10 miles per hour)	at 20 km./hr. (12.4 miles per hour)		at 16 km./hr.	at 20 km./hr.
Asphalt	good	0.93	0.97	4	1.0	1.0
Asphalt	poor	1.03	1.16	11	1.11	1.20
Wood block	good	1.10	1.15	5	1.18	1.18
Brick block	good	1.12	1.21	8	1.20	1.25
Brick block	slightly worn	1.14	1.27	11	1.23	1.31
Granite block	good	1.83	2.16	18	1.97	2.23
Granite block with cement joints	good	1.16	1.37	18	1.25	1.41
Macadam, water bonded	dry and hard	1.06	1.17	10	1.14	1.20
Macadam, water bonded	fair, heavily oiled	1.63	1.76	8	1.75	1.82
Macadam, water bonded	poor, damp some holes	1.65	1.89	15	1.78	1.95
Tar macadam	good	1.17	1.27	9	1.26	1.31
Tar macadam	very soft	1.67	1.76	5	1.80	1.81
Tar macadam	many holes, extremely poor, soft	2.38	2.75	16	2.55	2.85
Cinder	fair, hard	1.25	1.39	11	1.35	1.43
Gravel	fair, dusty	1.37	1.50	9	1.47	1.55

curves for items 1, 2, and 3, for the case of asphalt roads in Fig. 12, results in curve 4. The constant resistance (1) may be briefly called the *displacement resistance*, item 2 the *impact resistance*, and item 3 the *air resistance*. The displacement resistance is low for hard pavements (curve 1, Fig. 12) and high for soft pavements (of low resilience), as is illustrated by curve 5, Fig. 16; The impact resistance is very marked in granite-block roads, as already mentioned, (Fig. 14). The air resistance, at any definite velocity, is the same for all curves; because the

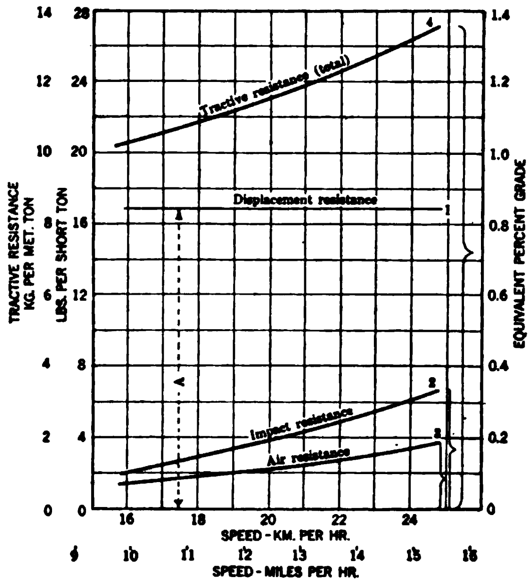

FIG. 19—APPROXIMATE ANALYSIS OF TYPICAL TRACTIVE RESISTANCE INTO ITS ELEMENTS, FOR ASPHALT ROAD IN POOR CONDITION (CURVE 3, FIG. 12)

air-resisting parts of the truck were left unchanged throughout the tests. For the particular type of road represented by Fig. 19 (asphalt road in poor condition, see curve 3, Fig. 12), at a speed of 20 km. per hour (12.4 miles per hr.) the displacement resistance is 0.84 per cent, the air resistance is 0.11 per cent, the impact resistance 0.20 per cent and the total 1.15 per cent equivalent grade.

The displacement resistance of a road manifestly varies, not only with the type and surface quality of the road, but also with the type, dimensions and quality of the tires on the wheels of the vehicle. In the tests here reported, the same tires were used throughout, and they remained in substantially the same condition.

The impact resistance of a road manifestly depends not only on the type and surface quality of the road, and the sizes of its irregularities; but also on the type, dimensions and quality of the wheel tires, the weight of the truck, and the quality of its springs.

The air resistance per unit weight of truck manifestly depends upon the weight, dimensions and shape of the vehicle, as well as on the speed of the vehicle relatively to the surrounding air.

The wind resistance per unit weight of truck manifestly depends upon the weight, dimensions and shape of the vehicle, as well as on the direction and velocity of the wind and the velocity of the vehicle. It is assumed that at low wind and vehicle-speeds, like those here considered, only that component of the wind which is in the direction of the vehicle's path needs to be taken into account, and that the mean of the wind resistances in opposite directions, along the road, is zero.

The following studies are suggested for future experimenters along the line of this investigation:

(1) Researches on vehicle tractive resistances on country roads.

(2) Tractive resistances to vehicles with different wheel tires.

(3) Tractive resistances of urban roads at low speeds from 0 to 10 miles per hour (16 km. per hr.)

(4) Tractive resistances at speeds higher than 15 miles per hour, (24 km. per hr.)

(5) Tractive resistances for heavy-duty trucks.

In conclusion, the authors wish to express their indebtedness to Mr. Thomas A. Edison and the Gould Storage Battery Co., who contributed the funds for carrying out the work; to the General Vehicle Co. for the loan of the truck used in the tests; and to the Edison Electric Illuminating Co. of Boston for their helpful assistance in several stages of this research. Further acknowledgment is due to Messrs. A. C. Brown (S. B., M. I. T. 1914) and F. B. Barns, (S. B., M. I. T. 1915), who took most of the observations during road and laboratory tests, and to Messrs. D. J. McGrath (S.B., M. I. T. 1912) and L. H. Webber (S. B., M. I. T. 1914) who rendered assistance in the preparation of the results.

Summary of Conclusions

The following conclusions are indicated from the preceding results: as confined to urban roads, with a solid rubber-tired motor truck between the speed limits of from 13 to 25 kilometers per hour, (8 to 15.5 miles per hour.)

(1) The over-all efficiency of the test-truck mechanism, as described in this report, between battery terminals and rear-wheel treads, reached a maximum value of about 78 per cent, under the most favorable conditions.

(2) The mechanical efficiency of transmission from motor shaft to rear-wheel treads, for the truck tested, shaft-driven through a single-reduction worm gear, was found as high as 90 per cent.

(3) Tractive resistances are most conveniently expressed as an equivalent percentage grade; *i.e.*, a level road of definite tractive resistance may be regarded as a road of zero tractive resistance, but rising uniformly x units in 100 units of road length, or having an equivalent grade of x per cent.

(4) Under the conditions of these tests, the tractive resistance on level roads, in the absence of wind, is composed of (a) displacement resistance, (b) impact resistance, and (c) air resistance.

(5) The displacement resistance varied from 0.85 per cent equivalent grade, for a hard smooth asphalt or bituminous concrete to 1.6 per cent for a very soft tar-macadam road, and was practically constant, for all speeds considered, on any given road.

(6) The impact resistance increases with the velocity, with the total weight of vehicle, and with increasing road-surface roughness. In these tests, the impact resistance of good asphalt or bitulithic or other smooth pavement, was practically negligible, and reached its highest values on granite-block roads with sand-filled joints, and on badly worn macadam pavements. The rate of increase of impact resistance with speed was most marked on the roughest roads.

(7) At the vehicle speed of 20 km. (12.4 miles) per hour, the air resistance for the vehicle tested, assumed to be dependent only on the speed, was roughly 0.11 per cent equivalent grade; *i. e.*, from 4 per cent of the highest, to 12.5 per cent of the lowest, total tractive resistance.

(8) The following urban pavements are enumerated in the order of their desirability for vehicle operation from the point

of view of tractive resistance at 20 km. (12.4 miles) per hr., as found in this investigation. (1) asphalt, (2) wood block, (3) hard smooth macadam, (4) brick block, (5) granite block with cement-filled joints, (6) cinder, (7) gravel, (8) granite block with sand-filled joints.

(9) The equivalent grade at 20 km. (12.4 miles) per hr. of a badly worn city macadam road, was found to be nearly three times as great as that of the best asphalt road tested. This means, at this speed, a consumption of energy at wheel treads, of nearly three times as much on level poor macadam roads as on good level asphalt roads.

(10) Increasing the gross weight of the vehicle by 12 per cent, through load, was found to have no effect on tractive resistance within the observed speed limits for smooth roads in good condition; but on rough roads, a distinct increase in tractive resistance with this extra weight was observed.

(11) The presence of a layer of dust, say one cm. thick, on a fair macadam road, was found to increase the equivalent grade of tractive resistance, at all tested speeds, by about 0.15 per cent.

(12) A freshly tarred and therefore very soft tar-macadam road was found to have an increased tractive resistance equivalent, at substantially all tested speeds, of about 0.5 per cent. The tires in this case sank about 0.8 inch (2 cm.) into the road bed, the gross car weight being 2140 kg. (4710 lb.)

(13) The total range of tractive resistance equivalent grade covered in the tests, was from 0.93 per cent on the best asphalt road, at lowest speed, to 2.7 per cent on the worst macadam road, at nearly the highest speed.

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[1]These experiments cover tractive resistances, principally at low speeds of about 3 miles per hr. (4.8 km. per hr.), for gun carriages, freight cars, artillery wagons, freight wagons, stage coaches, carriages, and wagons, (the latter three with springs), on miscellaneous surfaces.

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[3]Experiments on the effect of tire width on road resistances for various surfaces are reported in this paper.

[4]In this report are given the results obtained by Mr. T. I. Mairs for rolling resistances of wagon wheels of different sizes on various surfaces.

Discussion on "Tractive Resistances to a Motor Delivery Wagon on Different Roads and at Different Speeds", (Kennelly-Schurig), Cleveland, Ohio, June 30, 1916.

A. A. Nims: (communicated after adjournment): There is one factor of tractive resistance which has not been separated and listed in this paper. Its value may be of small significance and perhaps may not affect the accuracy of the results to any great extent, but its existence should be recognized at least, if for no other present reason than technical accuracy.

The authors of the paper define "road resistance" as "the horizontal force required to pull the truck over the horizontal road" and "air resistance" as "the horizontal force on the truck required to overcome the resistance of the air". Eliminating "wind resistance," the power delivered to the driving wheel treads at constant speed on a level road is considered equal to the sum of the power consumed by road and air resistances. Yet, in calibrating the truck, belt losses on the wheel treads are found to be an appreciable item, especially at the lighter loads.

The driving wheels of any self-propelled vehicle do double duty—they carry a large share of the load and also deliver to the road, by a friction transmission, the power for propelling the vehicle. It would therefore seem logical that, in evaluating "the horizontal force required to pull the truck" the losses of the friction transmission, consisting of driving wheels and road, be considered in addition to those transmission losses that occur entirely within the vehicle mechanism. A simple means of covering all these losses is to make the term "vehicle efficiency" include all losses from the battery terminals to the ground instead of to the wheel treads only. When "vehicle efficiency" has this meaning, it may be used to determine a value of vehicle output which, at constant speed on a level road, is equal to the power required to tow the vehicle under the same conditions.

O. R. Schurig: In the discussion communicated by Mr. Nims, the "vehicle efficiency", (*i.e.*, the efficiency from battery terminals to the ground) is mentioned as being technically more accurate than the "overall efficiency of driving mechanism", the latter meaning the efficiency between battery terminals and wheel treads, the difference between the two efficiencies being that in the first, the losses in the tire treads are considered as part of the *vehicle losses*; while in the second, they are considered as part of the power delivered by the *vehicle*. In order to group the tire-tread losses among the vehicle losses, it would obviously be necessary to separate the former from the losses occurring in the road surface proper. Since an accurate practical method for the separation of these two mutually dependent losses is not known to the authors, the "vehicle efficiency" as defined by Mr. Nims seems to be purely theoretical. If the latter efficiency were practically obtainable, it would seem to be less useful than the overall efficiency employed by the authors, because it would be dependent not only on the truck speed and battery output, but also on the nature of the road surface.

The "overall efficiency of driving mechanism" as defined and determined in the paper, (1) is believed to be technically accurate, because it takes account of all components of the power originating at the battery terminals; (2) it is readily obtainable experimentally by the procedure outlined in the paper; and (3) it is the term employed in the determinaton of all those portions of the battery output, which are dependent upon the nature of the road surface, *i.e.*, the joint tire-tread and road-surface losses. These joint losses serve as a basis for the calculation of the horizontal force required to move, at constant speed, a truck having ordinary tire losses, but being otherwise frictionless.

Presented at the 33d Annual Convention of the American Institute of Electrical Engineers, Cleveland, O., June 30, 1916.

APPLICATION OF A POLAR FORM OF COMPLEX QUANTITIES TO THE CALCULATION OF ALTERNATING-CURRENT PHENOMENA

BY N. S. DIAMANT

ABSTRACT OF PAPER

In the *calculation* of alternating-current phenomena by means of complex quantities, as a rule, the rectangular components of the vector are used, and the rectangular form involving the operator $j = \sqrt{-1}$ is more common than the polar or exponential forms which involve the operators $(\cos \theta + j \sin \theta)$ or $\epsilon^{j\theta}$; although it is recognized that the latter are very convenient in certain cases.

A simple method for dealing directly with the vectors themselves is described in the paper and it consists in introducing the operator j^n, where n, contrary to ordinary usage, may be any positive or negative fraction. Just as j or j^1 rotates the quantity before which it is placed through 1×90 degrees, so j^n rotates the number into which it is multiplied through $n \times 90$ degrees.

The operator j^n follows the rules of ordinary algebra and according to these the different algebraic operations of multiplication etc., are developed in section II. In section III a few illustrative problems are given; these are followed by a critical résumé in section IV. At the end, for convenience of reference a summary of formulas is given, and a very short bibliography is included.

I—INTRODUCTION

ACCORDING to the usual method of dealing analytically with alternating-current problems a stationary vector[1] representing the harmonic quantity under consideration, is expressed algebraically by a complex number of the following forms:

(*a*) The rectangular form, (see Fig. 1).

$$\dot{E} = e + je' \tag{1}$$

1. As to the classification of vectors into stationary, rotative, non-rotative, etc. an interesting paper by A. E. Kennelly, TRANS. A. I. E. E. June 1910, may be consulted. It should be noted, in this connection, that in electrical engineering we deal with two-dimensional *vector representation of harmonic quantities* rather than the two- or three-dimensional, non-localized true vectors of vector analysis or quaternions.

where e and e' are the rectangular coordinates of the point representing the complex number.

(*b*) The polar form, (see Fig. 1).

$$\underset{\cdot}{E} = E\ (\cos\theta + j\sin\theta) \quad (2)$$

where $E = \sqrt{e^2 + e'^2}$, and $\theta = \tan^{-1}\left(\frac{e'}{e}\right)$, are the polar coordinates of the same point representing the same complex number. Equation (2) can also be written in the exponential form by means of the identity,

$$(\cos\theta + j\sin\theta) \equiv e^{j\theta}$$

Thus

$$\underset{\cdot}{E} = E e^{j\theta} \quad (3)$$

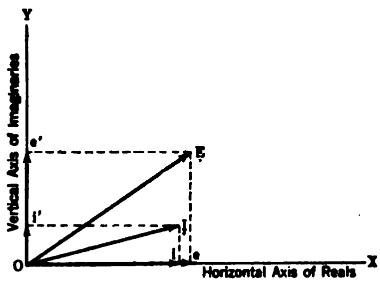

Fig. 1

Convenient and useful as it is in engineering problems (whether electrical, civil or mechanical) involving vectors, to resolve these into two rectangular components, it is preferable at times to deal directly with the vectors themselves. Indeed, it is not uncommon in the derivation of general expressions for regulation, etc., to use vectors rather than their components; for instance, the (primary) impressed voltage of a transformer may be written as

$$\underset{\cdot}{E}_1 = \underset{\cdot}{E}_{i1}(1 + \underset{\cdot}{Z}_1\, \underset{\cdot}{Y}_0 + \underset{\cdot}{Z}_1\, \underset{\cdot}{Y}/a^2), \text{ instead of,} \quad (4)$$

$$= e_{i1}\left[1 + r_1\left(g_0 + \frac{g}{a^2}\right) + x_1\left(b_0 + \frac{b}{a^2}\right) + jx_1\left(g_0 + \frac{g}{a^2}\right) - jr_1\left(b_0 + \frac{b}{a^2}\right)\right] \quad (5)$$

Equation (4) not only looks simpler than (5) but it is a much better *mathematical shorthand*, so to speak, since it allows at a glance to see into the physical meaning of the expression; this is very important and valuable in engineering, both from a practical and educational point of view. Translating (4) into words it will be seen that it states in a simple and direct manner that the voltage impressed upon a transformer = (the primary induced voltage) + (the exciting current, $E_{i1} Y_0$, times the primary impedance Z_1) + (the load current [reduced to primary] times the same impedance Z_1); where the plus sign signifies vector addition.

In *actual calculations*, however, so far as the writer is aware, in standard a-c. engineering works or technical papers, use is made of expression (5) rather than such an equation as

$$\underset{\bullet}{E}_1 = e_{i1}\left[1 + Z_1 e^{j\alpha}\left(Y_0 e^{-j\beta} + \frac{Y}{a^2}\, e^{-j\gamma}\right)\right]$$

$$= e_{i1}\left[1 + Z_0\, Y_0\, e^{j(\alpha - \beta)} + Z_1 \frac{Y}{a^2}\, e^{j(\alpha - \gamma)}\right] \qquad (6)$$

The object of the paper is to discuss briefly the use of a simple polar form of complex quantities and indicate some of its advantages when used either by itself or in combination with the usual present day methods.

II—Principles

1. *General.* A sinusoidal e. m. f. or current may be represented by (see Fig. 1)

$$\underset{\bullet}{E} = e + je'$$

$$\underset{\bullet}{I} = i + ji'$$

where the symbol $j\ (= \sqrt{-1})$, as it is well known, rotates the quantity before which it is placed through 90 deg. However, since j follows the laws of *ordinary algebra* it is entirely plausible, and interesting to inquire into the meaning of j^n, where n, contrary to common usage is not an integer but any positive or negative number.

Just as j or j^1 indicates rotation through 90×1 deg. and j^3 indicates rotation through 90×3 deg., so $j^{\frac{1}{2}}$ must be interpreted as rotation through $90 \times \frac{1}{2} = 45$ deg. In general Aj^{α} $(\alpha > 0)$

may be interpreted as rotation of the number A through $90 \times \alpha$ deg. or $\frac{\pi}{2}\ \alpha$ radians in the positive or counter-clockwise direction; similarly: $\dot{A}j^{-\alpha}$ $(\alpha > 0)$ represents a vector which has been turned through $\alpha\ \frac{\pi}{2}$ radians in the negative direction. Thus the exponent of j may be any number and it indicates the phase relation of the quantity under consideration. For instance, an e. m. f. of E volts and 60 deg. out of phase with the current will be represented according to the above, as $\dot{E} = E\,j^{2/3}$ where $\alpha = (60/90) = 2/3$ and $\dot{I} = I\,j^{\circ} = I$, since j to the zero power $= 1$, just as for any other algebraic quantity.

If desired the above statements can also be proven by means of De Moivre's theorem, as follows:

$$(\cos\theta + j\sin\theta) = \left(\cos\alpha\frac{\pi}{2} + j\sin\alpha\frac{\pi}{2}\right) \equiv \left(\cos\frac{\pi}{2} + j\sin\frac{\pi}{2}\right)^{\alpha} \equiv j^{\alpha}$$

i. e., the operator j^{α} is identical with $(\cos\theta + j\sin\theta)$, where $\theta = \frac{\pi}{2}\alpha$.

2. *Multiplication and Division.* As we have seen a vector $\dot{A}$ can be represented as:

$$\dot{A} = a + ja', \text{ or} \tag{7'}$$

$$\dot{A} = A\,j^{\alpha} \tag{7}$$

Similarly a vector $\dot{B}$ can be written as:

$$\dot{B} = b + jb', \text{ or} \tag{8'}$$

$$\dot{B} = B\,j^{\beta} \tag{8}$$

According to the ordinary method,

$$\dot{A}\dot{B} = (ab - a'\,b') + j\,(ab' + a'\,b) \tag{9}$$

NOTE: It will found convenient to denote angles in degrees by $\alpha^{\circ}, \beta^{\circ}$ etc. and the same angles in radians by α', β' etc. In the method herein described α may then be taken as:

$$\frac{\alpha^{\circ}}{90^{\circ}} \text{ or } \frac{\alpha'}{\pi/2}; \text{ thus } j^{\alpha} = j^{\frac{\alpha^{\circ}}{90^{\circ}}} = j^{\alpha'/\pi/2}.$$

But $a = A \cos \alpha°, a' = A \sin \alpha°; b = B \cos \beta°$ and $b' = B \sin \beta°$ where $\alpha° = (90\ \alpha)$ deg., and $\beta° = (\beta\ 90)$ deg.

Substituting in equation (**9**) we get:

$$\dot{A}\dot{B} = AB(\cos(\alpha° - \beta°) + j \sin(\alpha° - \beta°))$$

The last expression according to the notation under discussion becomes:

$$\dot{A}\dot{B} = AB\, j^{(\alpha+\beta)} = Cj^{\delta}\,. \qquad \textbf{(11)}$$

Translating (**11**) into words it will be seen that the product of two harmonic quantities represented, as vectors A and B by means of complex quantities of the form (**7**) or (**7'**) and (**8**) or (**8'**) is equal to a new quantity $C = AB$ turned through $\left(\frac{\pi}{2}\ \delta\right)$ radians with respect to the reference axis.

Similarly it will be seen that,

$$\frac{\dot{A}}{\dot{B}} = \frac{A}{B}\, j^{(\alpha-\beta)} \qquad \textbf{(12)}$$

If in equation (**12**) $\dot{A}$ represents an e. m. f. and $\dot{B}$ a current produced by it, their quotient, the impedance of the circuit, is given by:

$$\dot{Z} = Zj^{\gamma}$$

where $Z = A/B$ and $\gamma = (\alpha - \beta)$. In this connection it is of interest to consider in a little detail the meaning of the reciprocal of a plane vector, such as $\dot{Z} = Z\,j^{\gamma}$

Let $\dot{Y}$ be the reciprocal of $\dot{Z}$; then by definition,

$$\dot{Y}\dot{Z} = 1 = (Yj^{\epsilon})\ (Zj^{\gamma})$$

$$= YZj^{(\epsilon+\gamma)} = 1j^{0}$$

$$i.e., (\epsilon+\gamma) = 0 \text{ or } \epsilon = -\gamma.$$

In short, it is seen that the reciprocal of a vector $\dot{Z} = Zj^{\gamma}$ is a new vector turned through $(-\gamma)\ \frac{\pi}{2}$ radians and having a length equal to $(1/Z)$. The great simplicity of this result is not, of course, unknown in connection with the exponential representation of a vector; but it is not shared with the ordinary notation, and the average student or even engineer is loath to use such expressions as:

$$\dot{Y} = \left(\frac{r}{Z^2} - j\,\frac{X}{Z^2}\right) = (g - jb)$$

since the admittance $\underset{\cdot}{Y}$ in terms of r, x and Z is rather involved and *its physical meaning* is not quite apparent.

In general the product or quotient of any number of vectors can readily be written down:

$$\frac{\underset{\cdot}{A}\underset{\cdot}{B} \text{ etc.}}{\underset{\cdot}{C}\underset{\cdot}{D} \text{ etc.}} = \frac{AB \text{ etc.}}{CD \text{ etc.}} j^{(\alpha + \beta \text{ etc.}) - (\gamma + \delta \text{ etc.})} \tag{13}$$

3. *Addition and Subtraction.* Consider two vectors, $\underset{\cdot}{A}$ and $\underset{\cdot}{B}$:

$$\underset{\cdot}{A} = A j^{\alpha} = a + ja' \tag{14}$$

$$\underset{\cdot}{B} = B j^{\beta} = b + jb' \tag{15}$$

Their sum $\underset{\cdot}{C}$ in terms of rectangular components is:

$$\underset{\cdot}{C} = C j^{\delta} = (a + b) + j\,(a' + b') \tag{16}$$

whence, placing $\alpha' = \frac{\pi}{2}\alpha$ and $\beta' = \frac{\pi}{2}\beta$,

$$C^2 = A^2 + B^2 + 2\,AB \cos(\beta' - \alpha') \tag{17}$$

This follows also directly from elementary trigonometry, (see Fig. 2).

The phase angle $\delta' = \frac{\pi}{2}\delta$ can be calculated by means of one of the following expressions.

$$\delta' = \tan^{-1} \frac{A \sin \alpha' + B \sin \beta'}{A \cos \alpha' + B \cos \beta'} \tag{18}$$

$$= \alpha' + 2\left(\sin^{-1} \sqrt{\frac{S\,(S - B)}{AC}}\right) \tag{19}$$

where $\quad 2\,S = A + B + C.$

Similarly the sum of three or more vectors can be obtained by the use of the above formulas; however, judgment should be exercised in the choice of the method or methods to be used in any given problem in order to simplify calculations as much as possible. Thus in case of more than two vectors it may be more convenient to obtain the resultant by means of the rectangular form of complex quantities.

To find the difference of any two vectors $\underset{\cdot}{A}$ and $\underset{\cdot}{C}$ (see Fig. 3) it may be noted that if $\underset{\cdot}{A} = A\,j^{\alpha}$ then $-\underset{\cdot}{A}$ is equal to $\underset{\cdot}{A}\,j^{2}$ and consequently,

$$\underset{\cdot}{B} = C j^{\delta} - A\,j^{\alpha} \qquad (20)$$

$$= C j^{\delta} + A\,j^{\alpha+2} \qquad (21)$$

where $\alpha^{\circ} = 90\,\alpha$ and $(\alpha + 2) = (\alpha^{\circ} + 180)$ deg. Therefore according to equation (17) we get:

$$B^{2} = C^{2} + A^{2} - 2\,A C \cos\,(\delta^{\circ} - \alpha^{\circ}) \qquad (22)$$

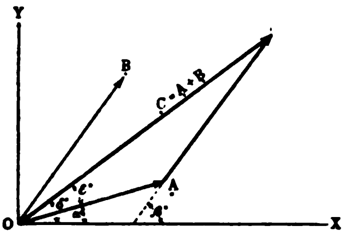

Fig. 2

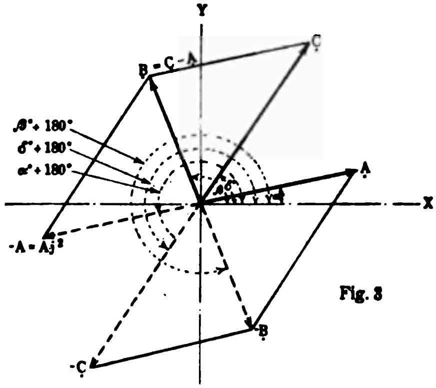

Fig. 3

The phase angle is given by:

$$\beta^{\circ} = \tan^{-1} \frac{C \sin \delta^{\circ} - A \sin \alpha^{\circ}}{C \cos \delta^{\circ} - A \cos \alpha^{\circ}} \qquad (23)$$

In this connection it may be noted further that, (see Fig. 3)

$$\underset{\cdot}{B} = \underset{\cdot}{C} - \underset{\cdot}{A} = C j^{\delta} + A\,j^{(2+\alpha)} = (C j^{(2+\delta)} + A\,j^{\alpha})\,j^{2}, \qquad (24)$$

or

$$\underset{\cdot}{B}\,j^{+2} = (\underset{\cdot}{C} j^{2} + \underset{\cdot}{A}) = (\underset{\cdot}{A} - \underset{\cdot}{C}) \qquad (25)$$

4. *General Expression for Power.* The general expression for power which applies to a-c. or d-c. circuits of any wave shape and phase displacement is:

$$P = \frac{1}{T} \int_{0}^{T} e i d t = \frac{1}{\pi} \int_{0}^{\pi} e i d \theta \qquad (26)$$

where e and i are instantaneous values expressed as functions of the time, t, or the time angle, θ, and in the simplest case when e and i are constant, $P = EI$. If, however, e and i are given by a Fourier's series, products of harmonics of different frequencies will contribute nothing, and for the nth harmonic the power P_n will be given by:

$$P_n = \frac{1}{2} (E_{n\,max}\, I_{n\,max} \cos \alpha^\circ) = E_n\, I_n \cos \alpha^\circ \qquad \textbf{(27)}$$

where E_n and I_n are the effective values of the nth harmonic of e. m. f., and current, and $\alpha^\circ = (90\ \alpha)$ deg. is the phase angle between E_n and I_n.

According to our notation if $\underset{\cdot}{E}_n = E_n j^\alpha$ and $\underset{\cdot}{I}_n = I_n$ then,

$$P_n = E_n\, I_n \cos \alpha^\circ$$

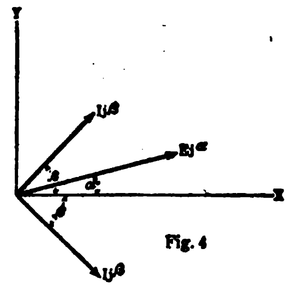

Fig. 4

If in general (see Fig. 4)

$$e = E_{max} \sin (\theta + \alpha^\circ) \qquad \textbf{(28')}$$

$$i = I_{max} \sin (\theta \pm \beta^\circ) \qquad \textbf{(29')}$$

or

$$\underset{\cdot}{E} = E j^\alpha \qquad \textbf{(28)}$$

$$\underset{\cdot}{I} = I j^{\pm\beta} \qquad \textbf{(29)}$$

where E and I represent the effective values of E_{max} and I_{max} and $\alpha^\circ = (90\ \alpha)$ deg. and $\beta^\circ = (90\ \beta)$ deg., the power P will be:

$$P = \frac{1}{\pi} \int (ei)\, d\,\theta = \tfrac{1}{2}\, E_{max}\, I_{max} \cos (\alpha^\circ - \beta^\circ) \qquad \textbf{(30)}$$

$$= E\, I \cos (\alpha^\circ - \beta^\circ) \qquad \textbf{(31)}$$

where β may be positive or negative; *i. e.* whether the current be leading or lagging the power is given by equation (**31**).

Comparing this result with the usual rectangular notation we have:

$$P = \frac{1}{\pi} \int (ei)\, d\,\theta = E_n\, I_n\, (\cos \alpha^\circ \cos \beta^\circ + \sin \alpha^\circ \sin \beta^\circ) \qquad (32)$$

$$= ei \pm e'\, i' \qquad (33)$$

where $\dot{E}_n = (e_n + je_n')$ and $\dot{I}_n = (i_n \mp ji_n')$

The general expression (**31**) is very simple and it states that the power in any circuit due to any harmonics of the same order is equal to the product of the r. m. s. value of voltage and current into the cosine of their (algebraic) phase difference. As to equation (**32**) it is seen that it can be translated into the general law that the power produced by a voltage $\dot{E} = (e + j\,e')$, and a current, $\dot{I} = (i \pm j\,i')$, is given by the real part of their product, with one important provision of *reversal of sign*. This change of sign impairs the simplicity of the rule although it may be accounted for by introducing the idea of double frequency quantities, etc.; however, this seems rather unnecessary and round about since it is not advisable to define average power as the product of two (plane) vectors, in the first place; it is best to base definitions on general and fundamental propositions as it was done above.

5. *Logarithm of* $A\,j^n$. This is readily obtained by following the rules of algebra according to which:

$$\log\,(A\,j^n) = \log A + \log\,(j^n) \qquad (34)$$

$$= \log A + n \log\,(j) \qquad (35)$$

But the logarithm of any complex quantity $a + jb$ is known to be:

$$\log\,(a + jb) = \log\,(\sqrt{a^2 + b^2}) + j\,(\theta + 2\,\pi\,m) \qquad (36)$$

where $\theta = \tan^{-1}(b/a)$ and m is any integer which for simplicity can be taken as zero. Consequently,

$$\log\,(j) = \log\,(j\,1) = j\left(\frac{\pi}{2} + 2\,\pi\,m\right) \qquad (37)$$

and therefore substituting (**37**) in (**35**):

$$\log\,(A\,j^n) = \log A + j\,\frac{\pi}{2}\,n + 2\,\pi\,m\,n \qquad (38)$$

where m may be assumed to be zero.

6. *Differentiation.* Assuming again that the operator j^n can be treated as an algebraic quantity we have:

$$d\,(\underset{\cdot}{A}) = d\,(A\,j^n)$$

$$= j^n \cdot d\,(A) + A \cdot d\,(j^n) \qquad \textbf{(39)}$$

Assuming that (j^n) follows the rules of calculus we have:

$$d\,(j^n) = j^n \cdot \log\,(j) \cdot dn \qquad \textbf{(40)}$$

Whence substituting (**37**) and (**40**) in equation (**39**):

$$d\,(\underset{\cdot}{A}) = j^n \cdot d\,A + A\,\frac{\pi}{2} \cdot j^{(n+1)} \cdot dn \qquad \textbf{(41)}$$

The same result can also be obtained as follows:
The differential of a complex quantity is known to be:

$$d\,(\underset{\cdot}{A}) = d\,(a + j\,a')$$

$$= d\,(A \cos\theta + j\,A \sin\theta)$$

$$= \cos\theta \cdot d\,A - A \cdot \sin\theta \cdot d\,\theta$$

$$+\, j\,(\sin\theta \cdot d\,A + A \cdot \cos\theta \cdot d\,\theta)$$

$$= (\cos\theta + j \sin\theta)\,d\,A$$

$$+\, A\,d\,\theta\,j\,(\cos\theta + j \sin\theta)$$

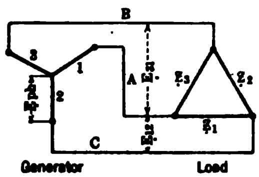

Fig. 5

It is easy, by substituting j^n for the operator $(\cos\theta + j \sin\theta)$, where $\theta = \frac{\pi}{2}\,n$, to obtain equation (**41**).

Or again, if desired the exponential form can be used and by substituting j^n for $e^{j\theta}$ in

$$d\,(A e^{j\theta}) = e^{j\theta} . d\,A + A\,e^{j\theta}\,j\,.\,d\,\theta \qquad \textbf{(42)}$$

expression (**41**) be derived.

III—Illustrative Problems

In order to illustrate the use and application of the method just described a few simple examples will be considered.

(1) A Y-connected generator feeds an unbalanced Δ-connected

DATA:

Phase Voltages of Generator:

A		B	C	D
$\dot{E}_{1ph} = E_{ph}$	=	$\begin{cases} e_{ph} \\ e_1 \end{cases}$	$= E_{ph1}$	$= E_{ph}$
$\dot{E}_{2ph} = E_{ph} j^{-\frac{4}{3}} = E_{ph} j^{-\frac{120°}{90°}}$	=	$\begin{cases} -0.5\, e_{ph} - j\, 0.866\, e_{ph} \\ e_2 + j\, e'_2 \end{cases}$	$= E_{ph}\left(\cos \frac{2\pi}{3} - j \sin \frac{2\pi}{3}\right)$	$= E_{ph}\, \epsilon^{-j\frac{2\pi}{3}}$
$\dot{E}_{3ph} = E_{ph} j^{-\frac{8}{3}} = E_{ph} j^{-\frac{240°}{90°}}$	=	$\begin{cases} -0.5\, e_{ph} + j\, 0.866\, e_{ph} \\ e_3 + j\, e'_3 \end{cases}$	$= E_{ph}\left(\cos \frac{4\pi}{3} - j \sin \frac{4\pi}{3}\right)$	$= E_{ph}\, \epsilon^{-j\frac{4\pi}{3}}$

Impedances of Load:

$Z_1 j^{\alpha} = r_1 + j x_1$	$= Z_1 (\cos \alpha' + j \sin \alpha')$	$= Z_1\, \epsilon^{j\alpha'}$
$Z_2 j^{\beta} = r_2 + j\, x_2$	$= Z_2 (\cos \beta' + j \sin \beta')$	$= Z_2\, \epsilon^{j\beta'}$
$Z_3 j^{\gamma} = r_3 + j\, x_3$	$= Z_3 (\cos \gamma' + j \sin \gamma')$	$= Z_3\, \epsilon^{j\gamma'}$

where,

$$Z_1 = \sqrt{r_1^2 + x_1^2}; \quad \alpha' = \frac{\pi}{2}\, \alpha = \tan^{-1}\left(\frac{x_1}{r_2}\right)$$

Similarly for the others.

SOLUTION:

Line voltages at load:

A		B	C	D
$\dot{E}_{12} = E j^{\frac{1}{3}} = E j^{\frac{30°}{90}}$	=	$\begin{cases} e_{12} + j\, e'_{12} \\ 0.866\, E + j\, 0.5\, E \end{cases}$	$= E \left(\cos \frac{\pi}{6} + j \sin \frac{\pi}{6}\right)$	$= E\, \epsilon^{j\frac{\pi}{6}}$
$\dot{E}_{23} = E j^{-1} = E j^{-\frac{90°}{90°}}$	=	$\begin{cases} -j\, e'_{23} \\ -j\, E \end{cases}$	$= E(-j)$	$= E\, \epsilon^{-j\frac{\pi}{2}}$
$\dot{E}_{31} = F^{5/3} = E j^{\frac{150°}{90°}}$	=	$\begin{cases} e_{31} + j\, e'_{31} \\ -0.866\, E + j\, 0.5\, E \end{cases}$	$= E \left(\cos \frac{5\pi}{6} + j \sin \frac{5\pi}{6}\right)$	$= E\, \epsilon^{j\frac{5\pi}{6}}$

where $E = \sqrt{3}\, E_{ph}$.

load as shown in Fig. 5. To find the respective phase and line currents, voltages, phase angles and power.

This problem will be solved by the use of complex quantities and the exponential form as follows:

A —Notation discussed above.
B —The usual reactangular form.
C —The usual polar form.
D —The exponential form.

Phase currents of load:

$$\underset{\cdot}{I}_{1ph} = \frac{E}{Z_1} j^{(\frac{1}{3}-\alpha)} = \frac{(e_{12} + j\,e'_{12})\,(r_1 - j\,x_1)}{Z_1^2}$$

$$= \frac{E}{Z_1}\left[\cos\left(\frac{\pi}{6} - \alpha'\right) + j\sin\left(\frac{\pi}{6} - \alpha'\right)\right] = \frac{E}{Z_1}\epsilon^{j\left(\frac{\pi}{6} - \alpha'\right)}$$

$$\underset{\cdot}{I}_{2ph} = \frac{E}{Z_2} j^{-(1+\beta)} = \frac{(-j\,e'_{23})\,(r_2 - j\,x_2)}{Z_2^2}$$

$$= \frac{E}{Z_2}\left[-\sin\beta' + j\cos\beta'\right] = \frac{E}{Z_2}\epsilon^{-j\left(\frac{\pi}{2} + \beta'\right)}$$

$$\underset{\cdot}{I}_{3ph} = \frac{E}{Z_3} j^{(5/3-\gamma)} = \frac{(e_{31} + j\,e'_{31})\,(r_3 - j\,x_3)}{Z_3^2}$$

$$= \frac{E}{Z_3}\left[\cos\left(\frac{5\pi}{6} - \gamma'\right) + j\sin\left(\frac{5\pi}{6} - \gamma'\right)\right] = \frac{E}{Z_3}\epsilon^{j\left(\frac{5\pi}{6} - \gamma'\right)}$$

Line Currents A

$$\underset{\cdot}{I}_A = (\underset{\cdot}{I}_{1ph} - \underset{\cdot}{I}_{3ph})$$

$$= j^{\delta}\left[I^2_{1ph} + I^2_{3ph} - 2\,I_{1ph}\,I_{3ph}\cos\left(\frac{5\pi}{6} - \gamma' - \frac{\pi}{6} + \alpha'\right)\right]^{\frac{1}{2}}$$

$$\underset{\cdot}{I}_B = (\underset{\cdot}{I}_{3ph} - \underset{\cdot}{I}_{2ph})$$

$$= j^{\theta}\left[I^2_{2ph} + I^2_{3ph} - 2\,I_{2ph}\,I_{3ph}\cos\left(\frac{5\pi}{6} - \gamma' + \frac{\pi}{2} + \beta'\right)\right]^{\frac{1}{2}}$$

$$\underset{\cdot}{I}_C = (\underset{\cdot}{I}_{2ph} - \underset{\cdot}{I}_{1ph})$$

$$= j^{\lambda}\left[I^2_{1ph} + I^2_{2ph} - 2\,I_{1ph}\,I_{2ph}\cos\left(\frac{\pi}{6} - \alpha' + \frac{\pi}{2} + \beta'\right)\right]^{\frac{1}{2}}$$

B.

$$\dot{I}_A = (\dot{I}_{1ph} - \dot{I}_{3ph}) = (i_{1ph} - i_{3ph}) + j\,(i'_{ph} - i'_{3ph})$$

$$\dot{I}_B = (\dot{I}_{3ph} - \dot{I}_{2ph}) = (i_{3ph} - i_{2ph}) + j\,(i'_{3ph} - i'_{2ph})$$

$$\dot{I}_C = (\dot{I}_{2ph} - \dot{I}_{1ph}) = (i_{2ph} - i_{1ph}) + j\,(i'_{2ph} - i'_{1ph})$$

where,

$$(i_{1ph} + j\,i'_{1ph}) = [(e_{12}\, r_1 + e'_{12}\, x_1) + j\,(e'_{12}\, r_1 - e_{12}\, x_1)]\, Z_1^{-2}$$

$$(i_{2ph} + j\,i'_{2ph}) = [-\,e'_{23}\, x_2 + j\,e'_{23}\, r_2]\, Z_2^{-2}$$

$$(i_{3ph} + j\,i_{3ph}) = [(e_{31}\, r_3 + e_{31}\, x_3) + j\,(e'_{31}\, r_3 - e_{31}\, x_3)]\, Z_3^{-2}$$

C.

$$\dot{I}_A = \left[\frac{E}{Z_1}\cos\left(\frac{\pi}{6} - \alpha'\right) - \frac{E}{Z_3}\cos\left(\frac{\pi}{6} - \gamma'\right)\right] + j\left[\frac{E}{Z_1}\sin\left(\frac{\pi}{6} - \alpha'\right) - \frac{E}{Z_3}\sin\left(\frac{5\,\pi}{6} - \gamma'\right)\right]$$

$$\dot{I}_B = \left[\frac{E}{Z_3}\cos\left(\frac{5\,\pi}{6} - \gamma'\right) - \frac{E}{Z_2}\sin\beta'\right] + j\left[\frac{E}{Z_3}\sin\left(\frac{\pi}{6} - \gamma'\right) + \frac{E}{Z_2}\cos\beta'\right]$$

$$\dot{I}_C = \left[\frac{E}{Z_2}\sin\beta' - \frac{E}{Z_1}\cos\left(\frac{\pi}{6} - \alpha'\right)\right] - j\left[\frac{E}{Z_2}\cos\beta' + \frac{E}{Z_1}\sin\left(\frac{\pi}{6} - \alpha'\right)\right]$$

In case of method D in order to carry on actual computation for I_A, I_B and I_C it is necessary to make recourse to one of the other methods.

In regard to the expression given under B and C, it may be noted that the square root of the sums of the squares of the two components has to be taken in order to find the magnitude of the line currents I_A, I_B and I_C.

Phase angles of the line currents: A.

$$\delta^\circ = \tan^{-1}\frac{I_{1ph}\sin\left(\frac{\pi}{6} - \alpha'\right) - I_{3ph}\sin\left(\frac{5\,\pi}{6} - \gamma'\right)}{I_{1ph}\cos\left(\frac{\pi}{6} - \alpha'\right) - I_{3ph}\cos\left(\frac{5\,\pi}{6} - \gamma'\right)}$$

$$\theta^\circ = \tan^{-1} \frac{I_{3ph} \sin\left(\frac{5\pi}{6} - \gamma'\right) + I_{2ph} \sin\left(\frac{\pi}{2} + \beta'\right)}{I_{3ph} \cos\left(\frac{5\pi}{6} - \gamma'\right) - I_{2ph} \cos\left(\frac{\pi}{2} + \beta'\right)}$$

$$\lambda^\circ = \tan^{-1} \frac{-I_{2ph} \sin\left(\frac{\pi}{2} + \beta'\right) - I_{1ph} \sin\left(\frac{\pi}{6} - \alpha'\right)}{I_{2ph} \cos\left(\frac{\pi}{2} + \beta'\right) - I_{1ph} \sin\left(\frac{\pi}{6} - \alpha'\right)}$$

where $\delta^\circ = 90\ \delta$ degrees, and similarly for the others.

B

$$\delta^\circ = \tan^{-1} \frac{i'_{1ph} - i'_{3ph}}{i_{1ph} - i_{3ph}} \qquad \theta^\circ = \frac{i'_{3ph} - i'_{2ph}}{i_{3ph} - i_{2ph}}$$

$$\lambda^\circ = \tan^{-1} \frac{i'_{2ph} - i_1{}'_{ph}}{i_{2ph} - i_{1ph}}$$

C

$$\delta^\circ = \tan^{-1} \frac{\frac{E}{Z_1} \sin\left(\frac{\pi}{6} - \alpha'\right) - \frac{E}{Z_3} \sin\left(\frac{5\pi}{6} - \gamma'\right)}{\frac{E}{Z_1} \cos\left(\frac{\pi}{6} - \alpha'\right) - \frac{E}{Z_3} \cos\left(\frac{5\pi}{6} - \gamma'\right)}$$

similarly for θ° and λ°.

Power at the load: A

$$P_{1ph} = I^2_{1ph} Z_1 \cos \alpha^\circ \text{ or } P_{1ph} = E I_{1ph} \cos (30^\circ - \alpha^\circ - 30^\circ)$$

$$P_{2ph} = I^2_{2ph} Z_2 \cos \beta^\circ \text{ or } P_{2ph} = E I_{2ph} \cos (-150^\circ - \beta^\circ - 150^\circ$$

$$P_{3ph} = I^2_{3ph} Z_3 \cos \gamma^\circ \text{ or } P_{3ph} = E I_{3ph} \cos (150^\circ - \gamma^\circ - 150^\circ)$$

B

$$P_{1ph} = I^2_{1ph}\, r_1 \text{ or } P_{1ph} = e_{12}\, i_{1ph} + e'_{12ph}\, i'_{1ph}.$$

$$P_{2ph} = I^2_{2ph}\, r_2 \text{ or } P_{2ph} = -\, e'_{23}\, i'_{2ph}$$

$$P_{3ph} = I^2_{3ph}\, r_3 \text{ or } P_{3ph} = e_{31}\, i_{3ph} + e'_{31}\, i'_{1ph}$$

C and D

$$P_{1ph} = \frac{E^2}{Z_1} \cos \alpha^\circ \; P_{2ph} = \frac{E^2}{Z_2} \cos \beta^\circ \; P_{3ph} = \frac{E^2}{Z_3} \cos \gamma^\circ$$

which are, of course, similar to the expression given for method A.

Numerical example: Let $E = 100$; $E_{ph} = \frac{100}{\sqrt{3}}$;

$$\begin{aligned} \text{and, } \dot{Z}_1 &= 1. \; j^{\frac{45^\circ}{90^\circ}} && 0.707 + j\,0.707 \\ \dot{Z}_2 &= 1.2\, j^{\frac{20^\circ}{90^\circ}} && = 1.128 + j\,0.408 \\ \dot{Z}_3 &= 1.3\, j^{-\frac{10^\circ}{90^\circ}} && = 1.28 - j\,0.226 \end{aligned}$$

then,

$$\dot{I}_{1ph} = 100\, j^{-\frac{15^\circ}{90^\circ}} \qquad \dot{I}_{2ph} = 83.3\, j^{-\frac{110^\circ}{90^\circ}} \qquad \dot{I}_{3ph} = 77\, j^{\frac{160^\circ}{90^\circ}}$$

$$I_A = [\overline{100}^2 + \overline{77}^2 - 200 \times 77 \cos 175^\circ]^{\frac{1}{2}} = 177 \text{ amperes.}$$

$$I_B = [\overline{83.3}^2 + \overline{77}^2 - 2 \times 83.3 \times 77 \cos 270^\circ]^{\frac{1}{2}} = 114 \text{ amperes.}$$

$$I_C = [\overline{83.3}^2 + 100^2 - 200 \times 83.3 \cos 95^\circ]^{\frac{1}{2}} = 137 \text{ amperes.}$$

$$\delta^\circ = 18^\circ = \delta\,(90^\circ);\; \delta = 0.2$$

$$\theta^\circ = 112.8^\circ = \theta\,(90^\circ);\; \theta = 1.255$$

$$\lambda^\circ = 202.8^\circ = \lambda\,(90^\circ)\lambda = 2.259$$

Power at load:

$$\begin{aligned} P_1 &= 100 \times 100 \times \cos 45^\circ \\ &= 1 \times \overline{100}^2 \times \cos 45^\circ && = 7070 \text{ watts} \end{aligned}$$

$$\begin{aligned} P_2 &= 100 \times 83.4 \times \cos 20^\circ \\ &= \overline{83.4}^2 \times 1.12 \times \cos 20^\circ && = 7860 \text{ watts} \end{aligned}$$

$$\begin{aligned} P_3 &= 100 \times 77 \times \cos 10^\circ \\ &= \overline{77}^2 \times 1.3 \times \cos 10^\circ && = 7600 \text{ watts} \end{aligned}$$

Total power at load = 22,520 watts.

Power at generator:

$$P_1 = 177 \times \frac{100}{\sqrt{3}} \times \cos 18^\circ = 9710.$$

$$P_2 = 114 \times \frac{100}{\sqrt{3}} \times \cos 120^\circ = 6520.$$

$$P_3 = 137 \times \frac{100}{\sqrt{3}} \times \cos 240^\circ = 6290.$$

Total power at generator = 22,520 watts.
The vector diagram is shown in Fig. 6.

2. A load having a variable power factor and consuming a constant voltage is supplied through an inductive line whose characteristics are: $(r + jx) = \dot{Z} = Zj^\alpha$. To investigate the effect of leading and lagging current on the generator voltage.

Taking the load voltage as the reference vector, the generator voltage, E_g, is:

$$E_g = e + Ij^{\pm\beta}.Zj^\alpha = e + IZj^{(\alpha\pm\beta)}$$

where the positive sign refers to leading and the negative sign to lagging current.

Inasmuch as we are dealing with vector addition of a quantity (IZ), making $(\alpha^\circ \pm \beta^\circ)$ degrees with a horizontal line (e) volts, a little consideration will show that for any given value of β° the resultant E_g will be larger when β° is negative, *i. e.* when the load is inductive than when the load is condensive. Indeed it is not difficult to form a mental picture of the sum of the two vectors, e and $(IZ)j^{(\alpha\pm\beta)}$, and see that when $(\alpha^\circ \pm \beta^\circ) = 0$, E_g is maximum, and when

$$(\alpha^\circ \pm \beta^\circ) = 90^\circ \; E_g \text{ is minimum.}$$

Suppose now we prove this elementary but fundamental proposition by means of the usual rectangular form of complex quantities:

$$E_g = [(e + ir - i'x)^2 + (i'r + ix)^2]^{\frac{1}{2}}, \text{ for leading current.}$$

$$E'_g = [(e + ir + i'x)^2 + (ix - i'r)^2]^{\frac{1}{2}} \text{ for lagging current.}$$

It is not apparent by comparing these equations to see whether $E_g > E_g'$ or vice-versa.

3. Finally consider the calculation of the characteristics of a long transmission line with distributed inductance and capacity. It is known that the voltage and current at any point along the line, at a distance l from the receiving end, are given by the following expressions:

$$E_1 = E_r\ (1 + ZY/2 + Z^2Y^2/24) + ZI_r\ (1 + ZY/6 + Z^2Y^2/120)\ ..$$

$$I_1 = I_r\ (1 + ZY/2 + Z^2Y^2/24) + YI_r\ (1 + ZY/6 + Z^2Y^2/240)..$$

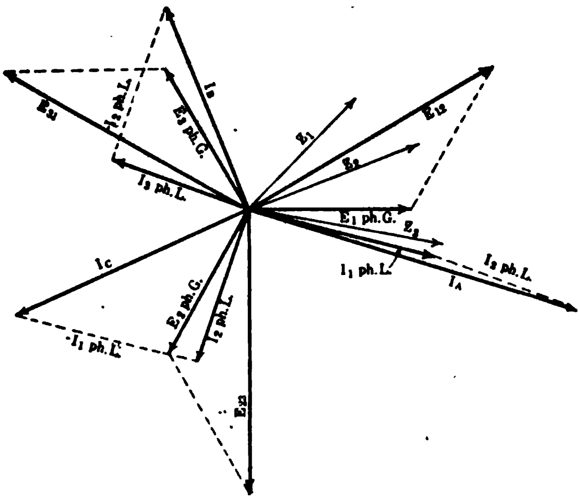

Fig. 3

Generator phase voltages, E_1,*ph. G.* etc., line voltages, E_{12}, etc. are to same scale. Phase currents of load, I_1*ph L.* etc., and line currents, I_A etc. are to same scale which is different from the voltage scale.

where Z and Y are the impedance and admittance of the length of the line under consideration, and the subscript refers to the receiving end. These equations are fairly long for purposes of calculation on account of the many multiplications involved furthermore computations become rather tedious owing to the fact that ordinarily, either the real or imaginary components of some of the quantities involved are very small, but still cannot be neglected. These objections will remain true, although to a lesser degree, even when the equations are simplified by dropping the terms containing Z^2 and Y^2. For the sake of comparison the

e. m. f. equation is given in the usual notation and in the one discussed above:

$$\dot{E}_1 = (e_r + je'_r)\,[1 + (r + jx)\,(g + jb)/2 + (r + jx)\,(i_r + ji_r')]$$

$$E_1 = E_r j^{\delta} + E_r Z Y j^{(\alpha + \beta + \delta)} + I_r Z j^{(\alpha + \gamma)}$$

As an example the curves in Fig. 7 give the characteristics of a transmission line 100 miles long and delivering 20,000 kw. at 100 kv. (or $100/\sqrt{3}$ to neutral) with a periodicity of 25 cycles per second. The line consists of two No. 00 B. & S. aluminum conductors in parallel, spaced 7 ft. apart and strung on separate steel towers. The resistance is 32.2 ohms, the inductive react-

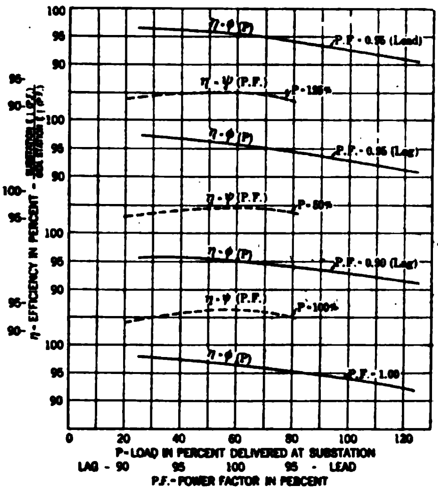

FIG. 7

ance is 4376 ohms and the condensive reactance is 0.664 ohms per conductor.

The calculations are too lengthy to be given in detail and would be of little value since nothing can take the place of testing for ones' self, by actual calculations, the advantages and disadvantages of the different methods.

IV—CRITICAL RÉSUMÉ AND SUMMARY

It has been shown that without any radical modification of the present day method of alternating-current technology it is possible to deal in *calculations* directly with vectors in a simple manner by using the polar form of complex quantities involving the operator $j^{\alpha} = (\sqrt{-1})^{\alpha}$, which indicates rotation through $90\ \alpha$ deg. in the positive direction. Thus,

$$\dot{E} = Ej^{\alpha}, \text{ in the polar form given herein;}$$

$$\dot{E} = e + je', \text{ in the rectangular form.}$$

The choice of mathematical methods and notations is necessarily to a certain extent, influenced by personal tastes and it is not practicable to give any general rules as to when the notation given herein, either by itself or in combination with others, will prove most advantageous. At present some engineers prefer to use trigonometric methods entirely, while others employ complex quantities almost exclusively; still others use either of these methods or exponentials and hyperbolic functions, etc. according to whichever they think lends itself best to the case under consideration. Although the last ones are probably in the minority, it is no doubt best to avail oneself of the peculiar advantages of the different notations so far developed.

The judicious choice of either the rectangular or polar form of complex quantities as given here and the judicious combination of the same in dealing with alternating-current problems will be found useful in the theory and calculation of alternating currents and alternating-current machinery.

For convenience of reference the summary below is given:

I. A sinusoidal or equivalent sinusoidal function may be represented by means of one of the following notations:[2]

$$(1)\ \dot{A} = A\,j^{\alpha}$$

$$(2)\ \dot{A} = a + ja'$$

$$(3)\ \dot{A} = A\,(\cos\alpha^{\circ} + j\sin\alpha^{\circ})$$

$$(4)\ \dot{A} = A\,e^{j\alpha'}$$

$$(5)\ \dot{A} = A\underline{/\alpha^{\circ}}$$

Where $\frac{\pi}{2}\,\alpha = \alpha'$ radians and $\alpha\,90 = \alpha^{\circ}$ deg.

---

2. The exponent of j in (1) is a number; the exponent of (4) must be j (radians); and the angle in (3) and (5) may be expressed in radians or degrees. In this connection it may be noted that (5) is more of a ***symbol*** than a ***mathematical notation.***

II. The product of any number of vectors is:

$$\dot{B} = \dot{A}\dot{B}\dot{C} \text{ etc.} = (ABC \text{ etc.})\,(j^{(\alpha + \beta + \gamma \text{ etc.})})$$

III. The quotient of any number of vectors is:

$$\frac{\dot{A}\dot{B} \text{ etc.}}{\dot{C}\dot{D} \text{ etc.}} = \frac{AB \text{ etc.}}{CD \text{ etc.}}\, j^{(\alpha + \beta \text{ etc.}) - (\gamma + \delta \text{ etc.})}$$

The reciprocal of a vector Zj^{α} is $(I/Z)\,j^{-\alpha}$

IV. The sum of two vectors is:

$$A\,j^{\alpha} + Bj^{\beta} = [A^2 + B^2 + 2\,AB\cos(\alpha^{\circ} - \beta^{\circ})]^{\frac{1}{2}}\,j^{\delta}$$

where,

$$\delta^{\circ} = \tan^{-1}\frac{A\sin\alpha^{\circ} - B\sin\beta^{\circ}}{A\cos\alpha^{\circ} - B\cos\beta^{\circ}} = (90\delta) \text{ and } \alpha^{\circ} = (\alpha\,90);$$

$$\beta^{\circ} = (\beta\,90)$$

V. The difference of two vectors is:

$$Aj^{\alpha} - Bj^{\beta} = [A^2 + B^2 - 2\,AB\cos(\alpha^{\circ} - \beta^{\circ})]^{\frac{1}{2}}\,j^{\delta}$$

where,

$$\delta^{\circ} = \tan^{-1}\frac{A\sin\alpha^{\circ} - B\sin\beta^{\circ}}{A\cos\alpha^{\circ} - B\cos\beta^{\circ}}$$

VI. The power in a circuit due to a current $Ij^{\pm\beta}$ propelled by an e.m.f. Ej^{α} is:

$$P = EI\cos(\alpha^{\circ} - \beta^{\circ})$$

VII. The differential of Aj^{α} is:

$$d\,(A\,j^{\alpha}) = j^{\alpha}\,(dA + A\,j\,\frac{\pi}{2}\,.\,d\,\alpha)$$

VIII. The logarithm of $A\,j^{\alpha}$ is:

$$\log\,(A\,j^{\alpha}) = \log A + j\left(\frac{\pi}{2}\,\alpha + 2\,\pi\,m\right)$$

where m may be taken as zero.

IX. Some other expressions of interest are as follows:

1. $\dot{A} = A\, j^{a}$ or strictly $\dot{A} = A\, j^{a+4m}$, where m may be taken as zero, this being the usual practise in all similar cases. For instance, $1/2 = \sin \pi/6$ or strictly $1/2 = \sin(\pi/6 + 2\,\pi\, m)$

2. $(A j^{a})^{m} = A^{m}\,(j^{ma})$. Similarly,

$$\sqrt[m]{Aj} = A^{1/m}.j^{a/m}$$

3. $j^{a} = e^{j\,a\frac{\pi}{2}} = (\cos\alpha^{\circ} + j\,\sin\alpha^{\circ})$, where $(\alpha \times 90) = (\alpha^{\circ})$ deg.

Therefore, $j = \sqrt{-1} = e^{j\,\pi/2}$

4. $$\log j = \log(e^{j\,\pi/2}) = j\,\frac{\pi}{2}$$

$$\log j^{a} = \log(e^{j\,a\,\pi/2}) = j\,\alpha\,\frac{\pi}{2}$$

In conclusion the writer wishes to thank Mr. W. C. Graustein, of the department of mathematics of the Rice Institute, for valuable criticisms and suggestions.

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Discussion on "Application of a Polar Form of Complex Quantities to the Calculation of A-C. Phenomena" (Diamant), Cleveland, Ohio, June 30, 1916.

Alexander Gray: Every September, before I meet my classes, I have to review the subject of complex quantities as applied to the solution of the problems in electrical engineering because, during the rest of the year, I never have occasion to use this method in my own work.

I am afraid that, in some of our schools, the use of this method is carried to extremes. An induction motor for example becomes a curly line and is called $r + j x$ but, while the solutions obtained are elegant, the student does not always know what they mean nor does he obtain such an idea of the operation of the machine as to argue regarding its characteristics when away from his formulas.

It is true that in circuit work solutions may more readily be obtained by the use of complex quantities than by other methods but I find that if the problem is not in the book the student is not satisfied with the solution until he has checked it by vector diagrams and trigonometry.

Unfortunately the average student is not equipped with sufficient mathematics to understand what he is doing when he uses the methods of Dr. Steinmetz or this elegant method now suggested by Prof. Diamant.

E. E. F. Creighton: I think it is very exceptional indeed that mathematics is used after leaving college. Men come to me, who have been out of college a year, and are unable to use the mathematics which they learned there. Of course, there are exceptions. I should say this condition is somewhat a reflection on the methods of teaching mathematics. There are a good many things interesting about mathematics, although you would never know it by the way it is taught.

It happens that other methods seem to be favored in the industrial concerns. One can get a solution of a problem in general more quickly and better by some non-mathematical method. I must say, however, I have had several men with me who have been of the greatest help to me by being able to use freely the mathematics favored by Dr. Steinmetz.

May I ask Mr. Diamant just where is a good place to apply this mathematical method?

John B. Whitehead: I want to ask Professor Gray what is his explanation and justification of the original vector diagram. How can he give the vector diagram to a student, without taking it back somewhere to a mathematical expression, and if to a mathematical expression, why not to the polar diagram? I take it that he will agree with me that there is no justification for the crank diagram. Therefore, I think this paper should be of some interest to those of us who have to teach.

I do not suppose Mr. Diamant will claim that this paper should be used by the work-a-day engineer. In fact I question whether Dr. Steinmetz, although he has taken his own method so far into the range of application, would maintain that to be its end and object. The great debt we owe to Dr. Steinmetz is for having developed a method which is so universally applicable in the teaching of principles. I do not agree that the exponential expression is the proper one for the fundamental instruction, and I think the polar diagram, taking its origin from the exponential expression, and the method of division into two components, is the most valuable. The method of Dr. Steinmetz in the division into two components seems to me to fail at the problem of power expression—the product of two vectors. The present paper offers something to fill this vacancy, and hence merits attention.

E. H. Colpitts: Referring to Professor Gray's question inquiring as to the usefulness of Dr. Steinmetz's mathematics, I feel safe in saying that the telephone engineer at least finds these methods of very substantial value in handling many problems.

N. S. Diamant: I think the general trend of remarks was about complex quantities in general, rather than the particular method given in the paper and showed a little prejudice in connection with the question. Probably this is mainly due to the fact that some persons want to use nothing but complex quantities, while a great many others will have nothing to do with them.

In regard to the question raised as to the usefulness of mathematics I think we must recognize that mathematics in engineering is very useful as a tool. I could give actual examples where great advance has been made by the use of mathematics, and very wonderful scientific and practical work has been produced by the use of it. After all, as I say, I am not here to defend mathematics. I think the trouble comes in when we use too much, or try to cover up our ignorance by the use of mathematics, and that is done quite often; you will find it in many so-called text-books.

E. E. F. Creighton: I asked what your particular method of mathematics is, how you could apply it, in what particular way could you apply it.

N. S. Diamant: I have indicated that in the summary of the paper. However, as it has been brought out by Prof. Gray—the choice of method depends considerably upon the type of mind. Some persons like one method, and some persons like another; one is just as good as the other.

Another point of interest that Prof. Gray brought up was that the student, when he is working with complex quantities, is not entirely satisfied, and does not well understand the problem until he has translated it graphically by means of a vector diagram. In that connection I would like to add that the advantage of my method is that it is a better mathematical shorthand by means of which to visualize vector relationships. This is not easy to do in complicated vector diagrams, when you have to deal with the components; when for example, we have $e + j\,e$ equal to E, or similar expressions. It is easier to visualize the different phase relationships if the method described in the paper be used, rather than the ordinary method. For example, in a certain case, one hundred volts, making 45 deg. with the horizontal axis will be represented as 141 $j^{\frac{1}{2}}$, instead of 100 $+ j$ 100.

The question was brought up by Dr. Whitehead in regard to double-frequency quantities. Really, that does not come entirely within the scope of this paper. I would like to take that up in detail with Prof. Whitehead, but here I may say that personally I think that double frequency is an unnecessary complication. It was introduced by someone who was interested in it, and I think it leads into rather unscientific inconsistencies, and I do not think it has any importance.

John B. Whitehead: Perhaps I have used an unfortunate expression in the words "double frequency". Certainly I have not made myself understood by Mr. Diamant. I simply refer to the fact that it was not meant to include what is usually called the double-frequency quantity, which is treated by Mr. Diamant, at some length.

N. S. Diamant: In answering I may say that some persons start with vector quantities, and use these exclusively and suppress the use of instantaneous values. But the scientific definition of power is the one given in the paper involving instantaneous values, where the mean power is obtained by integrating or summing up the instantaneous power over a half cycle. This does not lead into the difficulties of changing the sign, and dropping out the imaginary portion of the product into which one is led when he uses vectors entirely. This vector definition of power leads into what we might consider a quaternion, that is, a quantity made up of scalar and vector components; but power itself is a kind of scalar quantity since it is fixed when its magnitude and sign—whether positive or negative—are given, and it requires no additional information as to its direction, as the true non-localized vectors of vector analysis do. The double-frequency idea is designed to get around this difficulty, and in a way gives physical explanation of it, but I think it is unnecessary, and a round-about step to take.

Presented at the Pacific Coast Convention of the American Institute of Electrical Engineers. Seattle, Wash., September 5, 1916.

A DISTRIBUTION SYSTEM FOR DOMESTIC POWER SERVICE FROM COMMERCIAL AND ENGINEERING STANDPOINTS

BY CARL H. HOGE AND EDGAR R. PERRY

ABSTRACT OF PAPER

The adoption of electric heating and cooking has begun to reach such large proportions that the average distribution system is unable to take care of the increased load. As the domestic power load in all probability will increase until every house is electrically equipped, this paper has endeavored to lay outa distribution system to take care of this class of business and to estimate the revenue to be derived from it. Units of load, consumption and revenue were taken from tests conducted in different parts of the city and applied to a definite section of the city thought to be representative, as it contained every class of house, with schools, churches, etc. In view of the results obtained, it would seem that this business would be profitable at a still lower rate, and that it would be advisable for the central station man to make provision for this increased load when rebuilding any lines in the future.

DOMESTIC power is so rapidly attaining large proportions in the central station business that present distributing systems and practises are quite inadequate, and it is daily becoming more imperative to revise our methods to include this class of service. By domestic power we mean all the electricity that is used in the home, and have classed it thus:

Lighting, including ironing, washing machines, small motors and appliances of all sorts, excepting those used in preparing meals.

Cooking, including toasters, chafing dishes, etc.

Heating, all current consumed in keeping the house at a habitable temperature.

Hot water heating for such water as is consumed in the household.

The past few years have brought such rapid advances in the perfection of cooking and heating appliances that our distribution systems are beginning to groan under the load, having been designed to provide amply for illumination only. The downward trend of rates, such as Seattle has experienced, has

MAP SHOWING HOUSES AND PROPOSED DISTRIBUTION SYSTEM.

TABLE I

CLASSIFICATION OF HOUSES

B	= Large residence over 2 stories	*Ch.*	= Church
C	= Full two stories, medium size	*Ap.*	= Apartment House, average about 20 apartments each
D	= Story and one-half, medium size	*Apt.*	= One apartment in an apartment house
E	= One story, medium size	*Sch.*	= School building of the Public School System
F	= One story, small size	*F.H.*	= Fire Apparatus Station
St.	= Store in a store building		

done much to popularize the use of electric current for all purposes, and the central station man is becoming more concerned about the return from this class of business. Hence, we have prepared herewith a preliminary analysis of the ultimate conditions in five, or ten, or twenty years, when every house will be electrically equipped with light, cooking, heat and water heating, and have designed such a distribution system as would be required, keeping in mind the commercial aspects of the situation.

In order to arrive at definite ends we have made numerous assumptions of conditions, which are based on the most advanced knowledge of the present time, and from these have projected our hypothesis. A definite section of one of Seattle's leading residence districts was selected and from a thorough canvass each house was assigned to a class representative of its size and electrical consumption, as shown on the accompanying map, the key for which is given in Table I.

This district is known as Capitol Hill and is very representative as it includes houses of every type, with schools, stores, etc., and might be used as a " unit " in estimating similar conditions for a city. We have also assumed that all construction must comply with the State Law and City Ordinances governing overhead lines, and that the rights of other public service companies must be observed, and further that all apparatus, wire and materials shall be such as are now considered as standard. Our assumptions also provide that no further houses are to be built in this district and that property now vacant will be utilized for park purposes, so as to require no electrical energy.

During the past two years, we have conducted a series of tests on cooking and heating loads, the results of which have been indicative but not conclusive. Certain constants and factors have been determined, however, upon which we can base our computations. These factors are fully defined in Table II.

For the lighting we have taken a group maximum demand factor of 25 per cent as indicated by a check of conditions in this district; cooking has a demand factor of about 19 per cent; heating will average 50 per cent, while hot water heating as used here is a full 100 per cent. It is well to remember that these factors will vary materially with the kind of people who use the service and their daily habits, hence conditions obtaining in Seattle may differ materially from those in other cities. In the cooking tests, fifteen ranges in different parts of the city were selected, and by means of recording meters the characteristics of the load were determined. The heating tests included fifteen consumers who used all types of heating apparatus. From these sources then the data of Table III were selected, being the units of load, consumption and revenue assigned to each class of house. The rates applying to this business are quoted in Table VI. Having chosen suitable units, they were applied to the dis-

TABLE II

DEFINITIONS

Connected Load = Sum of the rated loads

$$\text{Group Maximum Demand Factor} = \frac{\text{Maximum of the resultant curve combining all the individual max's.}}{\text{Connected load}}$$

$$\text{Individual Maximum Demand Factor} = \frac{\text{Individual max. demand}}{\text{Connected load}}$$

$$\text{Group Daily Load Factor} = \frac{\text{Total kw-hr. consumed per day}}{\text{Group max. demand} \times 24}$$

Peak Demand Factor = Per cent of the group maximum demand that occurs during the system peak between 5:30 p.m. and 6:30 p.m.

$$\text{Individual Daily Load Factor} = \frac{\text{Kw-hr. consumed per day}}{\text{Max. demand} \times 24}$$

Peak Max. Demand = Group max. demand × peak demand factor

$$\text{Diversity Factor} = \frac{\text{Arithmetical sum of all the individual maximums}}{\text{Maximum of the resultant curve combining all the individual maximums.}}$$

The term "group" is here used to indicate all the appliances of one class, such as "water heaters." or "cooking," that occur in the district under discussion.

Lt. = Lighting, etc.
Ck. = Cooking, etc.
Ht. = Heating
W.H. = Water Heating

trict outlined and the totals for this district computed, as in Table IV.

In order to properly design a distribution system to take care of heavy loads of this kind, it is necessary first to combine them into units; second, to determine the connected load in each unit from which the unit maximum demand can be figured using the group maximum demand factor; and third, to design a feeder system to take care of the load. For example, we find that in

TABLE III.

UNIT OF LOAD, CONSUMPTION AND REVENUE

		Connected load in kw.				Kw-hr. per mo.				Dollars per mo.			
	No.	Lt.	Ck.	Ht.	W.H.	Lt.	Ck.	Ht.	W.H.	Lt.	Ck.	Ht.	W.H.
B	17	3	8	30	1.0	70	300	2130	720	3.00	6.00	16.0	3.50
C	321	2	6	20	0.8	80	224	1332	576	1.65	5.00	10.0	2.80
D	210	1.5	5	15	0.6	20	106	1000	432	1.10	3.00	7.5	2.10
E	57	1.0	5	5	0.5	13	94	667	360	.70	3.00	5.0	1.75
Apt.	145	1.0	5	5	0.5	25	166	667	360	1.40	4.00	5.0	1.75
Sch.	1	5.0	20	50	5.0	172	1000	13320	3600	5.00	20.00	100.0	17.50
Ch.	3	5.0	6	30	0.5	172	250	8000	360	5.00	5.00	60.0	1.75
St.	16	3.0	—	10	0.5	170	—	2670	360	5.10	—	20.0	1.75
P.H.	1	3.0	—	20	1.0	170	—	1332	720	5.10	—	10.0	3.50

TABLE IV.

TOTALS FOR DISTRICT

LOAD, CONSUMPTION AND REVENUE

	Connected load in kw.				Kw-hr. per month			
	Lt.	Ck.	Ht.	W.H.	Lt.	Ck.	Ht.	W.H.
B	51	136	510	17.0	1190	5100	36200	12240
C	642	1926	6420	256.8	9630	71904	428000	184896
D	315	1050	3150	126.0	4200	22260	210000	90720
E	57	285	285	28.5	741	5358	38000	20520
Apt.	145	725	725	72.5	3625	24070	96700	52200
Sch.	5	20	50	5.0	172	1000	13320	3600
Ch.	15	18	90	1.5	516	750	24000	1080
St.	48	—	160	8.0	2720	—	42700	5760
P.H.	3	—	20	1.0	170	—	1332	720
Total	1281	4160	11410	516.3	22964	130442	890252	371736

	Dollars per month				Dollars per year			
	Lt.	Ck.	Ht.	W.H.	Lt.	Ck.	Ht.	W.H.
B	51.00	102	272	59.50	612	1224	3264	714
C	529.65	1605	3210	898.80	6356	19260	38520	10786
D	231.00	630	1575	441.00	2772	7560	18900	5292
E	39.90	171	285	99.75	479	2052	3420	1197
Apt.	203.00	580	725	253.75	2436	6960	8700	3045
Sch.	5.00	20	100	17.50	60	240	1200	210
Ch.	15.00	15	180	5.25	180	180	2160	63
St.	81.60	—	320	28.00	979	—	3840	336
P.H.	5.10	—	10	3.50	61	—	120	42
Total	1161.25	3123	6677	1807.05	13935	37476	80124	21685

block No. 1 there are 14 class *C* houses and 12 class *D* houses having a connected load of 46 kw. in light, 460 kw. in heat, 144 kw. in cooking, and 18.4 kw. in hot water heating, a total of 668.4 kw. Using the group maximum demand factors as shown in Table V, we have 11.5 kw. in light, 27.8 kw. in cooking, 230 kw. in heat and 18.4 kw. in water heating, making a total of 287.7 kw. for the maximum demand of this unit. Proceeding similarly with blocks 5, 9 and 13, we find unit maximum demands of 310 kw., 273 kw. and 234 kw. respectively.

After covering the entire district in this manner, it seemed

TABLE V.

LOAD CHARACTERISTICS AND REVENUE

	Conn. load kw.	Group max. dem. factor	Group daily load factor	Max. dem. on peak	Peak dem. factor	Diversity factor	Group max. dem.	Aver. daily load kw.
Lt.	1281	25.00%	10.0%	320.	100.0	1.0	320	32
Ck.	4160	19.34%	22.5%	804.	100.0	2.5	805	181
Ht.	11410	50.00%	21.7%	5705.	100.00	1.5	5705	1238
W.H.	516	100.00%	100. %	516.	100.00	1.0	516	516
Total	17367	38.6	29.4	7325.				1965

	Average kw-hr. per			Dollars per year	Av. rate per kw-hr.	Av. rate per kw-yr.
	Day	Month	Year			
Lt.	765	22964	275568	13935	5.06c	$43.50
Ck.	4348	130442	1563304	37476	2.40c	46.50
Ht.	29675	890252	10683024	80124	0.75c	14.00
W.H.	12391	371736	4460832	21685	0.48c	42.00
Total	47179	1415394	16984728	153220	0.902	10.90

advisable to install a feeder from a centrally located substation for each 1000 kw. or thereabouts, which is the case in blocks 1, 5, 9 and 13. We find that in order to properly distribute 1000 kw. at 2300 volts, a three-phase, 4/0 feeder would be the most efficient, on account of initial cost, voltage regulation, carrying capacity of the wire and economy of space on the poles. We propose to maintain a constant voltage at the center of load on each feeder, and if necessary, to install transformers with variable taps to give the same voltage over the entire secondary. The load being essentially single phase will necessitate installing single-phase regulators on each circuit at the substation. As all standard apparatus for domestic use is built for 110 volts to 120 volts, we will string a 1/0 neutral over the entire system, which will give 120 volts between this wire and any outside leg of the three-phase, 207-volt secondary bus, and will provide a ground for the transformers. The secondary bus will be a 500,000-cir. mil cable, except in cases where the load is concentrated at the transformer. We propose to install transformers either in single-phase units or in one three-phase unit as near as possible to the center of load in each block or group of blocks, depending upon the load. On the accompanying map we have shown the distribution as outlined above, including transformers.

TABLE VI.

RATES FOR DOMESTIC SERVICE

Lighting and Cooking:

Electricity for these two purposes is sold through one meter, at the following rates:

First 45 kw-hr. per month @ 5½ cents per kw-hr.

All over 45 kw-hr. per month @ 2 cents per kw-hr.

Minimum charge 50 cents per month.

Heating:

Rate: 1 cent per kw-hr. unrestricted, or ¾ cents per kw-hr. if used off peak. Minimum $12.00 per h.p. per year.

Peak hours are from 4:30 p.m. to 7:00 p.m. in winter and 5:30 p.m. to 7:00 p.m. in summer.

All service has been figured at ¾ cents per kw-hr.

Water Heating:

Rate: Flat charge of $3.50 per kilowatt-month.

Heater to run continuously.

In order to determine a reasonable cost for this system, we have assumed prices of material and transformers that were current prior to the present war prices and have arrived at a total figure of $111,400.00. This includes all local distribution outside of the substation, services and meters.

In Table V the revenue from the business as outlined has been computed, making a gross of $153,220.00 per year. The kilowatt-hours total up to 16,984,728 per year, and the average rate for all classes of service is 0.9 cents. The average return is $20.90 per kilowatt-year.

In concluding, we believe that the development of domestic power will necessitate the complete reconstruction of existing lines. New substations will have to be built for each 10,000 kw. of load and located approximately at the center of the district served. The heavy load in this service will require three-phase distribution, which will also take care of small power loads. We believe that domestic power can be developed into a profitable part of the central station business, and sold at a price that will be attractive to the consumer. The present rate schedules, which necessitate two meters and a flat cut-in for this business, are not satisfactory and a new basis for charge must be developed that will utilize a simple, inexpensive meter and can readily be understood by the layman. With increasing volume of business, the rates can be lowered materially below those quoted herein, and still yield an adequate return. It is up to the central stations to make an intensive campaign for domestic power service, for this is the solution of the problem of profitably serving residence business.

DISCUSSION ON "A DISTRIBUTION SYSTEM FOR DOMESTIC POWER SERVICE FROM COMMERCIAL AND ENGINEERING STANDPOINTS" (HOGE AND PERRY), SEATTLE, WASH., SEPT., 5, 1916.

D. F. Henderson: In Table III the paper gives the consumption per month for the heating installation, as 1332 kw-hr. I would like to ask the author how that figure is computed. Is it taken from actual experience? I have been heating my own residence this past winter electrically, and have installed a maximum demand very similar to his. I have a demand of 21 kw., but the kw-hr. consumption is almost ten times what is given in this figure. Of course our climate in Spokane is somewhat more severe than it is here, but it seems to me there should not be such a great difference in the kw-hr. consumption.

E. R. Perry: I think, Mr. Henderson, that that figure is sort of an average that we found around here with our climatic conditions. Of course you realize here that the people only use their heating equipment about six months out of the year.

D. F. Henderson: That is based on a six months' period?

E. R. Perry: It is an average for the twelve months; that is the total for the year divided by twelve months. You say that you have about ten times that much in a year?

D. F. Henderson: Yes, during the severe winter months.

E. R. Perry: Per month you have about that much you say? If you add up the total amount of current you use during the year and divide it by twelve?

D. F. Henderson: It would reduce it very materially.

E. R. Perry: And the difference in temperature between Seattle and Spokane is very great.

J. B. Fisken: I believe that the idea is to run out single-phase feeders from the substation. That was our practise up to within the last year or two and then when times got hard and expenses were going up and income was going down, we skirmished around to find some way of serving the same load a cheaper way. We converted our single-phase feeders into three-phase feeders; our cables were six-conductor cables and formerly contained three single-phase feeders. We converted those into one three-phase feeder with a neutral wire, installing the single-phase regulators on each leg. Each leg was controlled by a single-pole automatic switch so that trouble on any of the three-phases did not affect the other two. We have found that worked out very satisfactorily and I would like to ask the author whether, in his figures as to costs, he figured on three single-phase feeders or one three-phase feeder with a neutral brought back?

The other point that occurred to me was whether or not the secondary was one interconnected system? Of course, in d-c. work, we find it is economical to connect the mains together everywhere, and it should be done the same way in a-c., work, but just how it is to be done, I don't know. There are two ways I have heard of, although I have had no practical experience and

I would like to ask for the practical experience from those who have had it. One is to introduce fuses between the secondary districts so that the trouble in one will take care of itself and not interfere with the others. And the other method is to introduce reactance so high that a short circuit on one section, which might blow the fuses in the transformer and stay on, would not over load the neighboring districts materially. Of course, they would be overloaded to some extent, but the voltage drop through the reactance would be such that the neighboring districts would be fully maintained and fairly satisfactory service rendered until the trouble could be removed.

E. R. Perry: I believe, Mr. Fisken, that your idea, or the system which you describe, the three-phase system with a return neutral, is the one we have here. We have in mind a single regulator on each phase; it will not be necessary in this case to have a single-pole switch because there will be three-phase distribution down each street or alley, as it were. We will not take the single phase off the three phase at any place, or run a separate feeder line with bus line, single phase. All bus lines will be three phase and the secondaries will be three phase, and will extend over districts of approximately one block, or one unit as we have determined here; in some cases a little over a block, depending on the load. There is a transformer for each block, each transformer with its own secondary circuit about one block long; the secondaries not inter-connected.

M. T. Crawford: The plan of the distribution system outlined in this paper is most economical in first cost, but it has the disadvantage of not being easily installed from time to time as business grows. The complete domestic electrical installation, anticipated here, will only be gained one unit at a time, and will be many years in coming. The trend of distribution systems in the better city districts, is toward underground construction. A 4000-volt three-phase four-wire distribution system using 2200-volt standard transformers between the outside wires and the neutral would permit the use of about one third of the primary copper specified in this paper. A small transformer vault installed adjacent to the basement wall of each residence, would permit service wires of approximately No. 12 copper, which would be duplex cable and in an iron pipe. This would take 2200-volt power direct to the consumer's house, and make the short service leads between the main switch and this transformer vault, the only heavy copper necessary. This system would cost more, principally because of the larger transformer capacity necessary, it being impossible to utilize the diversity factor of the various consumers' installations. In practise, some way of overcoming this difficulty could be devised, as by feeding several houses close together from one transformer vault, or putting in secondary tie connections. One consumer could be taken at any time on any part of the system, and this method of installation could be put in for that consumer; and as more are obtained the same scheme followed until eventually, when the complete electrification mentioned is obtained the mains could be put under ground, if desirable, at a reasonably small additional cost; that is, little of the existing equipment would have to be changed. That is simply my idea of what would be the best service, even though at a higher total cost, and it would certainly meet with more favor from the people. The size of copper on the lines and in the service wires, as mentioned in this paper, would make such heavy wires as to detract somewhat from the appearance of a strictly first class residence district.

F. D. Weber: The author has a demand factor of about 19 per cent for heating. I would like to ask if any demand factor has been computed for residences, apartments and the various classes of cooking. In Portland we have been very much interested in knowing what size feeders should be supplied for group cooking, such as apartment houses.

E. R. Perry: We have no information upon that, Mr. Weber.

C. R. Collins: It is rather difficult to appreciate the magintude of this proposed heating load. You will notice in Table I, nearly every block shows a load of 250 or 300 kw. The present density of load in the down town district of Seattle averages 150 kw. per block. The proposed distribution system for residence districts must take care of at least twice the kw. load per block that we now have in our most densely settled business district. The author calls our attention to the fact that we will have difficulty with our distribution system. It is also interesting to consider the increased demand on our generating equipment. I have taken the figures given in this paper and secured the average kw. requirement per customer, which is about eight kw. In Seattle we have probably 50,000 consumers such as would come under the description given in Table I, 400,000 kw. would therefore be required to supply our residence districts. At the present time it requires not more than 25,000 kw. to supply the residence load.

This means increasing our present residence load sixteen times. It is also interesting to note that when we do increase our present load by that amount, that load is going to determine our peak and all other loads will be incidental.

In Table V, in the lower right-hand corner are given the returns for a kw-yr. You will note the return for the heating, figured at $\frac{3}{4}$ of a cent per kw-hr., is $14 per kw-yr., and you will also note that the kw-hr. consumption for heating is approximately 65 per cent of the total kw-hr. consumption given. The only chance of electric heating becoming commercially possible is that it will be possible to reduce very materially the cost per kw-yr. of generating power. $14.00 per kw-yr. is very much below the present cost.

W. D. Peaslee: I am very glad to see brought out, the open advocation of a one-meter rate for lighting, cooking and heating. To my mind that point strikes the key of the whole situation. The idea of electrical engineers being held down at the present date, in the present state of our art to having to insist that every time a man wants to do something, he has a different rate put on his load, is something of a joke. In the case of the little town of Corvallis, I have some electric light and cooking appliances in the house for which I have a separate meter; if I put in a hot water heater, I have another meter for that or a flat rate, which really gives me three separate services in that house, with the attendant overhead expenses and clerical expense for the company on each of those billings.

Now, there are two solutions of the rate as given here. Either have a very high minimum and a low energy rate, which the public will immediately object to; or take the rate as given in the paper, the first 45 kw-hr. per month at 5½ cents, a minimum charge at 50 cents per month and the rest of it at two cents per kw-hr. That first 45 kw-hr. is going to make the man's bill big enough if he uses any electric heating and cooking at all in the house, so that the company will be protected. They will get their cost of testing meters and their cost of billing and all those things that go into the beautiful theoretical rates that are worked up. At the same time the customer will have one meter in his house and he can subtract the previous month's reading from the present reading and figure out for himself what his bill is coming to; but you take the class rates of power companies today, and he is a better man than some engineers if he can do it. I think that one of the biggest factors we are going to find in the development of heating and lighting load for electrical power, is to have a rate that protects the power company by having either a high enough minimum to take care of these incidental expenses, or have the first block of energy at a sufficiently high rate so that any ordinary consumer is going to get a big enough bill to come up to the point necessary, and then a very low energy charge for the rest of it.

I know of one location in Oregon where it worked out. A man is permitted to take on a load for heating, lighting, cooking and hot water and anything less than a one-horse power motor at any time of the day or night at $5 a month minimum, and one cent per kilowatt hour energy charge. That is a little drastic and it may be a $5 minimum is wrong, but personally I believe that some form of rate of that kind for the high minimum and low energy consumption is going to build up the load until our heating and lighting load will not be as it is now, but may ultimately approach the figure given in this paper of 200 or 300 kw. per block in first-class residence districts. I think that, the only way the power companies will be able to build up is to get a rate of that kind.

F. D. Weber: Near the end of the paper I note the author computes his gross income per year. I wonder if anybody has investigated the statistics and found out the amount of money an average family both poor and rich can spend per month for lighting, heating and power. At one time I saw a statement covering 20 years in the lighting industry, showing that the annual monthly bill has been nearly a constant amount. I think it would be well to investigate on the customer's side and see how much money they will actually spend. If they are using gas, they spend so much money; if they change to electricity they will spend a certain percentage more for the added convenience.

E. R. Perry: I think that in selling electricity we sometimes lose sight of the fact that we are really selling a commodity just like sugar in the open market, and we have to compete with all the other forms of energy that people use to reach the same end that we want to sell our electricity for; and for that reason it is well to think of how much a man in moderate circumstances can afford to pay for the electric energy that we want to give him. Now we might imagine a family of three or four living in a house of six or seven rooms, and if he heats with hot water, his heating bill is going to be somewhere about $70 or $75 a year, if he is economical, and his cooking bill for gas will be something like $35 or $40 a year,—cooking and hot water, possibly. His hot water service, however, will be intermittent and he will only light up the gas heater when he wants it, and he will not have hot water all the time. That I think will total up somewhere in the neighborhood of $140 or $150, that he is paying per year for lighting, cooking, heating, and hot water from the different forms of energy that he gets now.

Suppose he purchases electric energy according to the way the rates are now. He would pay somewhere around $200 on an average for the same service; it is a little bit difficult at the present time to make people see the $50 additional value in the electric service. Possibly they do not realize they will only have to pay $50 a year more for an entire electric installation. This is an average case. Of course, some cases are going to run higher and some lower. I do not think the people at the present time are educated up to that point where they would want the electric service with the additional value in it and the additional convenience of it. With the competition we have in all other forms of energy, it is very hard to sell electricity at the present rates, and with the handicap of installations already put in for the other types of service. Now, if a man is just building a house and he could get all these things and it would cost him only $50 a year more, he would put them in without hesitation, I believe. But where he has already tied his money up in apparatus to use coal, gas and so forth, it is pretty hard to make him junk all that and put in the new electric service.

The point about the metering of the service is one which I feel is very important in the sale of energy for domestic use. Selling electricity as we do now, with two or three or four meters, is just like selling sugar by the quart to a man for putting up fruit, and by the pound for making candy. He can not see it, and the quicker the central station gets to the point where they can sell a man so much electricity for a certain price and don't care what he uses it for and have it taken care of in the rates, that much quicker are we going to get simplicity in accounting, metering and in the whole business, even down to selling it to the customer. The quicker people understand about our electric game, just that much quicker are we going to make strides in it.

E. G. Robinson: I have been considering the one-meter rate a good deal and I have come to this conclusion: That if you make your heating load 220 volts instead of putting in a three-wire meter,—if we put a straight 220-volt meter in, and then tap our lighting on the neutral,—run in three wires, the two 220 volts and the neutral, then we can tap around the two wires with the neutral and fix it so that all our electrical appliances for heating would be 220-volt. Then for our lighting, simply tap the series circuit of the meter, and that will make our lighting current register just twice as fast as our heating current. So, if we were making a heating rate at three cents for a certain block, while that was being used, we should be getting six cents on all our 110-volt socket appliances and we would be getting three cents out of the straight 220-volt current, because the current flowing through the meter would register at 220, while only being used at 110. I simplified our system that way and used but one meter for the man who takes power. We tap a neutral around the polyphase meter and let him use current at 110 volts, with all appliances forge blowers and such as that. I am quite in sympathy with simplifying the rate, and I believe that any man who is figuring on doing this should simplify it as much as possible, because the average layman thinks that blocks of kilowatts, amperes and so forth, are intended and designed to befuddle him as to what he is buying. I have not yet tried out the 110-220-volt scheme on heating, only on power, but I hope to do it; and I believe it gives a complete solution of the problem of one meter with two rates.

By the way, I would like to ask that if in this distributing system where you are going to use one neutral, would that not necessitate the hooking up of your transformer star instead of to delta? It has been my experience that 90 per cent of our transformers for distribution are delta connected. Now if you wire them up star and one goes out, that puts that entire system out. I would like to know how you take care of that?

E. R. Perry: It has that disadvantage, and a protective device would have to be used.

E. G. Robinson: In thinking that over we, of course, think you are going to have delta transformers.

E. R. Perry: It would have to be star to utilize the neutral. Nearly all our apparatus is 110 volts and 220 volts, and it would be necessary to have both voltages in each house. In order to accommodate present wiring we would have to have the three-wire circuit, as it is called, in each house.

L. T. Merwin: I would like to ask the author whether the decision on using four-wire three-phase as against a three-wire three-phase connection is made on the basis of regulation for commercial economy.

E. R. Perry: I think, Mr. Merwin, that we provided a four-wire delta connection in order to accommodate the present type of household utensils which require 110-220 volts. We have a star system with three-phase 207 volts on the outside; that would give us 120 volts to the neutral.

H. W. Buck: The author spoke a few minutes ago about the average householder not being educated up to the use of certain applications of electric power. I should like to ask what the experience has been on the Pacific coast with the average householder in the use of household electrical appliances. Is it necessary to have an electrical engineer in each house to satisfactorily operate these various devices, or do the public as a whole take hold of them intelligently and operate them efficiently? It does not take much intelligence to turn on an electric lamp, but it takes considerably more technical knowledge to operate an electric washing machine, electric range and some of the other devices that are now used.

E. R. Perry: I think that the people who have taken out electrical devices have learned to use them very intelligently, and the amount of trouble developing with the different appliances is very small. Once people get interested in these things, and really appreciate their value, they seem to develop an undue amount of electrical wisdom. I think that if we can only get to the people and get them interested, it would be easy enough to educate them.

The next step in that direction is the electrical equipment of all of the home economic departments of the various schools and colleges in the country, and the training of the girls of the younger generation to know and use intelligently all forms of electrical appliances and apparatus, and to make their own minor repairs. I believe that the coming generation of girls are going to know a great deal more about electric household utensils than the present generation of housewives do. It is only through educating the younger people that we are going to successfully solve this problem. The older people do not learn quite so readily, but those who do, as far as experience around here is concerned, have been able to take up these things and learn to use them very quickly.

S. M. Kennedy: The question which you have asked in reference to the manner in which the purchasers use apparatus is one that is very easy to answer, if you have had much to do with the handling of such appliances. What are called lamp socket appliances are very readily handled and it does not need any engineer and requires very few demonstrations to teach the housewife to readily use any such appliances. Even the washing machine, which is a little more complicated to operate, practically runs itself with a turn of the switch. However, when you get into the broader field of cooking—I mean major cooking,—we find that the average housewife in Southern California, while she is anxious to learn, does not pick up quite as readily the methods of handling the electric range and of substituting it for whatever method of cooking she has been used to, heretofore. In the kitchen the average housewife is a little bit sensitive; she has a pride in her work; and she does not like anyone to come in to show her how to do her work. That kind of education must be done very diplomatically,—the average engineer cannot do it at all. We find that it pays to have tactful, experienced and good looking lady-demonstrators, who can follow up the range installations and go from place to place, and find out first, whether the lady who is doing the cooking thoroughly understands the method of operation and whether she is getting the best that is possible out of the range and for the least amount of energy put into it. If she finds that things are going all right, the demonstrator tells her so. If, however, she finds that they are not going all right, that in some parts there is too much heat turned on when it is not required, and not enough in other parts of the stove, she must be tactful and explain just how the operation should be done in order to get the greatest efficiency. The demonstrator must be educated and trained for that particular kind of work, so that she not only understands the stove and the operation of the stove, but she must also understand human nature.

J. B. Fisken: The average farmer of eastern Washington is notorious for not taking care of his appliances,—I do not mean electrical appliances, I mean his agricultural appliances,—and it might be interesting to learn whether the electrical appliances, cooking and so forth, have caused much trouble. Mr. Chrysler handles four country towns and a number of farmers and he could tell us what his experience has been.

W. L. Chrysler: We find less trouble with farmers taking care of their electric equipment than the consumers in town. These farms are run on a large scale by combined harvester tractor and modern machinery, which makes the farmer a mechanic for he has to operate and keep up his own equipment. We have a few farmers on our lines who have quite complete electric-equipment. They make their own minor repairs, while the consumer in town will call the fix-light department.

J. R. King: The point I want to bring out is the fact that it is becoming more and more apparent in the development of electric house heating, not cooking or hot water heating, but to heating the home, that the ideas of the electrical engineer, more especially of the man who has charge of the operation and the control of the delivery of power, have got to be changed. That is, he has got to recognize new conditions coming in. For instance, you will note in Table V, that there is a group maximum demand, 320 kw. for light, 805 for cooking, 5705 for heating, and 516 for water heating. Referring to one of the other tables the rate is one cent per kw. hour unrestricted or $\frac{3}{4}$ cents per kw. hour if used off peak. It appears to me from this paper that the factor which produces the peak is no longer lighting, which comes on about half past four to seven o'clock. Power is a more or less off-peak product and cooking can be considered so to a certain extent. All the efforts have been made to take on this house heating rate under the same assumption and under the same condition, that the consumer will not use it during what is called peak. Now, the great preponderance of energy is used for heating and this demand would indicate that the time of the peak has shifted. Therefore, this paper would point out that in order to estimate in the future, demands for domestic service in residence districts, it is necessary to consider primarily what demand will be required for heating; and the lighting, cooking and hot water heating would be incidental to that. In other words, the determining factor is no longer lighting, but it is heating. In the Institute meetings and in the National Electric Light Association meetings and in other meetings, discussion on that has raged up and down and the argument that heating was a by-product has been advanced and contradicted. It appears to me, it will be necessary to figure very carefully in the future. What is the use of keeping off the peak, if the heating itself establishes that peak? If we keep the heating off the peak, it will not occur in the afternoon any more than it will occur at any other time during the day. Furthermore, what are you going to do on a cold winter day when the customer comes home and insists on having his heat? If he cannot have it, he comes right back and asks why he is not entitled to have it? Those are points that I think must be considered in planning the installation of any house heating. They are points that have arisen in connection with the sale of energy in Seattle. They are points that will be raised as long as house heating is promoted, whether or not the peak be shifted to another time of the day, and another class of energy other than lighting be responsible for it.

H. J. Gille: In the first place, this heating rate was filed with the Public Service Commission of this state as an experimental rate,—simply a try-out proposition. Second, the peak hours are the lighting-peak hours, which control at this time the distribution peak. It seems to me that in any discussion of the question of laying out a prospective distribution system to take care of heating and other appliances in residences, it should be important to know whether you are talking of a station peak or a distribution peak. The residence peak as we know, comes at a different time from the power peak, and the power peak at a different time from the commercial lighting peak, but all of the resultant peaks establish a certain peak on the station or a generation peak. By developing the electric heating, of course, the generating station peak would probably be transferred from the point where it is now, to some other part of the day.

C. R. Collins: We have conducted tests in connection with electric heating and one of our conclusions is that the electric heating peak may come at any hour in the day; sometimes it may be in the morning, sometimes in the afternoon and very frequently you will have a load almost as large as the peak about six or 6:30 p. m. So this peak cannot be considered as some other not coming on the system peak, which occurs about. 6:00 p. m.

Robert Howes: In the early days the load on any separate feeder was small and scattered over considerable territory and it seemed to be necessary to use the low voltage of 110 or 220. With the growth of business and the growth in power consumption by each residence, such as is contemplated in this paper, the question raised by Mr. Crawford of placing individual transformers at the residence and omitting the secondary distribution system, may become one of material importance. In the development of power plants, in this district, at least, after you have reached a capacity of forty or fifty thousand kilowatts, the cost of generating power and bringing it to the central substation is not varied so very greatly, although it is to some extent, by additional capacity. You begin to reach a point where the cost of operation per kilowatt hour and the investment cost per kilowatt of development, does not vary by a very wide margin, although it will to some extent. It would seem it might be a decided advantage in such a case as described in this paper, to omit the secondary mains and simply use a high-potential distribution with transformers at each house or for two or three houses grouped together, using low voltage only for the houses. That would reduce the copper requirements and cost of good regulation. We cannot expect to obtain a great deal of reduction in initial cost per kilowatt after we reach a certain power plant capacity, but with additional capacity there is room for considerable improvement in the distribution systems and that seems the most promising field to look for reduction of cost per kw. hour in operating the system. It at least appears possible that with the demand per residence increased to such extent as here contemplated, there may be room to reduce the meter installation and attendance per kilowatt hour of consumption, and substitute small transformers at the point of use; distributing to advantage both in simplicity and in cost of investment and operation per kilowatt hour sold.

Presented at the Pacific Coast Convention of the American Institute of Electrical Engineers, Seattle, Wash., September 5, 1916.

SOME FEATURES OF DOMESTIC ELECTRIC COOKING AND HEATING

BY H. B. PEIRCE

ABSTRACT OF PAPER

Although electric cooking and heating has always been considered possible, it has only recently become popular; hence the engineer is found unprepared with information on the characteristics of the load.

From tests made on a number of domestic cooking and heating installations, it would appear that electric cooking has a better load factor than a lighting load and that this load factor improves as the number of ranges increases.

The errors incident to these tests are discussed.

The demand factors on being plotted against number of ranges appear to follow a logarithmic curve which may be accounted for by the fact that a modification of the law of probability would no doubt determine the probable coincident demand of a number of ranges and that this law is a logarithmic function.

Suggestions are made for the checking of these results by others.

In the heating field, the effect of water heaters superimposed on range loads is discussed in relation to their effect on the central station loads and income.

SINCE the use of electrical energy first developed, the possibility of successful heating or cooking by heat, generated electrically, has never been questioned; the problem has always been—can it be done at a profit to the central station, with energy sold at a price low enough to put electricity in competition with other fuel?

Today we find a sudden stampede for this ideal fuel, but we find the electrical engineer unprepared to solve the problems of heating and cooking electrically.

It will be the province of this paper to show what may be expected by a central station after there has been developed a load of ranges and water heaters, and along what lines engineering assistance is needed to solve certain knotty problems connected with this phase of the industry.

First, to consider the effect on the central station of a cooking and heating load. It would be natural to expect that a cooking load would have a load factor considerably lower than the lighting load in the same community. This we find is not the case and it further appears that there is a greater increase in load factor in a cooking load by reason of an increase in number of consumers served, than would be gained in a lighting load by such an increase of consumers.

These deductions are the result of a number of tests made on actual water heater and range installations in homes using electrical energy for cooking and water heating.

The tests consisted of installing recording ammeters on the various cooking installations and reading the charts taken therefrom to the nearest five-minute interval; these readings were then assembled and the total load for any day at any hour determined.

A number of assumptions were of necessity made in securing these composite loads.

First, it was assumed that the clocks of the various meters were synchronous. This is in error for two reasons; (a) the charts were not all taken on the same calendar day but were taken at different seasons for different ranges and superimposed according to the day of the week on which the readings were taken; (b) the clocks were not absolutely accurate either as to time of day or as to speed.

Second, the readings were taken on a five-minute interval; this meant that the reading for the interval had to be integrated by inspection, which was, of course, is difficult to do with much accuracy, particularly in view of the fact that the swing of the needle on these instruments was considerable.

The first opportunity for error would appear to have more weight than it proved to exhibit in practise, since a set of charts for a week, taken at one time of the year, have a strong resemblance to similar charts taken during a week at another season. In other words, in the community observed, the habits of the public as it concerns the preparation of meals, appears to be uniform at different seasons of the year. The opportunity to run into error by inaccuracy of the clocks is so slight as to be incommensurable with the accuracy of the results which at best are only approximate.

Curves shown in Figs. 1, 2, 3, 4, 5, 6, and 7, exhibit the daily load of 42 ranges of assorted manufacture and varying capacity from 2.5 to over 6 kw. As the coincident maximum demand of these ranges can be obtained from the curve, and as

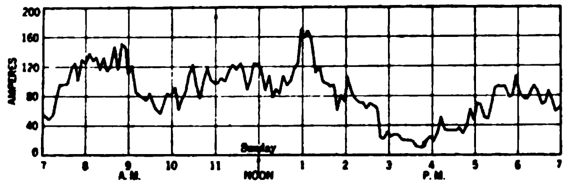


FIG. 1—COMPOSITE RANGE LOAD CURVE

Number of ranges 42—Connected load 155.4 kw.—maximum demand 20.07 kw., voltage 116.

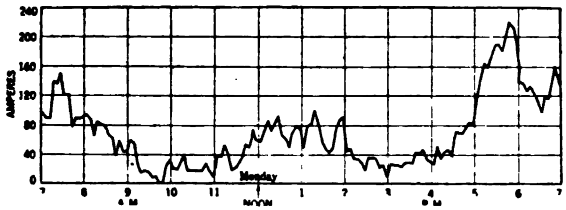


FIG. 2—COMPOSITE RANGE LOAD CURVE

Number of ranges 42—connected load 115.4 kw.—maximum demand 27.75 kw.—voltage 116

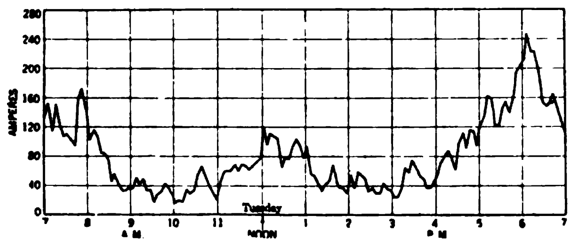


FIG. 3—COMPOSITE RANGE LOAD CURVE

Number of ranges 42—connected load 115.4 kw.—maximum demand 28.65 kw.—voltage 116

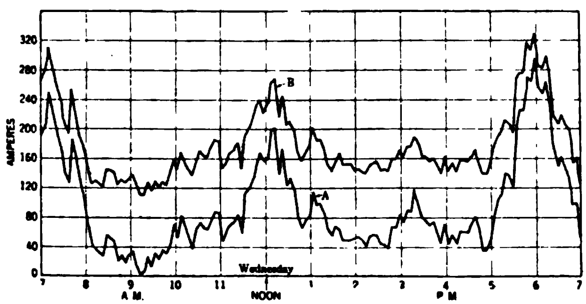


FIG. 4—COMPOSITE RANGE AND WATER HEATER LOAD, CURVE "B"

Number of ranges 42—number of water heaters 21—connected load ranges 155.4 kw.—connected load water heaters 12.18 kw.—maximum demand 37.47 kw.

the total connected load is known, the demand factor can be computed. As the average kilowatt-hour consumption of each range is known, it is also possible to figure the combined load

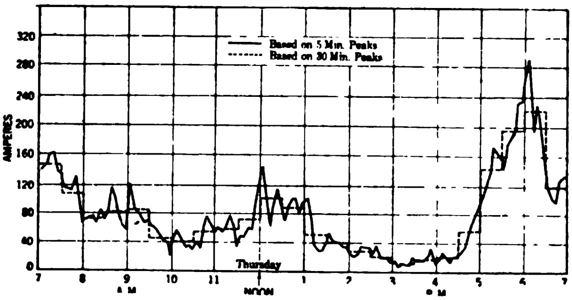


FIG. 5—COMPOSITE RANGE LOAD CURVE

Number of ranges 42—connected load 155.4 kw.—voltage 116—maximum demand (5 min.) 33.75 kw.— max. demand (30 min.) 25.63 kw.— demand factor 5 min. peak 4.6— demand factor 30 min. peak 6.1— demand factor 30 min. peak (Wed.) 5.5

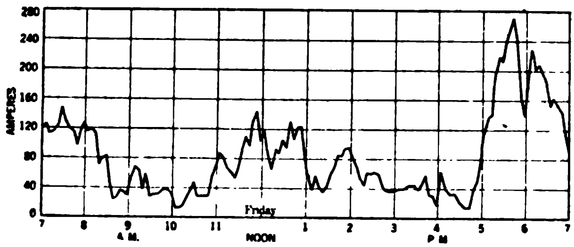


FIG. 6—COMPOSITE RANGE LOAD CURVE

Number of ranges 42—connected load 155.4 kw.—maximum demand 31.43 kw.— voltage 116.

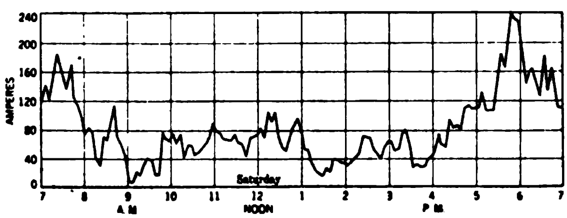


FIG. 7—COMPOSITE RANGE LOAD CURVE

Number of ranges 42—connected load 155.4 kw.—maximum demand 27.96 kw.— voltage 116.

factor of the group. These values show that even with as small a group as 42 ranges, the demand factor is 4.5; with 25 ranges, it has been found never to be less than 3.5.

It might be expected that the demand factor would increase as the number of ranges increases; this is shown in Fig. 8, where a number of groups of ranges have been observed for demand factor, and these demand factors plotted as ordinates with the number of ranges as abscissas.

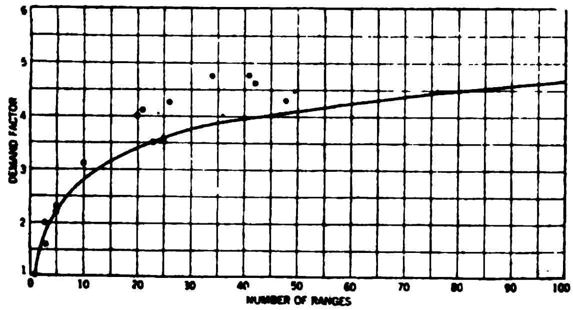


FIG. 8.

The result is a shot-gun diagram which interests us not so much in its upper limits as in its lower limits; that is, the worst condition which we are liable to experience in any given installation is that for which we must make provision. The curves

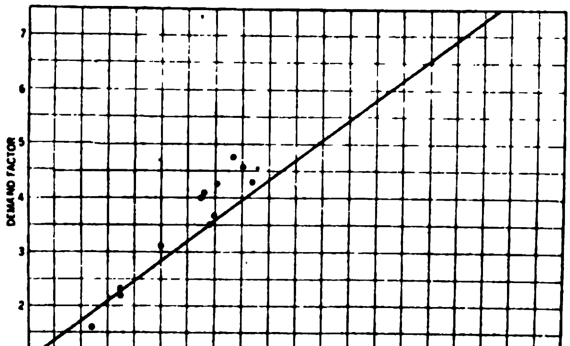


FIG. 9.

through the points on the lower limits appear to have logarithmic characteristics and by plotting the points on logarithm paper (Fig. 9) we find that they approximate a straight line, that is, they follow roughly a logarithmic curve.

Such a curve would have infinity as its upper limit and this we know is impossible, as the demand factor can never exceed the reciprocal of the average individual load factor.

It is possible that this last statement requires a word of explanation as it is not self-evident.

Consider ten installations, each with a demand of one kw., and an individual load factor of 10 per cent. The greatest demand factor, 10, would be secured when each individual installation was turned on for a tenth of the period and then turned off while a second was thrown on the line. The result would then be a demand never exceeding one kw. and a load factor of 100 per cent for the entire group.

Let us apply this to the ranges tested. The connected load, which for convenience may be assumed as the individual maximum demand of each individual range, will average about five kw. on the present types of electric ranges. These same ranges will each average a consumption of about 100 kw-hr. per month; that is, the individual installation will have a load factor of about 2.8 per cent. The reciprocal of 2.8 per cent, or 36, is then the maximum limit of the demand factor on ranges of this type. To reach this value it would be necessary for the combined load factor to be 100 per cent, which is of course impossible under present conditions as there are hours during the day in which there are no cooking operations being conducted.

As an academic example this result might be secured from a central station supplying energy to consumers extending around the globe in a zone of perfectly uniform density. If the logarithmic curve is followed out to demand factor 36, it will be seen that this amounts to an infinite number of ranges to all intents and purposes.

The theory, that demand factor will increase in accordance with a logarithmic rule will appear more logical when it is remembered that diversity and demand factor depend upon the theory of probabilities which has logarithmic characteristics.

To get the greatest practical good from this theory it should be checked in a number of different localities by different observers and the results compared; then, from the results, a rule adopted that would permit the probably coincident demand of a number of ranges to be more accurately predicted than is possible at the present time. These results should be of sufficient accuracy to enable the various electrical rules to be based upon them, so that it would not be required that excessive feed cables be provided for the care of apartment houses equipped with electric ranges, and so that the proper sizes of feeders and transformers for serving a load of ranges would be better computed by distributing engineers.

It will be noted that the demand factors have been figured in the computations so far made on the basis of a five-minute peak. For practical purposes such a peak is unnecessarily brief so that the effect of a 30-minute peak has been indicated on Fig. 5 by a dotted line which represents the results of measuring the demand by means of a demand meter of the type that integrates a load over a series of definite half hour periods.

Integrated peaks of half-hour duration will, of course, make the demand factor greater. This should be borne in mind in comparing charts taken in different cities.

In making comparisons, there should also be noted the class of people by whom the ranges are used. Those referred to in this paper are representative of all the classes that will eventually do their cooking electrically. They include families with incomes of less than $100 per month and homes in which the bill for current is a minor consideration. The apartment house dweller is, however, not as well represented as he should be. To show the effect of such consumers in helping to improve load factor, the demand factor of the ranges of one of the apartment houses in Salt Lake City is shown in Fig. 8. This demand factor, it will be seen is far in excesss of those secured from ranges installed in homes in Spokane, the city in which the individual tests were made. At first, this does not seem logical, as one would think that the dwellers in the same apartment house would come from the same walk in like and would be likely to do their cooking at the same hours. The answer probably is that they do less regular cooking than do the families in their own homes.

Another point that should be commented upon before leaving the subject of electric ranges is the average monthly consumption of the individual ranges in kilowatt-hours. This has been referred to above as being about 100 kw-hr. It is true that the value, 100 kw-hr., represents approximately the average condition, but to say that this is the probable consumption of any particular electric range, is quite another thing; the truth of the matter is that the consumption seems to vary between the limits of 50 and 250 kw-hr. while in exceptional cases the energy consumption of a range used by a farmer has been known to exceed 400 kw-hr. during a single month. This condition appears generally during the season of harvest when there is a large number of hands to feed. Attempts have been made to predict the consumption of a range by the size of the family by whom it is used; this the writer believes to be unsatisfactory as there are wide variations in habits between families of equal size.

It will be noted that for the ranges observed the daily peak occurs very nearly at 6 p. m. In other words, it will coincide closely with the lighting peak. This is unfortunate, but when it is remembered that with a fair number of ranges in use, the demand factor will probably be 8, the feasibility of making this business profitable with a low rate per kilowatt-hour becomes clearer.

For instance, if we assume a monthly consumption of 100 kw-hr. per range, an average individual demand of 5 kw. and a demand factor of 8, we get the following results with a rate of 3 cents per kw-hr. for energy:

Revenue per range per year	$36.00
" " kw-year of range demand	7.20
" " " " " station demand	57.60

So far this paper has dealt only with the electric range; the next point to be considered will be the heating of water for the home.

A supply of hot water is essential to the satisfactory use of the electric range; that this can, in many instances, be accomplished electrically, is not questioned. The problem is, how it shall be done.

To compete with coal, wood and gas, for hot water heating, electricity must be supplied at a very low rate. This can only be done by securing a high load factor for the service; by taking the supply from valley hours; or, by limiting the use of the heater to those hours when the range is not in use.

A high load factor can be secured for this service by installing the heaters on flat rate and assuming that they will be used continuously; this has the disadvantage of superimposing their load on the existing peak. The revenue they return must then be sufficient to yield enough per kw-year to pay for all the fixed charges depending upon maximum demand at peak.

The disadvantage of limiting the use of water heaters to the valley period of the system load is that a very large amount of hot water must be stored, as in most instances the valley hours are not of very long duration and occur at a time when there is no need for hot water. The result is that if the hot water supply is depleted during the day, there is no alternative for the consumer than to wait until the next day for more hot water. A further disadvantage is the expense of an installation to supply such a system. Time switch, large capacity heater, and large, well-insulated storage tank, all will be found to amount to a considerable sum.

The third method of limiting the use of the heater to the hours when the range is not in use, has some of the advantages of both systems with less of their disadvantages; it can be controlled by a double throw switch or by a special rotary snap switch now on the market for that purpose. The diagram of wiring for such an installation is shown in Fig. 10. The effect of such a water-

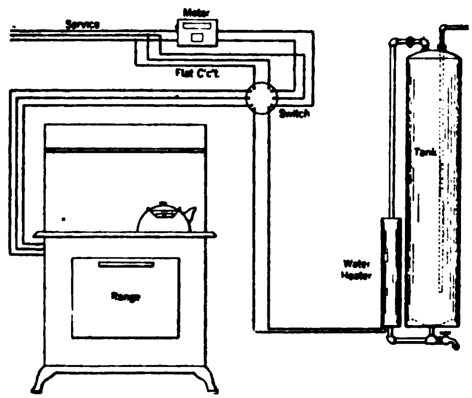


FIG. 10—WIRING DIAGRAM FOR ELECTRIC RANGE AND WATER HEATER CONTROLLED BY SPECIAL SWITCH

heater load when superimposed on a load of ranges is shown in Fig. 4.

It will be seen from the curves on this figure that a load of 42 ranges gave a peak of 33.41 kw. when operated without water heaters, (Curve *A*). When 21 of the ranges were equipped with 600-watt water heaters on double throw switches, the peak was only increased to 37.47 kw. (Curve *B*).

A common rate for a 600-watt water heater operated in this fashion is $2.00 per month and if the ranges use an average of 100 kw-hrs. each per month the rate for energy being 3 cents per kw-hr. they would return a revenue of $36.00 per year per range or a total revenue of $1512.00 for the 42 ranges. These ranges show a demand of 33.41 kw. which means a revenue of $45.00 per kw-year when operated without water heaters.

If 21 water heaters pay $24.00 each per year, we would get an additional revenue of $504.00, or a total of $2016.00 from the ranges and water heaters combined. The demand is now raised to 37.47 kw. which gives a return of $53.70 per kw-year. It is conceivable that the addition of such a water-heating load might make an otherwise unprofitable installation of ranges, profitable.

Regarding the size of heater required for this purpose, there are few accurate data which can be offered. The 600-watt size appears to be the smallest that will work satisfactorily while it is seldom that a heater larger than 1.5 kw. is required. The number of people in the family, their habits, the size of the storage tank, the system of hot water distribution, all affect the results.

Problems dealing with the electric heating of buildings are so large that they are felt to be beyond the scope of this paper. It is undoubtedly possible to secure a load of this nature when cheap power is available, in a locality whose climate is not so rigorous as to make the cost of heat units the main criterion by which the efficiency of the system will be judged. The writer feels, however, that his experience is so limited in this regard that anything said by him at this time might do more harm than good to the ultimate development of this field.

Another field that will bear investigation is the question of how best to distribute for a range and water-heater load. The use of individual transformers for each range with no connection between the secondary lines is objectionable by reason of the high cost of installation. The use of safety devices between transformer secondaries for providing safety to adjacent transformers connected in multiple may make it possible to secure greater benefit from the large diversity that undoubtedly does occur between different groups of these appliances.

The question as to how the electrical engineers of today can best promote the development of electric heating and cooking and whether there is any phase of this subject that has been neglected by the Institute to the detriment of the electrical heating and cooking field and to the standing of the profession of electrical engineering is worthy of our attention in closing.

The electrical cooking of food does not appeal to the average engineer as worthy of his august attention, as it smacks too much of the work of the humble house maid. The big problems of large transformers and high-tension transmission appear far more important.

Is this position well taken? Is not the service of society the main object that should stimulate the engineering profession and is there any problem more worthy of the attention of the engineer than the problem of supplying food to the citizens of the community? Certainly this is a problem far more important than the problem of supplying the luxury of light.

The humble work of heating water is certainly as vital to the advance of the community as any that may, on the surface, appear more poetic by reason of the handling in one unit of a large capacity of power. The cake of soap has been considered an index of the progress of civilization, but of what little use is the soap without hot water to use it with.

The standards of the Institute have been looked upon by both the engineers of this country and by those abroad as indicative of the progress of the art and as representing the formulated practise of the country. Be it to our shame that there is in the rules of standardization no mention of the proper installation of electric cooking and heating appliances, and but one brief mention of the insulation of the heating and cooking appliances that are now in use on the lines of every central station in this country.

In the early history of the art the engineer with mistaken ideas of dictating the possible for the practical, developed heating and cooking appliances that impeded the growth of the use of electrical energy for the saving of labor in the home. Be it to the credit of a few men of wide vision that this is not the case today.

DISCUSSION ON "SOME FEATURES OF DOMESTIC ELECTRIC COOKING AND HEATING" (PEIRCE), SEATTLE, WASH., SEPT. 5, 1916.

J. B. Fisken: I want particularly to call attention to the paragraph in which the author refers to the manner of heating buildings. It is true that electrical heating of buildings may be practicable in one community and not in another. In our community, where we have a temperature varying from, perhaps, twenty degrees below zero in winter to one hundred above in summer, it would require a very much larger installation to furnish heat for buildings than it would possibly in Seattle, where the temperature variations are not so great.

C. E. Magnusson: It is essential, in order to secure a low price for electric energy, that we have a good power factor and a good load factor, and that there be taken into consideration a seasonal load factor as well as a daily load factor. If the heating of buildings entirely by electricity is to be undertaken, it means that for a short period of the year there would be a tremendous peak, and the rest of the year the installation would stand idle. To install a system for supplying electric energy for heating purposes which would be adequate for two months of the year when the demand would be greatest, and during that time be obliged to supply several times as much power as in the other ten months, when the demand would be very low, seems to me to be out of the question. We can never do that, because it will never be practicable to provide the machinery which would be required to supply the heat consumed during that short period and allow that machinery to remain idle during the balance of the year. Therefore, in order to provide a seasonal load factor, the heating of buildings by electrical energy, should only be auxiliary to steam or hot air heating systems, and the peak of the winter would be taken care of by the ordinary furnace. It would be a great relief here in Seattle if we could have a small amount of heat available in electrical form during the fall and spring months. We could operate our furnaces, then, for two or three months each year—probably two months would be all that would be required—and by following this plan, we would be enabled to provide electric energy at a rate sufficiently low to make its use practicable for heating purposes. Some of the engineers of the city having in mind the paper that was presented this morning, asked us at the University to make some experiments in designing a heater of the induction type, having a high power factor. I think there is a general feeling that resistance heaters have too large a maintenance expense, and that the induction heaters on the market at the present time have too low a power factor to make them practicable. I will describe a hot water heater, modified so as to include an electric heating element, which was built at the University, and on which we have made a series of experiments. The core is an ordinary iron pipe and is surrounded by a copper layer sweated on to the pipe, forming the secondary coil; which in turn is surrounded by a primary coil connected to the electric circuit. With that simple arrangement, we have an induction heater with a power factor of over ninety-eight and one-half per cent. I think that with a heater of this type used as auxiliary on a hot-water heating system of a house, good results could be obtained.

W. D. Peaslee: There is on the market to day a heater constructed on that identical principal, with the exception that they claim that it is not a short-circuit transformer. The big fault that I have to find with that type of heater—I made some tests on one this year—was that it is so very sensitive to voltage variations. That is, a voltage variation of two per cent as the machine is commercially manufactured at the present time, gives a current variation of something like forty per cent. You are all very familiar with the short-circuited current-voltage curve of a transformer. Unless you make the impedance of the secondary so high that you lose a great deal of the beneficial effect of low power factor, all induction heaters that I have had occasion to examine, are extremely sensitive to slight voltage variations. For instance one machine that I put under test this year was rated at 1200 watts, and if it was put on a commercial load in the city in which it was to be used, it would have fluctuated between 900 and 1700 watts, and I don't believe the power companies care to have them connected with their feeders. If it is on a flat rate they are losing money on it. While that machine can be so designed as to give a very high power factor, at the same time its characteristics are such that it is very sensitive to low-voltage fluctuation. I know the one made in Portland has some kind of a silica flux put over the coils, and the only way to hurt it is to use current enough to actually melt the apparatus.

L. F. Curtis: It may be of interest to know that this heater has practically a straight line curve between current and voltage. The reactance of the unit is so small that it has practically no effect. The iron does not become saturated and therefore has little influence on the performance. The particular unit in question was used in a seven-section radiator, and when run at about two kilowatts gave a rise of about fifty degrees above room temperature centigrade in an hour and a half. When run at one kilowatt, the temperature was maintained at approximately fifty degrees above room temperature. The power factor was uniformly above ninety-eight per cent in all of the tests run at different voltages.

R. W. Pope: One of the authors of the paper this morning gave some figures in regard to household heating, lighting and cooking, which compared very well with my experience. My house is a nine room, frame structure clapboarded and shingled outside, and heated with hot air, and lighted with gas, with an auxiliary gas burning grate in the dining room which we have found exceedingly satisfactory. We can go into the house at any time of year, light it up and have heat available. We spend about $150.00 a year for all purposes, burning about fifteen tons of hard coal at $6.50, the gas bill for all purposes averaging about $4.00 per month. If the cost of electricity is $24.00 for heating water, and $36.00 a year for cooking, that would be a total of $60.00, leaving a $90.00 margin for the heating of the house. Heating by electricity is not considered economical, compared with other methods.

E. R. Perry: I think it will be interesting to consider the use of electric water heaters in connection with the electric range. It was first suggested, as stated in this paper, that a good load factor could be secured for this service by installing the heaters on flat rate, assuming that they would be used continuously, which would have the disadvantage of adding their load to the existing peak. To eliminate this disadvantage the water heater was alternated with the entire range by a double-throw switch arrangement. That condition gave rise to a little dissatisfaction, because the people, in preparing dinner, used a great deal of hot water, drawing it all out of their tank, and the small capacity heater provided did not heat the water up again soon enough for their purposes. It was then suggested, and in some cases, they tried to alternate the hot water heater with a part of the range, and the question then rose as to what part of it. It might be operated with part of the oven of equivalent capacity, or some other part of the stove with equivalent capacity, but this was found to give the hot water peak on top of their range peak. So the proposition generally came down to the situation where it was found best to connect the water heater on a flat rate, and make the rate high enough to give a sufficient revenue, and not bother with the range at all, because a hot water heater of 500-watts capacity cannot be satisfactorily operated in connection with a range.

Prof. Magnusson mentioned the seasonal load factor in connection with heating. I do not think that electrical heating will ever be very successful, as long as it is an auxiliary to other systems of heating. The general public will not have a duplicate system of heating installed in their homes, and use electricity as an auxiliary. The output of a hydroelectric station in this section of the country usually runs greatest from the month of January to the month of July, and then falls off during the rest of the year. It is evident that the seasonal load factor, then, which would be desirable, would be to use electric heating from January until summer. Unfortunately, there are about three cold months, October, November and December, which come along, when there is not a great deal of water. In most hydroelectric systems, I dont think that a heating load, which will cater to the seasonal load factor, will do the job of heating the houses. Some arrangement will have to be worked out for electric heating, that will run any time or all the time that the people want it, and give them all the capacity they will need to keep warm.

H. F. Holland: I think possibly we will have to consider our own cities in making deductions. As engineers, you must not overlook the fact that many houses are going to be heated by electricity. I will refer particularly to Idaho. In a school house there, something like 800 kw. of heat is used. In another case, about 500 kw. Many of the houses and the hospitals are heated by electricity. You will have to consider that you are not working in Spokane, or New York, or the middle west, but you will have to consider conditions all over the country, and it is well worth your while to consider electric heat as among the necessary things to be supplied by your power systems.

H. J. Gille: There is one thing in connection with this water heating proposition that has not been touched upon. Where heaters are used without any restrictions, and the heater is just a little larger than would be required for continous operation, a sufficient diversity factor will be obtained by the heater being used only during the night.

Presented at the Pacific Coast Convention of The American Institute of Electrical Engineers, Seattle, Wash., September 5, 1916

TEMPERATURE RISE OF INSULATED LEAD-COVERED CABLES

BY RICHARD C. POWELL

ABSTRACT OF PAPER

After a brief historical note the factors that determine the rating of a cable are considered.

The thermal conductivity of a cable is expressed in terms of the volume thermal conductivity of the insulation, the surface thermal conductivity of the lead sheath, and the dimensions of the cable. The values of the thermal conductivities as given by various observers including the author are compared. A diagram is shown for readily obtaining the thermal conductivities of one-conductor cables, and tables are given of the carrying capacity of one-conductor cables for various duct temperatures and thicknesses of insulation. Factors are added so that the carrying capacity of multiple-conductor cables may be taken from these tables.

Sometimes the lead sheath of a cable carries considerable stray current. A formula is given for calculating the increased temperature due to such current.

The carrying capacity of a cable is largely determined by the thermal properties of the duct line in which it is installed. This feature is discussed briefly.

The overload or intermittent rating is calculated from a formula involving the thermal capacity of the cable multiplied by a factor. Experimental values of this factor for several types of cables are given. A formula is given to take account of variable air temperature.

Various formulas given in the paper are developed in three appendixes.

I.—INTRODUCTION

THE limitation of the current-carrying capacity of electrical conductors due to heating effects has been a subject for investigation since 1849 when Joh. Müller[1] starting with Newton's Law of Cooling, arrived at the result that, for bare wires of the same material, the current required to produce the same rise of temperature varies as the 1.5 power of the diameter. We now know this to be incorrect as the exponent is nearer 1.25. However, the subject was not

1. Glühen von Metalldrähten durch den galvanischen Strom. Bericht uber die neuesten Fortschritte der Physik. Band I.

really seriously considered by engineers until taken up by Forbes[2] in 1882. Since then quite a number of investigators have published data relating to the heating of wires and cables, and a very good resume—of the whole subject up to 1905 is given by Teichmüller in his "Die Erwärmung der Elektrischen Leitungen."

Since Eurpoean practise is to employ armored cables buried in the earth, we find very few European data of any real practical value to American engineers desiring information on lead covered cables for a draw-in system.

It was not until 1905 when Fisher published the results of some quite extensive tests at Niagara that current ratings for lead-covered cables began to take definite shape. Based upon these tests, Fisher published in 1906 a table of current ratings, which has been quite extensively used by engineers.

This table is to be considered more as a good safe rule applicable under somewhat unfavorable conduit conditions, rather than data which enable an engineer to rate a cable intelligently in accordance with the actual conduit conditions. It is to be noted that Atkinson in 1913 at the discussion of an Institute paper by Atkinson and Fisher, gave the results of some tests in a form more suited to the use of engineers. This paper and discussion will be referred to later.

Previous to the above mentioned table by Fisher, cables were usually rated according to some rule allowing a certain number of amperes per unit area, generally thousand circular units or square inch; and Fisher's work was a very great advance.

In order to expedite matters for a subject such as cable ratings, where there is an almost endless variety of conductor sizes, insulation thickness, types of make up, etc. and at the same time make it possible to compare properly the work of various investigators, the problem must be reduced to its simplest physical terms. That is, the complexity must be reduced by considering only the independent physical constants. Once these have been established, any engineer having the dimensions of a cable, and sufficient data upon the surrounding temperature may obtain a dependable rating cable.

In searching through the available literature, the writer has found only a few papers that conform to the above requirements and which may, therefore, be a basis for proper comparison. These are:

2. On the Thickness of Wires Required to Carry Different Electric Currents without Overheating. *Electrician* (London) 1882.

Mie,—Über die Wärmeleitung in einem verseilten Kabel, *Elekt. Zeit.* 1905.

Melsom & Booth—The Heating of Cables with Current. *Jour. Inst. Elec. Engrs.* Vol. 47—1911.

Atkinson and Fisher—Current Rating of Electric Cables, TRANS. Am. Inst. Elec. Engrs. 1913, p. 325.

Dushman—The Heating of Cables Carrying Current. TRANS. Am. Inst. Elec. Engrs. 1913, p. 333.

The purpose of the present paper is to discuss more particularly the carrying capacity of paper-insulated cables, although it will be evident that much of what follows is applicable to cables insulated with other materials.

II—RATING OF CABLES

The rating of an insulated cable is determined by

A. —Continuous rating.

1. The maximum temperature at which the insulation may be operated without undue deterioration.
2. The thermal conductivity of the cable.
3. The thermal condition and properties of the surrounding medium, usually the air in a conduit system.

B. —Overload or intermittent rating, in addition to 1, 2, and 3 under A.

4. The thermal capacity of the cable and surrounding medium, that is, the ability of the cable to store a portion of the heat released in the conductor, and thereby, for short periods of time, to put less demand upon the cable as a dissipator of heat.

It is demonstrated in works on heat and is a fact so well known as not to require proof here that the thermal conductivity of an infinite hollow cylinder in watts per cm. of length per deg. cent. is

$$k_1 = \frac{2\pi\lambda}{ln\,\dfrac{d_1}{d}} \qquad (1)$$

in which λ = specific thermal conductivity of the material in watts per deg. cent. per cm.

ln = Naperian logarithm

d_1 = outer diameter of cylinder

d = inner diameter of cylinder

For a cable, d_1 and d are, of course, the inner diameter of the lead sheath and the diameter of the conductor respectively.

In applying equation (1) to thermal measurements of cables, it is necessarily assumed that the conductor and the sheath are in very close contact with the insulation, and that there is no appreciable temperature drop from the conductor to insulation or from insulation to sheath. This assumption may not be correct; hence it is always advisable to obtain values for λ from measurements on actual cables instead of from the insulation taped up on cylinders, etc. It may be said, however, that equation (1) when applied to cable measurements gives consistent values.

The surface thermal conductivity of the lead sheath to air is, in watts per cm. of length per deg. cent.

$$k_2 = \pi\, d_3\, h \qquad (2)$$

where h = specific surface thermal conductivity for lead to air in watts per deg. cent. per cm^2.

d_3 = outer diameter of the sheath in cm.

The thermal conductivity of the cable, that is, the watts per cm. per deg. cent. difference in temperature of the conductor and the air surrounding the lead sheath is

$$k = \frac{k_1\, k_2}{k_1 + k_2} \qquad (3)$$

This expression is at once recognized as that giving the electrical conductivity of two conductors in series and the analogous thermal conductors in series are the insulation and the lead sheath.

It is now readily seen that it is only necessary to agree upon values for λ and h in order to establish ratings for all one-conductor cables. Various observers have obtained somewhat widely differing values for these.

VALUES FOR λ AND h.

Observer	λ for saturated paper	h for lead sheaths
Melson and Booth	0.00102 to 0.00134	0.00088 to 0.00155
Atkinson and Fisher	0.00100 to 0.00115	0.00083 to 0.0096
Powell	0.00081 to 0.00114	0.00090 to 0.0011
Dushman		0.00081 to 0.0011
[1]Symons & Walker	0.00142 to 0.0017	

1. The Heat Paths in Electrical Machinery, *Jour. Inst. Elec. Engrs.*, Vol. 48. These values were obtained by wrapping the paper on a copper cylinder which was then placed in an oil bath.

It will be apparent, after examining into the conditions of the cables tested, that the above values are in reasonable agreement. Atkinson and Fisher state that they tested new cables with bright lead sheaths, and Dushman presumably made his tests upon new cables. The writers' values are from tests on old cables taken from service as well as on new cables, and it is to be especially noted that the variation in λ is greater than that given by any other observer, excepting Melson and Booth, and the writer is unable to state anything regarding the age of the cables tested by them.

The values 0.00114 for λ and 0.0009 for h were found for new cables with well saturated paper and bright sheaths, and are in very close agreement with the values by Atkinson and Fisher.

The value h = 0.0011 found by the writer for lead with discolored and roughed surface is the same as Dushman's value for lead painted black. It is, of course, well known that lead under these conditions is a better thermal dissipator.

The value 0.00081 for λ was measured upon a piece of 500,000-cir. mil. 5/32-in. lead cable which had been in service for a number of years. The paper was in excellent condition and of a very strong quality. It was so dry, however, that there was not a trace of free oil and it had the slightly translucent appearance of thick oiled paper. 'The writer has tested a number of pieces of old cables taken from service and the values for λ all ranged from 0.00081 to 0.00092, none showing so good values as for new, well saturated cables.

In the writer's opinion the degree of saturation and hence the age (since there is more or less continual drying action in service) has an important bearing upon the carrying capacity of paper insulated cables.

THERMAL CONDUCTIVITIES IN WATTS PER FT. PER DEG. CENT. OF NEW AND OLD PAPER-INSULATED CABLES

Size cir. mils	Thickness of insulation	Observer	
		Atkinson & Fisher A.I.E.E. 1913	Powell
500000	4/32	0.21	
500000	5/32		0.19
1,000000	4/32	0.275	0.26
1,000000 (new)	4/32		0.308
1,150000	4/32	0.31	0.318

Although the thermal conductivity of the paper decreases with service, that of the lead increases, and the two effects just about balance, so that an old cable has nearly as good carrying capacity as a new one.

The values due to Atkinson and Fisher are for new cables and are those calculated from the table given in the discussion of their previously mentioned paper and increased by 12 per cent to agree with their test values. Except as noted, the writer's values are for old cables.

Values of λ and h to be Used in Determining Carrying Capacity. The above mentioned table recommended by Atkinson and Fisher is based upon $\lambda = 0.00100$ and $h = 0.000833$.

It is believed that the value of λ is too high for cables after several years service, and h is too low even for new cables after being exposed to the air for a few months. The writer, therefore, proposes ratings for paper cables based upon $\lambda = 0.00085$ and $h = 0.001$. First class cables, particularly, in a short time after installation, will usually show 15 per cent to 20 per cent greater carrying capacity than that calculated from these values, and most old cables of the same quality, 10 per cent greater. However, allowance must be made for paper and saturation which may not be of the best, for inaccuracies of measurements on cables in a conduit system, and some uncertainty as regards heating due to sheath currents.

If t is the thickness of insulation in inches and $\lambda = 0.00085$, equation (1) becomes

$$k_1 = \frac{2\,\pi \times 0.00085}{ln\left(1 + \frac{2t}{d}\right)} \times 30.5$$

$$= \frac{0.1625}{ln\left(1 + \frac{2t}{d}\right)}$$

watts per ft. per deg. cent. (4)

Similarly, equation (2) becomes, if d_3 is in inches,

$$k_2 = \pi\, d_3 \times 0.001 \times 6.45 \times 12$$
$$= 0.244\, d_3 \text{ watts per ft. per deg. cent.} \qquad (5)$$

These two equations suggest a comparatively simple diagram for obtaining k, the thermal conductivity of the cable. Such a diagram is Fig. 1, proof of which is given in Appendix I. To use the diagram proceed as follows:

Follow the ordinate through the given value of $\frac{2t}{d}$ to its intersection with the curve C, thence horizontally to the scale at the left. Through this point on the vertical scale and the value for d_3 on the lower horizontal scale pass the edge of a transparent triangle or straight edge, and the intersection of this with the line L is k read off on the vertical scale.

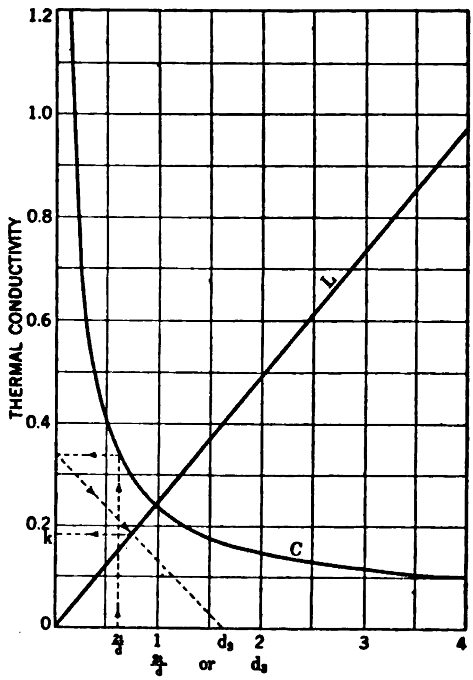


FIG. 1—DIAGRAM GIVING THERMAL CONDUCTIVITIES OF ONE-CONDUCTOR PAPER-INSULATED LEAD-COVERED CABLES.

With the help of this diagram, the three curves in Fig. 2 have been drawn. These curves give the thermal conductivities of one-conductor paper cables for various sizes of conductors and three thicknesses of insulation, viz. 4/32 in.; 8/32 in.; and 16/32 in. Values for any intermediate thickness of insulation may be readily interpolated.

As a maximum safe temperature for saturated paper 85 deg. cent., the value allowed in the Rules of the Institute may be accepted with every assurance that it is conservative and does not represent the maximum temperature that this material will stand without deterioration. The Institute Rules call for a reduction from 85 deg. cent. of one degree for each thousand volts of operating voltage.

The maximum current carrying capacity, or the rating of a cable is given by

$$W_\theta = I^2 r_\theta = k (\theta - \theta_d) \tag{6}$$

in which I = the current in amperes

W_θ = watts lost per ft. at temp. θ

r_θ = resistance, per ft. at temp. θ

θ = maximum allowable temperature for the conductor

θ_d = temperature of air in duct.

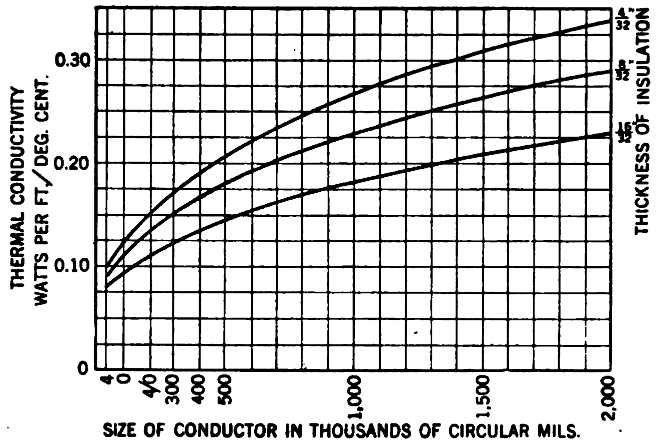


FIG. 2—THERMAL CONDUCTIVITIES OF ONE-CONDUCTOR PAPER-INSULATED LEAD-COVERED CABLES

It is sometimes assumed that the thermal conductivity of paper has a positive temperature coefficient comparable in value to the negative temperature coefficient of copper, so that the increase in loss due to the latter may be neglected. In order to check this point, the writer made the following test. The copper core was removed from a piece of 1,500,000 cir. mil 7/16 in. paper and ⅛-in. lead cable about 75 cm. long. A heating coil was wound on a piece of insulated pipe and covered with asbestos taping to such a diameter as just to fit snugly into the space formerly occupied by the copper. This core was then wound with fine copper wire to be used as a thermometer coil, which was in rather good contact with the paper when the core was finally slipped into place. To guard against the escape of heat at the ends, they were filled for several inches with felt.

The values of λ for core temperatures of 75.5 deg. cent. and 118 deg. cent. differed by less than 2 per cent. The writer, therefore, concludes that the above assumption is incorrect. Moreover, it is to be particularly noted that the error in neglecting the temperature coefficient of copper is not on the safe side. In the following tables $\frac{1}{8}$-in lead has been assumed. Although the smaller cables invariably have thinner lead, the difference from $\frac{1}{8}$ in. is not sufficient to cause appreciable error.

III. Tables of Carrying Capacity, in Amperes, of One-Conductor Paper-Insulated Lead-Covered Cables.

TABLE I.

Insulation 4/32 in. Working Pressure 750 Volts. Maximum Temperature 85 Deg. Cent.

Size	Temperature of air in duct deg. cent.				
	30	40	50	60	70
4	133	120	106	90	70
3	154	139	122	104	80
2	181	164	144	122	95
1	200	182	160	136	105
0	240	220	192	163	126
2-0	277	250	220	187	145
3-0	320	290	256	217	168
4-0	376	340	300	254	197
250M	418	380	333	282	219
300	475	430	379	320	248
400	570	515	454	385	298
500	670	608	535	454	351
750	870	790	695	590	456
1000	1070	970	855	725	560
1250	1240	1120	990	840	650
1500	1410	1275	1125	950	735
2000	1700	1535	1355	1150	890

TABLE II.

INSULATION 8/32 IN. WORKING PRESSURE 5000 VOLTS. MAXIMUM TEMPERATURE 80 DEG. CENT.

Size	Temperature of air in duct. Deg. cent.				
	30	40	50	60	70
4	125	112	97	79	56
3	145	129	112	91	64
2	166	149	129	105	74
1	181	162	140	115	81
0	214	192	166	135	96
2-0	251	225	195	159	112
3-0	290	259	225	183	130
4-0	339	303	262	214	151
250M	371	332	288	235	166
300	431	385	333	272	192
400	519	464	402	328	232
500	610	545	472	386	273
750	785	702	609	497	352
1000	955	855	740	605	427
1250	1100	980	850	695	490
1500	1255	1125	970	795	560
2000	1510	1350	1170	955	675

TABLE III.

INSULATION 16/32 IN. WORKING PRESSURE 15,000 VOLTS. MAXIMUM TEMPERATURE 70 DEG. CENT.

Size	Temperature of air in duct. Deg. cent.			
	30	40	50	60
4	107	93	76	53
3	122	106	86	61
2	139	120	98	70
1	152	132	108	76
0	181	157	128	90
2-0	208	181	147	104
3-0	239	207	169	120
4-0	284	246	201	142
250M	312	270	221	156
300	351	305	248	175
400	420	364	297	210
500	490	423	345	245
750	632	548	447	316
1000	766	664	542	383
1250	900	780	635	450
1500	1015	880	720	510
2000	1225	1060	865	610

IV. Carrying Capacity of Multiple-Conductor Cables

The preceding tables may be used for multiple-conductor cables by applying the following factors to the carrying capacity of one-conductor cables having the same total thickness of insulation.

Number conductors	Type of cable	Multiply one conductor capacity by
2	Flat or Figure 8	87 per cent
2	Round	80 do
2	Concentric	75 do
3	Round	70 do
3	Oval Sector	77 do
3	Cloverleaf Sector	80 do
4	Round	67 do

Thus, the carrying capacity of a 4/32 × 4/32-in. round, three-conductor cable is 70 per cent of that for an 8/32-in. one-conductor cable.

The subject of multiple conductor cables is treated more fully in Appendix II.

V. Increase of Temperature Due to Sheath Currents

It happens, not infrequently, that cable sheaths carry considerable current. This current may be stray railway, or neutral or currents induced by alternating currents in neighboring one-conductor cables.

Let w = watts per ft. loss in conductor

w' = watts per ft. loss in sheath

k, k_1, and k_2 = thermal conductivities, for cable, conductor to sheath, and sheath to air, respectively.

θ = conductor temperature above initial

θ' = sheath temperature above initial

Then $w = k_1 (\theta - \theta')$

$w + w' = k_2 \theta'$

Eliminating θ' we have

$$\theta = \frac{w}{k} + \frac{w'}{k_2}$$

or, the temperature of the conductor is increased by the amount $\frac{w'}{k_2}$, which is the temperature the sheath would have with the same current in the sheath but no current in the conductor.

As an example; a 1,000,000-cir. mil 4/32-in., $\frac{1}{8}$ in. lead one-conductor cable which has a sheath resistance of 0.00017 ohms per ft. will operate at an increase in temperature of 5 deg., 17 deg. and 40 deg. with sheath currents of 100 amperes, 200 amperes and 300 amperes respectively. The effect of small or moderate sheath currents may be neglected, but large currents must be avoided.

VI. Cables in Duct Lines

The carrying capacity of a cable is largely determined by the thermal properties of the duct line in which it is installed, and hence, will vary greatly with type of construction and character of soil. In order to determine the proper carrying capacity of cables with any degree of reliability, it is necessary to make a temperature survey of the conduit system. Or, at least, sufficient data must be gotten covering the various types of construction and soil conditions to enable one to make a reasonably accurate estimate of temperatures.

It will be found that the thermal conductivity of a duct line is a constant, and is

$$k = \frac{w}{\theta_d - \theta_a} \text{ watts per ft. per deg. cent.} \qquad (13)$$

where w = total watts per ft. loss in duct lines.
θ_d = mean temperature of air in ducts
θ_a = temperature of air at surface of street

This equation will apply after the temperatures in the ducts have become steady, usually only after one or two weeks. It is to be noted that the temperature of the external air has an important bearing upon the subject and that, under otherwise similar conditions, a duct line will run much warmer in summer than in winter.

In practise, loads are seldom steady; hence, the temperature of the air in ducts follows, more or less closely, the load variations, although it will be found that the earth directly in contact with the conduit changes only with the seasonal variation of load.

The problem may conveniently be divided into two parts; viz., one having to do with heat transference from the air in the ducts to the earth directly in contact with the conduit, and the other with transference from the earth to the air at the surface.

For the first, the thermal conductivity is

$$k_d = \frac{w_d}{\theta_d - \theta_s} \text{ watts per ft. per deg. cent.} \qquad (14)$$

In this, w_d = maximum watts per ft. loss at stationary maximum temperature θ_d for air in ducts.

θ_s = soil temperature.

For the second, we have

$$k_s = \frac{w_s}{\theta_s - \theta_a} \text{ watts per ft. per deg. cent.} \qquad (15)$$

where w_s = average watts per ft. loss for a given load cycle.

For most loads the cycle is probably a week.

All thermal measurements on duct lines should be made midway between manholes, as this is the warmest point. Soil under pavements which are a considerable distance from unpaved sections rarely has the variation in moisture content found in soil under unpaved streets. Hence, measurements in soil under pavements as above may be made at almost any time of the year, but in other soil should be taken at the dryest season.

The losses w_d and w_s may be calculated from the station load reports, and θ_d is taken with a recording thermometer. Measurements for θ_d should be taken in several ducts, particularly if there is a large number in the run.

After k_d and k_s have been obtained the effect of change in loading for the cables already installed, or effect of additional cables may be calculated.

Let w_d' be the maximum duct loss, and w_s' the mean loss over the cycle for the whole conduit, both in watts per ft. after the change.

Then the new soil and duct temperatures are:

$$\theta_s' = \frac{w_s'}{k_s} + \theta_a$$

$$\theta_d' = \frac{w_d'}{k_d} + \theta_s' = \frac{w_d'}{k_d} + \frac{w_s'}{k_s} + \theta_a$$

It is hoped that the preceding discussion of duct line temperatures may assist in forming a clear conception of the physical principles involved. For only in this way may we expect to make a duct line in any degree, amenable to design as a dissipator of heat. The writer does not wish to leave the slightest impression, however, that judgment and experience are not of the highest importance in designing duct lines and may be replaced by some equations and a table of data. But unless backed up with quantitative information, "judgment and experience" are apt to be nothing but snap judgment and mental impressions.

If the large investments in duct lines and cables are to be operated with the greatest economy and reliability, it is very necessary that we increase materially our rather meager supply of information on the question of heating in conduit systems.

VII—Overload or Intermittent Rating

If a constant load, in amperes, is applied to a cable, the temperature rise of the conductor, at any time after application of the load, is given by the equation

$$\theta = \Theta\,(1 = \epsilon^{-\beta t}) = \frac{w}{k-\alpha w}\left(1-\epsilon^{-\frac{k-a w}{c}t}\right) \qquad (11)$$

in which θ = temperature rise above initial temperature at time t,

Θ = final temperature rise,

ϵ = base of Naperian logarithms,

$\beta = \dfrac{k-\alpha w}{c}$ = constant,

t = time in hours.

w = watts loss per ft. at initial temperature.

α = temperature coefficient of copper referred to initial temperature.

c = constant depending upon thermal capacity of cable.

It is sometimes assumed that c is equal to the total thermal capacity of the cable, which is, of course, assuming that the rate of temperature rise is the same for all parts of the cable. This assumption is incorrect. It is at once apparent, for example, that the rate of temperature rise of the lead sheath is not so great as that of the conductor, particularly, for heavily insulated cables. The error is not appreciable for small cables, but for large well insulated cables the above assumption leads to results which are in error on the danger side, that is give too small a value for β and hence a lower temperature rise in a given time

We may put

$$c = c_1 + p\,(c_2 + c_3) \tag{12}$$

where c_1 = thermal capacity of the conductor in watt-hr. per ft.

c_2 = thermal capacity of the insulation in watt-hr. per ft.

c_3 = thermal capacity of the lead sheath in watt-hr. per ft.

p = constant, depending upon the type of cable.

Some values for p as found by the writer follow:

EXPERIMENTAL VALUES FOR CONSTANT p.

No. conductors	Size conductor	Thickness of insulation	Thickness Lead	p
1	4/0	7/16 Paper	[illegible]	0.81
	500,000	5/32 "	[illegible]	0.70
	1,000,000	4/32 "	[illegible]	0.70
	1,500,000	4/32 "	[illegible]	0.77
3	4/0	13/64 × 13/64 Paper	[illegible]	0.595
	250 M Submarine	(6/32 rubber + 2/32 Var. Cl.) × 5/32 Var. Cl.	5/32 + 41 No. 4 Steel Armor Wires	0.59

From data given by Dushman for a one-conductor 250,000, 4/32-in. rubber cable, p was found to be 0.80.

Hence, for practical purposes, it appears that we may put $p = 0.75$ for one-conductor and $p = 0.60$ for three-conductor cables.

The following quantities may be used in calculating the thermal capacity of a cable.

THERMAL CAPACITY IN WATT-HR. PER INCH CUBE

Copper, iron, steel	0.01525
Lead	0.0064
Rubber	0.00625 (Dushman
Paper	0.0047

For a further discussion of equations (11) and (12) see Appendix III.

In Fig. 3, is shown some test curves together with those plotted from equations of the form of (11).

With the assistance of a curve, Fig. 4 giving $(1 - \epsilon^{-\beta t})$ for various values of βt, we may very readily obtain the temperature at any time t, provided the final temperature Θ, and the

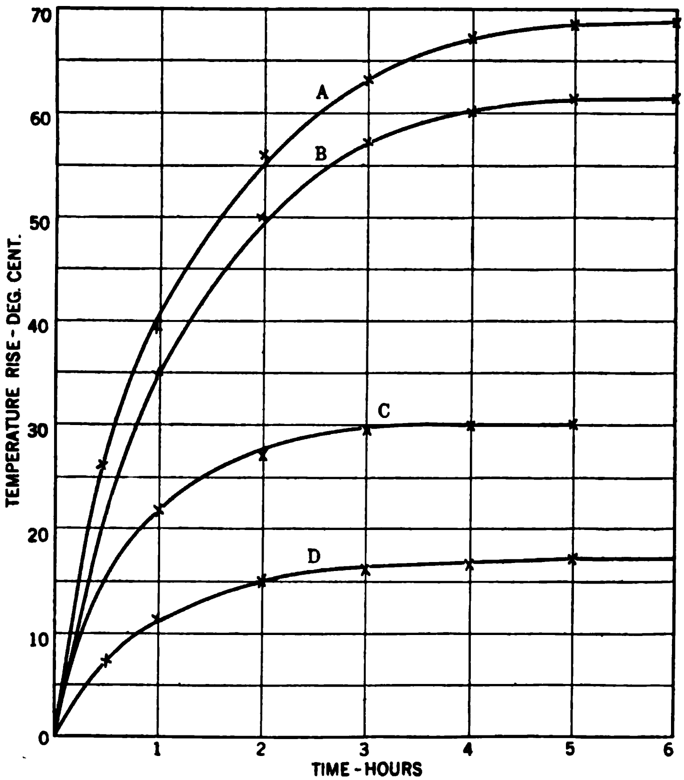


FIG. 3—RATE OF TEMPERATURE RISE OF CABLES

Curve	Type of cable	Load amps.	Equation
A	4/0 3-conductor round 13/64 × 13/64 paper ⅛″lead	300	$\theta = 69\,(1 - \epsilon^{-0.83\,t})$
B	1,500,000 cir. mil 1-conductor 4/32 paper ⅛ lead	1500	$\theta = 62\,(1 - \epsilon^{-0.86\,t})$
C	500,000 c.m. 1-conductor 5/32 paper ⅛ lead	500	$\theta = 30\,(1 - \epsilon^{-1.4\,t})$
D	250,000 c.m. 3-conductor submarine (6/32 rubber + 2/32 var. cl.) × 5/32 var. cl. 5/32 lead and 41 No. 4 steel armor wires.	310	$\theta = 17\,(1 - \epsilon^{-1.05\,t})$

Points calculated from equations shown X.

time constant β are known. These, however, may easily be computed with the preceding equations and data.

For example, let it be required to find the time for a 1,000,000-cir. mil 4/32-in. paper cable to reach 85 deg. cent. starting at a temperature of 40 deg. cent. with a load of 1200 amperes. It is assumed that the temperature of the surrounding medium remains constant at 40 deg.

w, at 40 deg., = 17.0 watts per ft.
α (40 deg. reference) = 0.0036
k = 0.27
c = 0.21

$$\Theta = \frac{w}{k - \alpha w} = \frac{17.0}{0.21} = 81 \text{ deg. cent.}$$

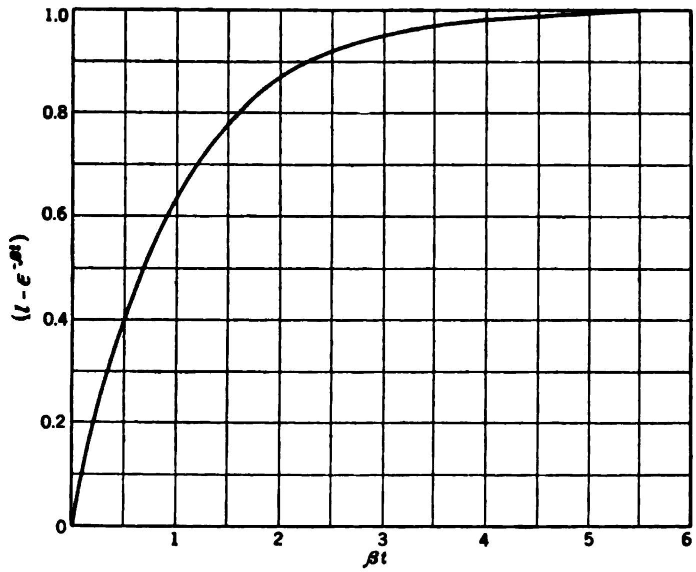


FIG. 4—CURVE OF $(1 - \epsilon^{-\beta t})$

The rise is to be 45 deg., hence

$$\frac{45}{81} = (1 - \epsilon^{-\beta t}) = 0.555$$

From the curve (Fig. 4), we find $\beta t = 0.8$

$$\text{But } \beta = \frac{k - \alpha w}{C} = \frac{0.21}{0.21} = 1.0,$$

and therefore, $t =$ 0.8 hour, or about 50 minutes.

In general, the duct temperature increases simultaneously with that of the cable, and usually at approximately the same rate. If this increase is small, that is, 5 or 10 deg., we may simply add this increase to the final temperature. For instance, in the above example, if the final duct temperature had been 50 deg. instead of 40 deg., we should have had $\Theta = 91$ deg. and the time about 40 minutes.

If the increase in duct temperature is large, the temperature coefficient of copper should not be neglected. A more correct value for the final rise of a cable is

$$\Theta = \Theta_1 + \frac{k}{k - \alpha w} \Theta_2$$

Here, Θ_1 is the final rise the cable would have at constant duct temperature, and Θ_2 is the final increase of duct air tempera-

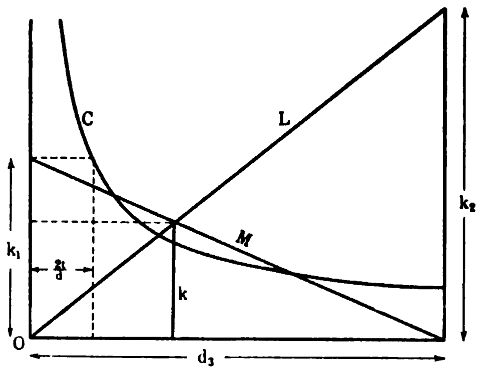


FIG. 5

ture. For the general equation involving variable air temperature see Appendix III.

Many of the cable tests, from which the data given above were taken, were made by the Laboratory Department of the Pacific Gas and Electric Company, San Francisco, and the writer desires to thank Mr. Knopp, the Superintendent and his staff for the very careful manner in which these were done.

APPENDIX I.

DIAGRAM FOR FINDING THERMAL CONDUCTIVITIES OF ONE-CONDUCTOR CABLES

This construction is based upon a well known geometric construction which is sometimes used for finding graphically the circuit resistance of two resistances in parallel.

Two perpendicular distances k_1 and k_2 (Fig. 5) are erected at the ends of a given line and the top of each is joined to the foot of the other by a straight line (the lines L and M in the figure). The perpendicular dropped upon the base line from the intersection of these two lines (k in the figure) is connected to k_1 and k_2 by the relation

$$\frac{1}{k} = \frac{1}{k_1} + \frac{1}{k_2}, \text{ or } k = \frac{k_1 k_2}{k_1 + k_2}$$

By plotting the equation $k_1 = \dfrac{0.1625}{ln\left(1 + \dfrac{2t}{d}\right)}$ the curve C is obtained giving k_1 for any value of $\dfrac{2t}{d}$.

The straight line (L in the figure), $k_2 = 0.244\, d_3$, is next drawn. After the point k_1 is found by means of the curve C, k is given, for any value of d_3 by the intersection of the line L and the line M through k_1 and the point P distant d_3 from 0. The thermal conductivity k is, of course, read off on the same scale as k_1.

It is more convenient to place a transparent straight edge through k_1 and d_3 than actually to draw the line.

APPENDIX II

Multiple-Conductor Cables

The thermal conductivity, k_1 from conductors to sheath for multiple-conductor cables having the conductors laid up in a single layer may be calculated from an equation given by Mie in his paper previously mentioned. This equation covers the usual two-, three-, and four-conductor cables for power purposes, and is

$$k_1 = \frac{2\, n\, \pi\, \lambda}{ln\left[(1 - \alpha\beta) + \sqrt{(1 - \alpha^2)(1 - \beta^2)}\right]} \text{ watts per ft. per deg. cent.} \qquad (7)$$

in which n = number of conductors

$$\alpha = \left(\frac{R_1}{R_2}\right)^n$$

$$\beta = q\, \alpha\,,\; q = \frac{R_1 - (n + 1)\, r}{R_1 + (n - 1)\, r}$$

r = radius of conductors

R_1 = radius of circle circumscribing the conductors

R_2 = inner radius of lead sheath

R_1 and R_2 depend upon the size and number of conductors and thickness of insulation.

If t_1 and t_2 are the thicknesses of insulation for conductors and belt respectively, then

$$R_2 = R_1 + t_1 + t_2$$

and $R_1 = 2r + t_1$, for two-conductor round cables

$$R_1 = \frac{2(r + t_1)}{\sqrt{3}} + r = 2.16r + 1.15t_1 \text{ for three conductors}$$

$$R_1 = \frac{2(r + t_1)}{\sqrt{2}} + r = 2.42r + 1.41t_1 \text{ for four conductors}$$

The quantity $(1 - \alpha\beta) + \sqrt{(1 - \alpha^2)(1 - \beta^2)} \equiv m$ is approximately a constant for a given type of cable, and the following values may be used,

1.90 for two conductors, and

1.96 for three and four conductors.

Equation (7) may, therefore, be somewhat simplified. We may put

$$R_1 = (a + b)\, r$$

whereupon, $\alpha - \beta = \alpha\,(1 - q) = \alpha \dfrac{2\,n}{a + b + n - 1} = \alpha\, C,$

$$\text{and, finally, } k_1 = \frac{2\pi\lambda}{l\,n \dfrac{R_2}{R_1 \sqrt[n]{\dfrac{C}{m}}}} \qquad (8)$$

That is, a multiple-conductor cable has the same thermal conductivity as a one-conductor cable of the same outside sheath diameter and a conductor diameter equal to

$$2\, R_1 \sqrt[n]{\frac{C}{m}} = 2f\, R_1$$

In practise, it is scarcely worth while to make calculations for the various sizes of conductors and thicknesses of insulation as it will be discovered that the factors for applying to one-conductor cable ratings do not differ by more than 5 per cent. To find the carrying capacity of a multiple-conductor cable, apply the following percentages to the carrying capacity of a one-conductor cable having the same total thickness of insulation.

No. Conductors	Multiply One-conductor Capacity by
2	80 per cent
3	70 " "
4	67 " "

Two-Conductor Flat and Three-Conductor Sector Cables

In addition to the above there are frequently used two-conductors flat and figure 8, and multiple sector cables. Sector cables are of two types, oval and clover leaf. The oval is laid up with fillers and the clover leaf without. It is evident that sector cable has greater carrying capacity than round, and that the clover leaf is somewhat better in this respect than the oval. The writer has found by test that a 4/0, 13/64-in. × 13/64-in. paper, three-conductor, oval sector cable has 12 per cent better carrying capacity than a similar round cable.

It is believed that the following percentages may safely be applied to two-conductor flat and three-conductor sector cables.

Type of Cable			Multiple One-conductor Capacity by
2 Conductor, flat			87 per cent
3	"	Oval sector	77 " "
3	"	Clover leaf sector	80 " "

Two-Conductor Concentric Cable

Concentric cable is sometimes used for direct-current feeders where duct capacity is limited.

Let d = diameter of inner conductor,
d_1 = inner diameter of outer conductor
d_2 = outer diameter of outer conductor
d_3 = inner diameter of sheath
d_4 = outer diameter of sheath

$$a = \frac{\text{total area of both conductors}}{\text{area outer conductor}}$$

The slightly increased loss in the inner conductor due to operating at a little higher temperature than the outer may be neglected. Sometimes the area of the inner conductor is made larger in area than the outer.

The thermal conductivity is

$$k = \frac{(a\, k_1) \cdot k_2'}{(a\, k_1) + k_2'} \text{ watts per ft. per deg. cent.} \quad (10)$$

in which $k_2' = \frac{k_2\, k_3}{k_2 + k_3}$,

$$k_1 = \frac{2\, \pi\, \lambda}{l\, n\, \frac{d_1}{d}}$$

$$k_2 = \frac{2\, \pi\, \lambda}{l\, n\, \frac{d_3}{d_2}}$$

$$k_3 = 0.244\, d_4$$

The carrying capacity of a two-conductor concentric cable with conductors of equal area may be taken as 75 per cent of that for a one-conductor cable.

Increasing the size of the inner conductor is of very little advantage, for example, a concentric cable with 1,250,000 cir. mil inner conductor and 1,000,000 cir. mil out has only about 9 per cent greater carrying capacity than a cable with both conductors 1,000,000 cir. mil.

APPENDIX III.

Rate of Temperature Change of a One-Conductor Lead-Covered Cable

In order to develop the theory of temperature rise of cables, one might follow along the usual lines of mathematical physics, but it will soon be evident that the mathematical difficulties are such that a rigorous development is not suitable for engineering purposes. The following discussion may be of interest.

It may be shown experimentally that the following equation, which is only approximately true but sufficiently so for engineering use, gives the rise of temperature of any part of a one-conductor cable from the time load is first applied:

$$\theta_r = \Theta_r\,(1 - \epsilon^{-\beta t}) \quad (1)$$

in which θ_r = temperature at time t and at any point P between the conductor and the lead sheath distant r from the axis of the cable, including also the conductor and the sheath.

Θ_r = final temperature (at $t = \infty$) at the point P.

ϵ = base of Naperian logarithms

β = constant for any given cable and loading.

With this assumption, the quantities Θ_r and β may be expressed in terms of known physical constants and the dimensions of the cable.

In the following, all temperatures are in degrees centigrade above the initial temperature assumed constant.

Let w = watts per cm. loss in cable at initial temperature.

α = temperature coefficient of copper referred to initial temperature.

θ = temperature of conductor at time t

θ_r = temperature of insulation at time t at point distant r from cable axis.

θ_b = temperature of lead sheath at time t

Θ = final temperature of conductor.

Θ_r = final temperature of insulation at point distant r from cable axis.

Θ_b = final temperature of lead sheath.

C_1 = thermal capacity of conductor in watt-hr. per cm.

C_2 = thermal capacity of insulation in watt-hr. per cm.

C_3 = thermal capacity of sheath in watt-hr./cm.

ρ = density of insulation, grams per cm.[3]

c = specific heat of insulation watt-hr. per gram.

λ = volume thermal conductivity of insulation; watts per deg. per cm.

h = surface thermal conductivity of sheath to air, watts per deg. per cm.[2]

α = radius of conductor

b = inner radius of sheath

d_3 = outer diameter of sheath

The following equation expresses mathematically the fact that the heat generated in the conductor is equal to that stored in the copper, insulation and lead plus that dissipated at the surface of the lead.

$$w\,(1+\alpha\,\theta) = C_1\frac{d\,\theta}{dt}+\int_a^b 2\pi\rho c r\,\frac{d\,\theta_r}{dt}\cdot dr+C_3\frac{d\,\theta_b}{dt}+\pi h\,d_3\theta_b \tag{2}$$

Differentiate equation (1) and

or,

$$\left.\begin{aligned} \frac{d\,\theta}{dt} &= \beta\,\Theta\,\epsilon^{-\beta t},\\ \frac{d\,\theta_r}{dt} &= \beta\,\Theta_r\,\epsilon^{-\beta t},\\ \frac{d\,\theta_r}{dt} &= \frac{\Theta_r}{\Theta}\cdot\frac{d\,\theta}{d\,t}. \end{aligned}\right\} \tag{3}$$

Substituting this value for $\frac{d\,\theta_r}{dt}$ in (2) and evaluating the integral, we find after substituting

$$k_1 = \frac{2\pi\lambda}{ln\,\frac{b}{a}},\; k_2 = \pi\,d_3\,h, \text{ and } k = \frac{k_1\,k_2}{k_1+k_2}$$

that

$$w\,(1+\alpha\,\theta) = \left[\,C_1+\rho\,c\left\{\pi\,(b^2-a^2)\left(1+\frac{k}{4\pi\lambda}\right)-\frac{\pi\,k\,b^2}{k_1}\right\}+C_3\,\frac{k_1}{k_1+k_2}\right]\frac{d\,\theta}{dt}+k\,\theta$$

Or, we may write this in the form:

$$w\,(1+\alpha\theta) = C\,\frac{d\,\theta}{dt}+k\,\theta \tag{4}$$

in which

$$C = C_1+p_2C_2+p_3C_3$$

$$p_2 = \left(1 + \frac{k}{4\pi\lambda}\right) - \left(\frac{k\,b^2}{k_1\,(b^2 - a^2)}\right)$$

$$p_3 = \frac{k_1}{k_1 + k_2} = \frac{k}{k_2}$$

In practise, we may approximate further and put

$$C = C_1 + p(C_2 + C_3)$$

The integral of (4) is

$$\theta = \frac{w}{k - \alpha\,w}\left(1 - \epsilon^{-\frac{k - \alpha w}{c}t}\right) \qquad (5)$$

VARIABLE AIR TEMPERATURE

Since the change of air temperature in a duct line or other location where cables are usually installed is due to increased load on the cables, an equation of form (1) will express the temperature change for the air. Let this equation be

$$\theta_a = \Theta_a\,(1 - \epsilon^{-\beta_a t}) \qquad (6)$$

in which the temperatures as before are those above the initial temperature.

The equation of heat balance for the cable now becomes

$$w\,(1 + \alpha\theta) = C\frac{d\theta}{dt} + k\,(\theta - \theta_a) \qquad (7)$$

and the solution is

$$\theta = \Theta_1\,(1 - \epsilon^{-\beta t}) + \frac{k\,\Theta_a}{C\,(\beta - \beta_a)}\,(1 - \epsilon^{-\beta_a t}) - \frac{k\,\beta_a\,\Theta_a}{C\,\beta\,(\beta - \beta_a)}\,(1 - \epsilon^{-\beta t}) \qquad (8)$$

In which

$$\Theta_1 = \frac{w}{k - \alpha w}$$

For most practical purposes, one may put $\beta_a = \beta$ so that (8) becomes

$$\theta = \left(\Theta_1 + \frac{k}{k - \alpha w}\Theta_a\right)\left(1 - \epsilon^{-\beta t}\right) \qquad (9)$$

That is, the final temperature of the conductor is greater by the amount $\frac{k}{k - \alpha w}\Theta_a$ over what it would have been with constant air temperature.

DISCUSSION ON "TEMPERATURE RISE OF INSULATED LEAD-COVERED CABLES" (POWELL), SEATTLE, WASH., SEPT. 5, 1916.

M. T. Crawford: Reference is made to cables in duct lines, stating it will be found that the thermal conductivity of a duct line is constant. A formula is given for applying this, considering the temperature of the air in the ducts, and the temperature of the air at the surface of the street. There is one thing which should be considered in a city where an underground system of steam heating service is maintained. Steam mains or steam service pipes frequently parallel and cross duct lines, and the close proximity of the steam pipe has quite an effect on the cables or the duct lines. This will be much greater in winter than in summer. If the steam line belongs to another utility, the exact location of it with reference to the duct line may not be very definitely known. Sometimes a steam line crossing a duct line at right angles may create a hot spot in a location which would not be noticed at man holes, or not easily discovered. This matter should be considered in addition to the temperature of the air in the ducts, and at the surface of the street.

L. T. Merwin: I think, perhaps, the experience of the Northwestern Electric Company in Portland, along the line Mr.Crawford has just spoken of, has been a little more severe, possibly, than he has had here, owing to the type of construction, in the alignment of the steam heating mains with the electric lines. Fortunately, or unfortunately, as the future may determine, our electric duct lines in those streets that carry steam heating mains, lie over or beside them. We have noticed no discomfort electrically or physically in handling the operation and maintenance of the system under ordinary conditions. But in our last seasonal high water period, which came this year in July, rather than, as usual, in June, owing to the late spring, we had a rather distressing set of conditions to combat. It was the first time, since our system was installed, that we had had very high water. As a matter of fact, the flood stage this year, reached a point that had been reached previously only twice since the weather bureau has been keeping its records. While, at the present time, for instance, the state of the Willamette River is, on United States Engineers' gauge, approximately six feet, it rose to the level of 23.9 feet on July 4th and 5th. That put the steam lines under water. So far as I know, it is practically impossible to make the installation of steam lines thoroughly waterproof, although, probably if we had forseen just the situation that subsequently arose, we might have obviated some of the difficulty; but the fact remains that the steam lines were under water, and subject to a considerable infiltration. The electric duct lines overlying the steam pipes were then subjected to a very high temperature, due to the fact that the ground was thoroughly saturated, and the moisture in the ground was heated not merely to the boiling point of water, but practically to the temperature of the pressure we are carrying, namely, about six or seven pounds,—say 227 or 228 degrees Fahrenheit. The electric duct lines are of vitrified clay, the joints presumably not the best especially in one street, where the construction was carried on with heavy interurban trains running beside it, so that there was more or less settlement when the lines were laid. We had the peculiar anomaly of suffering from high water and yet being face to face with the necessity of keeping the overlying electric duct lines flooded artificially with cold water in order to keep them cool. Our paper insulated cables were subjected to a temperature of 228 degrees, even imagining that the cables were carrying no current. Now, over the evening peak, the cables carried a current which would normally bring them, for the time of the peak, to something approaching, we will say, 150 degrees Fahrenheit. Then, in addition to this, they were subjected to a flat temperature of 228 degrees. I should say that in the neighborhood of 14,000 feet of lead covered, paper insulated cable was affected, and of that, we had failure in but one block. During the trouble, and subsequent to it, I have been endeavoring to find data that might be available covering the quantitative value of the deterioration that might have taken place. I have been unable to find anything in our literature on the subject to give me a hint as to what I might expect as to this quantitative value. I do know that in this one block, we had one cable fail. Unquestionably, we must attribute it to the excessive temperature, but whether it was augmented by other conditions, I do not know. Unfortunately, the trouble arose suddenly, and our force being small, it was impossible for us to make a lot of rapid determinations that would have been of great value to have on record. But if there are any here who can give me approximately what might be a quantitative value of the deterioration in these cables that I might expect in the future, I would be only too glad to receive it, or to be directed to any literature that may be printed on the subject. In this paper, reference is made to the maximum temperature at which the cable may be operated indefinitely without undue deterioration. Whether there is a time element involved there— presumably there is— I don't know. In our case for a period of at least 24 days, the temperature of certain portions of our cable was approximately 220 degrees Fahrenheit. In one instance where a steam service line crossed under a 10,000-volt lead-covered, varnished-cloth insulated cable, there was a failure—one of the crossings mentioned by Mr. Crawford. The cable was very old—one of the very early ones—and undoubtedly the breakdown was hastened by the excessive temperature. The 14,000 feet of cable that I am speaking of, however, is not high tension. It is single conductor used in the ordinary three-wire Edison system.

I wish to bring up the advisability of connecting with as strong a bond as possible, the neutrals of the system with the lead sheaths, so as to increase the carrying capacity of the neutral over and above the conductivity of the copper that is already in. In other words, to make the lead sheath act as a part of the neutral conductor. If there are any present who have followed out that system and have had any bad effects from it, I would like to hear from them. The author advises against this practise.

J. B. Fisken: In regard to the question Mr. Merwin asked as to using the lead sheath as part of the neutral conductor. I believe, where a street railway system is operated from the same power house as a d-c.distribution system using the same ground in the power house, it is impossible. A number of years ago, when we made the underground installation of our d-c. system in Spokane, we put in bare neutral conductors, and we found that with the variations on the street railroad load, the regulation of our lights was very bad. The investigation, of course, showed that the street railway current was coming back over the bare d-c. neutral and causing a very considerable drop. The result was that we had to take out all the bare neutral cables we had put in, and put in covered cables, and we had to keep our cables insulated to just the same degree as the outside wires.

S. C. Lindsay: We connect the neutral of the Edison system to the negative bus of the railway system where both systems are supplied from one station, but do not ground the Edison neutral at any other point. We also bond all the lead-covered cables together in each manhole and connect them to the negative bus of the railway system at the station, and have had no trouble from electrolysis on the cable sheaths during 13-years experience with this system of connections.

Referring to another part of Mr. Powell's paper, he says that the temperature of the duct lines should be taken midway between manholes. I am interested to learn of the method he used to obtain temperatures at those points. Further along in his paper, where he gives the rating of cables and loads to be placed on them at different temperatures, it seems to me that Mr. Powell's investigations do not enable us to load our cables any heavier than, nor quite as heavy as, some of the accepted methods of loading that we have been using. We have been loading our cables for a number of years heavier than any of the figures given by Mr. Powell, and we have been singularly free from cable troubles.

C. R. Collins: The author of this paper makes the statement in connection with the cables in duct lines: "The problem may conveniently be divided into two parts: viz., one having to do with heat transference from the air in the ducts to the earth directly in contact with the conduit, and the other with transference from the earth to the air at the surface." I do not see that he has taken into consideration the fact that a duct might be hotter at the center of the duct line than it would be near the edge. If we had some means of keeping the outside of a duct line cool, having it in contact with water for instance, the cable in the center duct would get much hotter than those in the outside ducts.

H. W. Buck: We had considerable experience at Niagara Falls in transmitting large amounts of current over large single-conductor cables, at 25 cycles. Our experience was in line with the paper, as to the serious amount of heating due to the induced current in the lead sheath. A one-million circular mil cable with an ordinary lead sheath carries 800 or 900 amperes. If the lead sheaths are short-circuited as secondaries to the copper, by connection together at the man-holes, the loss in the lead sheaths from induced currents is approximately equal to the copper loss. The question naturally arose as to whether these lead sheath currents could be stopped by breaking the connection between the lead sheaths. It could easily be stopped, but when the short-circuited connections were removed the induced voltages in the lead sheaths rose in some cases to as high as 500 volts. On this account we found that the damage due to the possible short-circuiting of these lead sheaths with an arcing contact, was a more serious matter than the power loss due to the current in the lead sheaths.

We also found, as referred to by the last speaker, that the temperatures, on the inside ducts of a group of ducts, might at times rise to a very high degree. Heat insulation of a nest of ducts is almost perfect to the inner ducts. We were obliged to abandon entirely all groupings of ducts more than two in width, so that the ducts would always have at least one side in contact with the earth. We made a number of tests on the heating of conduits, and found wide variations due to the seasons, and due to the character of the surrounding soil. When a new duct line was built, it did for a while operate at a low temperature. It would then gradually bake the moisture out of the surrounding earth, until the earth became a dry powder, and then the temperature would rise to a very much higher point. These wide variations in temperature, due to fluctuating conditions, should make engineers extremely cautious in estimating maximum temperatures, because the factors which enter vary within such wide limits.

Transmission of large alternating currents through single-conductor lead-covered cables should be avoided as much as possible on account of the eddy current heating. Not only is the heating objectionable, but the current flowing through the joints at manholes seems to have a disintegrating effect.

J. B. Fisken: Might I ask whether that was an alternating current?

H. W. Buck: Yes; alternating current; and the higher the frequency, the higher the eddy current loss.

S. C. Lindsay: Was any attempt made to cool your ducts at Niagara by forcing air through them with fans?

H. W. Buck: We tried various methods, and the air cooling method worked, but it required such a very high pressure of air that the power required was prohibitive. In some cases, where it was necessary to operate ducts having a large number of cables in a group, such, for instance, as 6 by 6, or 12 by 12, we placed water pipes through every other duct and kept a stream of water flowing through them. That was the only method which we found satisfactory for cooling the ducts under certain conditions.

S. C. Lindsay: The conditions for the absorption of heat into the soil were rather poor? The formation there is principally rock.

H. W. Buck: Yes; some broken rock, and some sand and clay.

S. C. Lindsay: Here in Seattle where the ground is saturated with water most of the time, we have a different condition. However, we had one particularly hot place in our underground system where we installed a fan in a manhole and ran an 8 inch pipe from the man hole to a pole on the sidewalk, and extended the pipe about twenty feet up the pole, forcing the hot air through this pipe with a 3-h.p. induction motor. The fan has been installed about two years and we are getting results from it.

H. W. Buck: The difficulties at Niagara were due to the large currents involved. The eddy-current loss in the lead sheath increases as the square of the current in the copper. We found that the permissible loss per duct foot varied from a minimum of about 1 watt per duct foot to 5 watts per duct foot, depending upon the conditions for getting rid of the heat.

L. T. Merwin: May I ask, if it were applicable, why did you not merely flood the ducts with water, rather than run a water pipe through adjacent conductors, as I understand you did?

H. W. Buck: If the ducts had been flooded, the manholes would also have been flooded, and it was easier to control the water by isolating it in pipes, than by allowing it to flow freely through the ducts themselves. In other words, it was not quite such a sloppy job.

L. T. Merwin: Would not the manholes have stood flooding?

H. W. Buck: No, they could not have been drained in this particular case, because they were below the level of the canal.

C. R. Collins: We tried the plan mentioned by Mr. Merwin, and found the water had disappeared before it got to the next manhole. A duct line will not always hold water.

H. W. Buck: That is true.

R. Howes: I would like to ask if any of you have had any experience with single-conductor cable on three-phase circuits under water, so as to state whether there is any electrolysis between the lead-covered cables?

H. W. Buck: Personally, I cannot answer that question from my own experience.

L. T. Merwin: Were these cables, lead cables?

H. W. Buck: Paper and rubber, both. Mostly paper.

L. T. Merwin Have you any means of knowing what limit of temperature was reached and for what duration, and could you place a value on the deterioration that took place in the insulation?

H. W. Buck: The temperature rose in some cases so high that the paper insulation was entirely carbonized.

J. B. Fisken: In reference to the remark made by Mr. Lindsay as to taking temperatures in the duct lines. I don't know whether this practise is followed or not, but it seems to me that in installing a large duct line, it would be good policy to leave a space vacant in the center. We have taken temperatures in our duct lines, not necessarily in the center of the duct line, but in other parts, by simply pulling in a registering thermometer, and leaving it there, for a certain time, and then pulling it out and reading it. I believe the heat in the center duct will be as great as in any in that duct line, especially if the ends were closed to permit the accumulation of heat in the duct. And then, by putting in the thermometer, we could make a thermal survey of that duct line, and tell very closely what the temperatures were.

H. W. Buck: I think that could be done very effectually, but it should be remembered that the temperature of the duct is not a correct indication of the temperature of the copper inside of the cables. The temperature gradient must be steep in order to force the heat out; consequently duct temperatures are very much lower than temperatures to which the cable insulation is subjected.

M. E. Cheney: In this capacity, I would suggest exploring coils in the center of the conduit lines, midway between the two manholes. You can determine the temperature in the cable by the difference in the resistance. That system is used a great deal in taking temperatures.

H. W. Buck: That method was adopted by Mr. Fisher in the tests referred to in this paper. All the temperatures were obtained by moving exploring coils along through the various ducts.

W. A. Del Mar: There are two conditions which Mr. Powell has not considered in his paper, which have an important bearing upon the carrying capacity of cables in ducts, namely: the influence of neighboring ca blesin reducing the continuous and short-time rating and the influence of the thermal capacity of the ducts in increasing the short-time rating. These are matters of the utmost importance but unfortunately experimental data are lacking. In the absence of such data the following suggestions are offered for discussion.

The influence of the number of similarly loaded cables in a conduit line may be estimated as follows, assuming the number of ducts to always equal the number of cables. Assuming a given temperature rise in the cable, let

n = Number of outside duct faces in the cross-section of conduit line.
N = Number of cables in the conduit line.
d = Heat dissipation per duct face per foot.
D = Heat dissipated per cable, per foot.
I_N = Current per cable with N cables similarly loaded.

I_1 = Current with one cable in a one-duct conduit line.
r = Resistance of cable, per foot, at ultimate temperture.

Then,

$$DN = dn$$

or,

$$D = \frac{dn}{N} \tag{1}$$

By Joule's law,

$$I_N = \sqrt{\frac{D}{r}}; \tag{2}$$

when the cable has reached its ultimate temperature.

Combining equation (1) and (2),

$$I_N = \sqrt{\frac{d}{r}} \quad \sqrt{\frac{n}{N}} \tag{3}$$

And,

$$I_1 = \sqrt{\frac{d}{r}} \quad \sqrt{4} \tag{4}$$

$$\therefore \frac{I_N}{I_1} = \sqrt{\frac{n}{4\,N}} \tag{5}$$

Thus in the case of twelve similarly loaded cables in twelve ducts arranged 3x4, $N = 12$, and $n = 14$ and therefore by equation five,

$$\frac{I_N}{I_1} = \sqrt{\frac{14}{48}} = 0.54$$

Hence, due to the neighboring cables, each cable will carry continuously only 54 per cent of what it would carry if alone.

Table I shows the estimated influence of the heat storage capacity of tile ducts upon the short-time rating of a two-circular inch cable. The temperature rise of the duct is purposely underestimated.

TABLE I.

	Weight lb-ft.	Specific heat	Watt-hours per deg. cent.	Temp. rise deg. cent.	Total watt hr. absorbed
Copper	6.18	0.094	0.31	74	23
Insulation	0.97	0.360	0.18	72	13
Lead	4.54	0.031	0.074	69	5
Duct	11.00	0.200	1.16	25	29
					Total 70

The effect of the tile duct, in this case, is to add at least 70 per cent to the effective thermal capacity of the 2-cir. in. cable, and this proportion would be greater with smaller cables. In the case of a 2-cir. in. cable, the two-hour rating would be increased at least 20 per cent due to the thermal capacity of the duct.

A table of reduction factors for rectangular duct groups is given in Table II. These factors, being based upon the assumption that all the heat generated in the cables is dissipated into the earth through the duct walls, are incorrect for short-time ratings. If the absorption of heat by cables and ducts be taken into account, the reduction factors will approach unity, the shorter the rating period. Thus, the one-minute rating of a cable would scarcely be affected by the number of adjacent similarly loaded cables, as practically all the heat generated would be absorbed by the cable and duct. The two-hour rating, on the other hand, depends more upon the heat dissipation than upon the heat absorption and the reduction factors may be used with it, without great error.

Hence, the ratings in Table II are derived by calculating the two-hour rating for one cable in a duct, taking into account the thermal capacity of the cable and duct, and then multiplying by the duct reduction factors. The error, due to the assumption that these factors are correct for the two-hour rating, will not be very great and will be on the safe side. The ratings thus obtained are considerably in excess of those usually published, in spite of the low reduction factor and low temperature rise (25 deg. cent.) assumed for the ducts. Experimental data to carefully confirm this table, are lacking, but several observations upon cables in large groups, indicate that the ratings given for sixteen ducts or more, are conservative.

TABLE II.

CARRYING CAPACITY FOR TWO HOURS.

Single conductor, 2 cir. in., 650 volts, paper-lead in ducts, (74deg. cent.)

Number of ducts	Factor	Amperes	Number of ducts	Factor	Amperes
1	1	2840	28	0.444	1260
2	0.845	2400	32	0.433	1230
3	0.82	2330	36	0.425	1210
4	0.79	2240	40	0.416	1180
6	0.678	1930	44	0.412	1170
8	0.611	1740	48	0.408	1160
12	0.540	1530	52	0.404	1150
16	0.500	1420	56	0.401	1140
20	0.474	1350	60	0.398	1130
24	0.456	1300	64	0.395	1120

Presented at the Pacific Coast Convention of The American Institute of Electrical Engineers, Seattle, Wash., September 6, 1916.

INDUCTIVE INTERFERENCE AS A PRACTICAL PROBLEM

BY A. H. GRISWOLD AND R. W. MASTICK

ABSTRACT OF PAPER

In this paper are given a review of the factors which affect inductive interference in telephone circuits from high-voltage power transmission circuits, a presentation of the practical considerations regarding the reduction of the interference, and a description of actual cases of the application of these means of reduction.

Distinction is made between the effect of balanced and of residual voltages and currents on the power circuit and between the effect of voltages induced between the wires and those induced between wires and ground.

The wave shapes of the voltages and currents in the power circuits have a very important effect in the amount of inductive interference in telephone circuits. The precision of the electrical balance of the power circuit is also important because of the relatively very large effects of unbalanced voltages and currents in producing inductive interference.

A discussion is given of the principles to be used in the design of coordinated transposition schemes for power circuits and telephone circuits which parallel each other, and schemes are described which have been devised for application to the telephone circuits in order to simplify the design of transpositions in the power circuits which make it possible to balance the induced voltages.

A detailed discussion is given of three particular cases of parallels showing the application to them of the different methods by which inductive interference can be reduced. In the appendix is an outline of information regarding parallels intended to facilitate the determination of the remedial measures desirable in any given case for reducing inductive interference.

THE discussions of the subject of Inductive Interference hitherto presented before the Institute and in the technical press, have dealt chiefly with the technical aspects of the problem. Very little has been said to show how the conclusions theoretically and experimentally established can be practically and successfully employed for the solution of problems in the field. It is the purpose of this paper to review some of the important aspects of inductive interference and to indicate by means of concrete examples, the solution of some of the practical problems met in the field. It will be our endeavor to show the simplicity of remedial measures in general in an effort to correct the idea prevalent among those who have not had time to carefully study the problem, that the measures developed to date are impracticable and burdensome.

Before proceeding to the discussion of remedial measures and their application, we believe it well to again review briefly, the factors involved, through which inductive interference arises. An understanding of these factors, and their relative importance, is necessary in order to appreciate the significance of the remedial measures.

In what follows, three-phase three-wire power circuits and metallic telephone circuits, physical or phantom, are assumed. We are concerned with voltages induced in the telephone circuit through two phenomena—electric and magnetic induction. Both effects are always present, and they combine to produce the resultant disturbance noted.

The voltage induced in the telephone circuit electrically and magnetically can be classified as:

1. Between the two sides of the circuit (referred to throughout this paper as the transverse effect).

2. Between the two sides of the circuit and ground, or along the circuit (referred to throughout this paper as the longitudinal effect).

The transverse induced voltages regulating through line impedances cause currents in the terminal apparatus. The longitudinal induced voltages, in addition to raising the telephone circuit to a potential with respect to earth which may be dangerous, cause currents in the telephone circuit owing to the differences in series impedances and admittances to ground of the two sides of the circuit.

A perfectly balanced power or telephone circuit may be defined as one in which the series impedances of the several phases and the admittances between the several phases and ground are exactly the same at every point.

If it were possible to construct a perfectly balanced telephone circuit, there could be theoretically no transverse induced voltage, regardless of the magnitude of longitudinal induced voltage provided that a sufficiently large number of exactly spaced transpositions were placed in it so as to equalize the induced voltages in each side.

Conversely, if it were possible to construct a perfectly balanced power circuit, there could be theoretically no voltages induced on a parallel telephone circuit, provided that a sufficiently large number of exactly spaced transpositions were placed in it so as to expose each phase of the power line equally to the telephone line.

In practise, the balance of neither power nor telephone circuits can be made perfect as defined above, and it is, therefore, necessary, in order to avoid induction into paralleled telephone circuits, to balance both power and telephone circuits as well as practicable, and also transpose both circuits with due regard to one another.

It is convenient to consider the voltages and currents in the power circuits, which cause induction, as consisting of two components:

1. Balanced voltages and currents.
2. Residual voltages and currents.

The balanced components are three voltages or currents equal in magnitude, displaced 120 degrees in time-phase with respect to one another, and whose vector sum is, therefore, zero.

Single-phase loads connected between wires cause voltage and current components whose effects are very similar to those of balanced three-phase voltages and currents, and are treated in a like manner.

The residual components are three voltages or currents equal in magnitude, in common time-phase, and whose vector sum is, therefore, not zero.*

The balanced voltages and currents are those which perform the useful functions of the power system. On the other hand, it is significant and fortunate that the residual voltages and currents are not essential to the operation of the power system.

Balanced voltages and currents are common to either of the two general types of power systems (grounded or isolated), and the remedial measures for the mitigation of inductive effects arising therefrom are identical. This is not true of the residual voltages and currents. These arise from different sources in the two types of power systems, and generally exhibit characteristics peculiar to the particular type of system.

The remedial measures for their mitigation are also distinctly different.

Thus, it will be seen that there are two different phases of the general problem of inductive interference, *i.e.*,

*See Appendix II, Report of Joint Committee on Inductive Interference. A. I. E. E. TRANSACTIONS, Volume XXXIII, p. 1461.

1. The mitigation of induction arising from the balanced voltages and currents, requiring remedial measures which are the same whether the power system be isolated or grounded.

2. The mitigation of residual voltages and currents requiring remedial measures peculiar to the particular type of power system involved.

Residual voltages and currents may arise in different types of power systems from one or more sources which act singly or together.

On grounded systems, the principal sources of residual voltages and currents are:

1. Unbalanced loads between the three-phases and neutral, causing unbalanced-load currents to flow through the neutral to earth.

2. The third harmonic and its odd multiples, due to a variation of permeability of the iron, occur in common time-phase in the three phases of the transformer banks, thus giving rise to a residual component of voltage and current in the connected transmission lines.

On systems isolated from ground, the principal source of residual voltages and currents is:

Unbalanced capacitance and conductance between the several phases and ground. The conductance factor is generally of minor importance on well constructed and maintained systems.

The tendency in the best power system design and operation is inherently toward practises which reduce the possibility of large residuals. Moreover, the majority of the future parallels with communication circuits will undoubtedly be short, owing to the increasing tendency of both power and telephone companies to seek private rights-of-way. Were this not so, the problem of mitigation of residuals would be as difficult to combat in the future as it is at present. With the increased attention being devoted to this matter we expect that the longitudinal effects of residual voltages and currents will, in the shorter parallels, be reduced to magnitudes small enough to be relatively unimportant.

It must be realized that the inductive effect per volt or ampere of residual voltage or current is proportionately far greater than for equal amounts of balanced voltage or current. It should be clearly understood that the mitigation of residuals where parallels of considerable length are involved is of great importance. The longitudinal effect then becomes of importance by maintaining the telephone circuit as a whole above ground potential and producing a transverse effect by virtue of the unbalances inherent to commercial circuits.

The wave forms have much to do with the severity of induction. Higher harmonics are present in both voltages and currents and their power of producing disturbances increases with very great rapidity up to about 800 cycles. Practically all noise in telephone circuits caused by induction from power circuits arises from the higher harmonic voltages and currents. Were these entirely absent, the problem of inductive interference would be indeed simple of solution, for then we should have to deal with only the fundamental frequency which is scarcely audible to the human ear.

The frequency and magnitude of these attendant harmonics should determine the extent of remedial measures to be applied owing to the variation in effectiveness of given remedial measures and severity of induction with the frequency.

Another important phase of the problem is the question of abnormal conditions, accidental or otherwise, on the power system. An abnormal condition in any type of power system, whether it be due to an accidental ground, short circuit, open-circuit or switching operation, produces a great increase in the residual voltage or current, or both, of the system momentarily, or for a considerable period of time, as the case may be.

On a star-connected grounded-neutral system, an abnormal condition generally produces a large residual current which is approximately equal to the short-circuit current to ground (if the condition be one of a grounded phase) on that portion of the circuit between the sources of power supplying the fault and the point where the fault occurs, or if the fault be an open one in phase, the residual current will equal the unbalanced-load currents flowing in the other two phases. A residual voltage is created in proximity to the fault and in certain instances throughout the length of the circuit from the fault to the receiving transformers, which voltage approaches as a maximum 58 per cent of the voltage between phases.

On an isolated system, a ground on one phase causes a large residual voltage throughout the entire length of the circuit whose magnitude is 173 per cent of the voltage between phases. A residual current is created in proximity to the fault, its magnitude depending upon the extent, voltage and frequency of the system.

Fortunately, abnormal conditions are becoming less frequent, owing to the demand for greater continuity of service, leading to better construction of power lines and to the use of better apparatus. There have been no remedial measures developed which can adequately care for the inductive disturbances attendant to abnormal conditions of power lines, nor are such expected.

It is, therefore, a question of reducing to a minimum the accidents on the power lines by proper construction and maintenance and of using methods and apparatus in switching which shall incur the least possible disturbances.

The difficulties encountered in attempting to mitigate the disturbances under abnormal power circuit conditions constitute an additional reason why it is very desirable to avoid parallelism wherever possible.

As an instance in which the use of improved methods and apparatus have resulted in a material reduction of transient disturbances, the charging of electrolytic lightning arresters can be cited. Since the adoption of the four-tank electrolytic lightning arrester, the use of charging resistances and metallic contact during charging, the formerly serious transient disturbances experienced on parallel telephone lines at times of charging, have been largely reduced.

The configuration and spacing of the power-circuit conductors has an important bearing on:

1. The liability to short-circuits on the line.
2. The residual voltage (of an isolated system).
3. The resultant induction from balanced components.

Since the last two items can be cared for by transposition, the first is of chief importance.

Vertical configuration of a power circuit renders it liable to short-circuits where snow and sleet are encountered.

The equilateral triangle is far superior to either vertical or flat construction with respect to residual voltage caused by capacitance unbalance. The wishbone configuration is intermediate. For induction from balanced components, the differences are less marked, the flat configuration causing the most induction.

The configuration of telephone circuits is standardized to a far greater degree, and since transposition is comparatively inexpensive and effective, the configuration of telephone circuits is relatively unimportant with regard to the mitigation of induction.

For the mitigation of inductive effects produced by the balanced voltages and currents, transpositions offer the most feasible, simple and effective means developed to date. A transposition in a circuit interchanges the positions occupied by its conductors. In a three-phase power circuit, a transposition changes the phase of the induction produced by the balanced voltages and currents by 120 degrees. Thus, by locating power-circuit transpositions so that each conductor occupies all of the several conductor positions for equal distances, a "barrel" is obtained within which the vector sum of the induced voltages on an untransposed parallel circuit is zero. The effect of transposing a power circuit may, therefore, be said to be one of neutralization.

A transposition in a telephone circuit changes the phase of the induced transverse voltage by 180 degrees, that is, it reverses in successive lengths the phase of the induction between the two sides of the circuit. Transposition of a telephone circuit, therefore, exposes each side of the circuit equally to the influence of the power circuit, and the effect may be said to be one of equalization. It should be noted that the phase of the longitudinally induced voltage is in no wise changed by transpositions in the telephone circuit.

This change of phase of the induction into a telephone circuit by transposition in either the power or telephone circuit, or both, affords a means of reducing inductive effects in that the induction in one section may be largely neutralized by the induction in neighboring sections.

A proper adjustment of neutralization and equalization effects by transpositions in both power and telephone circuits constitutes a "co-ordinated transposition scheme" as referred to throughout the remainder of this paper.

In Fig. 1 is shown a co-ordinated transposition scheme in the case of a three-phase power circuit and a simple metallic telephone circuit. Let the three configurations of the power circuit be designated A, B, C. Let a and a' denote the length of telephone circuit, exposed to configuration A; b, b' and c, c' are similarly defined. Primes denote that there is an odd number of telephone transpositions between the given length and the reference section of the telephone conductor. For balance to induction the lengths a, a', b, b', c, c' must fulfill the relation

$$\Sigma a = \Sigma a' = \Sigma b = \Sigma b' = \Sigma c = \Sigma c'$$

Longitudinal induction balance for balanced voltages and currents is obtained when the condition

$$\Sigma\,(a + a') = \Sigma\,(b + b') = \Sigma\,(c + c')$$

is fulfilled.

Transverse induction balance for balanced voltages and currents is obtained when the condition

$$\Sigma\,(a - a') = \Sigma\,(b - b') = \Sigma\,(c - c')$$

is fulfilled.

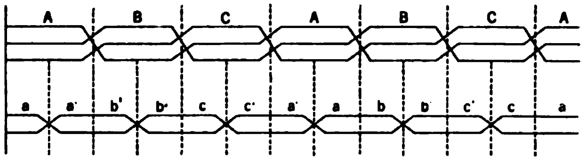


FIG. 1.

The system of "barreling" shown in Fig. 1 is called "continuous barrelling." In practise where long uniform parallels occur, it is possible and many times desirable to modify the co-ordinated system shown in Fig. 1 by omitting every third power transposition as depicted in Fig. 2, thus obtaining a system of "non-continuous barrelling."

The same conditions for balance hold for this system as given for continuous barrelling shown in Fig. 1. The only advantage

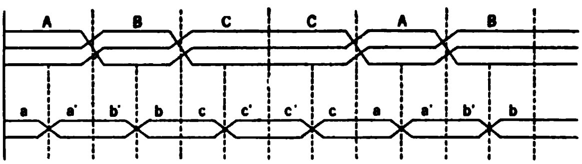


FIG. 2.

of continuous barrelling over non-continuous is that balance is obtained in any three consecutive sections regardless of the point of starting.

Power circuit transpositions with reversed rotation are sometimes used when it is necessary to obtain an exposure of a particular phase in a particular section to balance with another type exposure in some other section of the parallel. A simple illustration is shown in Fig. 3.

It is interesting to note that the use of reversed power transpositions in the manner shown also results in not altering the relation of power wires at ends of the parallel. Reversing the rotation of a power circuit transposition changes the phase of the induction in the section of parallel immediately beyond the transposition by 240 degrees. Since a telephone transposition changes the phase of the induced voltage by 180 degrees, it is obviously immaterial whether the rotation of telephone transpositions be normal or reversed. Normal rotation is considered as that of the existing transpositions in a given power line.

Transpositions of the power circuit in no way changes the phase or magnitude of induction produced in telephone circuits by residual voltages and currents, except in so far as it changes the residual voltages and currents themselves, which happens in some cases.

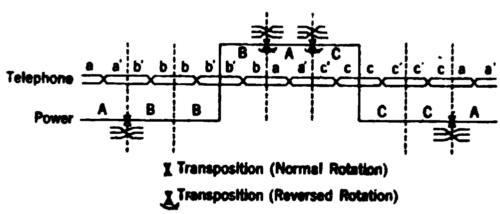


FIG. 3

Longitudinal induction from the residual voltages and currents cannot be reduced by either power or telephone transpositions. It follows, therefore, that the reduction or elimination of longitudinal induction from residual voltages and currents must come about through a reduction or elimination of the residuals themselves in the power system.

Transposition of the telephone circuit is an effective means for reducing the transverse induced voltage produced by residual voltages and currents.

Transverse balance for induction from residual voltages and currents is obtained when the condition (see Figs. 1, 2, or 3).

$$\Sigma\,(a + b + c) = \Sigma(a' + b' + c')$$

is fulfilled.

When the conditions for balance cited above are not fulfilled the unbalanced exposures are as follows:

TABLE I.

Type of Induction	Component of power circuit voltage or current	Length of unbalanced exposure
Transverse	Balanced	$\Sigma(a-a')\underline{/0^\circ} + \Sigma(b-b')\underline{/120^\circ} + \Sigma(c-c')\underline{/240^\circ}$
"	Residual	$\Sigma(a+b+c) - \Sigma(a'+b'+c')$
Longitudinal	Balanced	$\Sigma(a+a')\underline{/0^\circ} + \Sigma(b+b')\underline{/120^\circ} + \Sigma(c+c')\underline{/240^\circ}$
"	Residual*	$\Sigma(a+b+c+a'+b'+c')$

*Independent of all transpositions.

The "unbalanced exposure" is the length of exposure between untransposed telephone and power circuits which will produce inductive effects of the same magnitude as those produced in the actual exposure of the same configuration with the given transpositions in telephone and power circuits.

The unbalanced exposures of different circuits in any given parallel are of value to indicate the relative severity of the induction in the different circuits, and those corresponding to different transposition systems for a given parallel are indicative of the relative effectiveness of such transposition systems.

Summing up from the discussion above; the various factors involved and the conditions for induction balance between power and telephone circuits may be simply tabulated as follows:

TABLE II.

Type of induction	Component of power circuit voltage or current	Condition for balance	Balance depends on transpositions in
Transverse	Balanced	$\Sigma(a-a') = \Sigma(b-b') = \Sigma(c-c')$	Both lines
"	Residual	$\Sigma(a+b+c) = \Sigma(a'+b'+c')$	Telephone line
Longitudinal	Balanced	$\Sigma(a+a') = \Sigma(b+b') = \Sigma(c+c')$	Power line
"	Residual	—	—

The application of telephone transpositions in a manner to obtain the conditions for balance indicated in Table II is subject in practise to the condition that on telephone leads carrying more than one circuit, it is necessary to provide against induction from one telephone circuit into another, commonly referred to as "crosstalk". This necessitates a complicated telephone transposition system to provide balance for induction from outside sources such as power lines and also among all the circuits on the telephone lead.

Even though it were possible in practise to fulfill exactly the conditions for balance as indicated in Table II, there would still be present some inductive effect because of the changes in phase and magnitude of the voltages and currents along the power line. This point has an important bearing on the length of the power-circuit barrel, for it is necessary in order that this effect be rendered sufficiently small, that the conditions for balance outlined in Table II be fulfilled within as short a length of exposure as is practicable. In practise, it has been found, in some cases, that barrels in the power circuit six miles in length are satisfactory. Except under very severe exposure conditions we believe that barrels in the power circuit three miles in length will afford a satisfactory solution when uniform sections of parallel are long enough to permit their use.

Points of discontinuity within a parallel, such as changes in configuration of either power or telephone circuit, large changes in the separation of the two lines, crossovers, branch loads, loading points in the telephone line, or in fact any points at which an abrupt change in magnitude or phase of the power line voltages or currents or induced voltages occurs, should in general be made neutral points. In other words, balance to induction should be obtained between such points of discontinuity independently of the remainder of the parallel. Thus the number of and distance between points of discontinuity is a controlling factor in determining the length of power-circuit barrel. It should be noted in this connection that a loading coil in the telephone circuit is a discontinuity with respect to the transverse induced voltage, but not with respect to the longitudinal induced voltage, since the loading coils are non-inductively connected in the circuit formed by the telephone wires and ground.

Crossovers of power and telephone lines within the parallel are in general considered as points of discontinuity. In some cases, however, where the same separation obtains between the power and telephone lines before and after crossover, it is possible by interchange of the pin positions of the power wires to make the crossover equivalent to a transposition in the telephone circuit, or in both the power and telephone circuits. If the crossover is treated in such a manner, it need not be considered as a point of discontinuity.

In Fig. 4 are shown several types of crossover transpositions represented by the terms "0° crossover", "120° crossover" and "240° crossover" which number of degrees has reference to the change in phase of the longitudinal induced voltage between the two sections immediately adjacent to the crossover.

It has been previously pointed out that transposition of the telephone circuit is an effective remedy for reducing the transverse induction from residual voltages and currents; that longitudinal induction from the same source cannot be cared for by either power or telephone transpositions, hence must be reduced by a reduction of the residual voltages and currents within the power system.

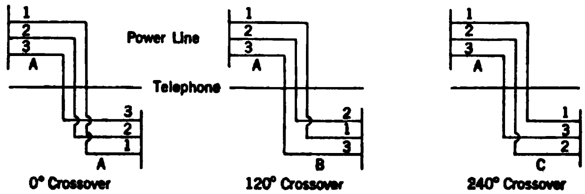


FIG. 4.

In the type of power system isolated from ground, the problem of reducing residual voltages and currents is a comparatively simple one. Earlier herein it was stated that the principal source of residual voltage and current in systems isolated from ground is the unbalanced capacitance between the several wires of the circuit and ground. Hence the remedial measure obviously necessary is a balancing of these capacitances to ground. This is most readily accomplished by transposing the power line throughout its extent (including all the lines metallically connected to the one in the parallel) so that each conductor occupies the several pin-positions for equal distances.

To a company operating an isolated system of large extent, this remedy appears to be a severe and costly measure, unless very few and widely separated transpositions will accomplish the desired result. In general, practise indicates that transpositions for this purpose can be relatively few and widely separated. Here again in determining the length of barrel required, the wave-shape of the residual voltage is a dominant factor, since with the higher frequencies shorter barrels are necessary.

It does not seem probable that barrels of less than 6 miles in length will generally be required and in some cases longer barrels will be sufficient. Branch lines, switching points and changes of configuration must be taken into account and frequently fix the length of barrel.

In the construction of new lines, it is a very simple and inexpensive matter to cut in transpositions at reasonable distances to accomplish the reduction of residual voltage without detriment to the operation of the system. Then if parallelism occurs in the future, the only transpositions required would be in and near the parallel.

With existing parallels, it may or may not be necessary to transpose the power line outside the parallel, depending upon the severity of the exposure. In any event, all of the measures should be applied within the parallel and found insufficient before giving consideration to this point.

In the type of power system operated with a star connection of transformers and grounded neutral, the reduction of residual voltages and currents is not so readily accomplished as in the case of systems isolated from ground. Two principal sources of residual voltages and currents for this type of system have been previously mentioned herein; namely, unbalanced loads between the three-phases and neutral, and the introduction of the third harmonic and its odd multiples as residuals.

The obvious measure against the former is the removal of all grounded neutrals but one, thus removing the ground path for the unbalanced currents. In some cases this may not always be considered safe or feasible, particularly if the network be of large extent. There seems to be, however, a growing tendency on the part of power companies operating systems of large extent toward the elimination of the ground connection at all but important generating and switching points. Since the use of grounded single-phase loads has almost disappeared from practise with the larger power companies, it is now generally true that power circuits operated by such companies can be very well balanced as to magnitude of load current in the three phases and the unbalanced load current can usually be practically eliminated.

The introduction of the triple harmonics as residual voltages and currents is the chief problem of the grounded neutral system. Since these triple-harmonic voltages and currents are introduced through the effect of variable permeability of iron in transformers and as their magnitude is directly dependent upon the magnetic density at which the transformer is operated, this type of residual is reduced by operating the transformers below their rated voltage. There is no doubt that the practise of operating transformers over rated voltage is the cause for the large residual current of triple frequencies observed on star-connected systems, since the magnitude of these harmonics increases very rapidly as the transformer iron approaches magnetic saturation.

The employment of the delta-star connection of transformers on grounded systems is greatly preferable to the star-star connection, in that the delta winding provides a low impedance path for the triple harmonics, in parallel with the path provided by the line and earth, hence reduces the magnitude of such currents over the line and earth path.

It is difficult to accurately predict on systems employing the star-delta type of connections whether or not the magnitude of triple harmonic residual will be large enough to cause severe inductive effects, since it depends upon a multitude of considerations dealing with the interaction of different portions of the system on one another.

In the case where both star-star and star-delta banks are used, the line sides being in star with grounded neutral, the star-delta bank offers a low-impedance path for the triple-harmonic magnetizing currents of the star-star bank. Hence in the line, between two such different banks, there will be a large residual current, and an exposure occurring there is liable to serious induction. Such a star-delta bank may, however, be used as a shunt path for the triple-harmonic residuals, and greatly reduce their magnitude in the line beyond. Thus, a remedial measure is suggested for the mitigation of triple-harmonic residuals on systems employing the star-star connection.

The triple-harmonic circulating current of the delta winding is greatly increased where such connection is used in combination with star-star banks and hence a star-delta bank of size comparable with the star-star bank is required to give effective results.

On a system employing only the star-star connection of transformers with grounded neutrals, it is always a safe prediction that serious triple-harmonic residuals will be present, and it is essential that measures for their reduction be considered. Tertiary delta windings on such transformers are beneficial and new transformers for proposed installations of this connection should be designed to provide such windings. Power engineers recognize the advisability of providing such windings for their own benefit when using this type of connection so that much of the trouble formerly experienced will thereby be eliminated in the future.

The interconnected-star is a method of reducing triple-harmonic residuals by neutralization. Besides being less efficient than the star-delta connection, it reduces the voltage rating by 13 per cent and requires a more complicated arrangement of the wiring.

It will be seen from the above discussion of the mitigation of residual voltages and currents under normal operating conditions, that:

1. In isolated delta-connected systems, residuals may be effectively and easily reduced by simple means.
2. In star-connected grounded systems, several measures can be practised for reducing residuals all of which will reduce them with some degree of success but none of which are entirely satisfactory.

Types of power-circuit transpositions and barreling have been described previously and their application to the practical case will be readily understood. In the case of telephone transpositions, only a single metallic circuit has been considered in the discussion of the co-ordination of transpositions, without reference to cases where more than one telephone circuit is involved other than to mention the fact that the problem was further complicated.

For the application of co-ordinated systems of power and telephone transpositions to the practical case, a telephone transposition system has been designed which will care for as many as forty telephone wires (20 physical and 10 phantom circuits), providing adequate crosstalk balance between the telephone circuits themselves and being capable of properly co-ordinating with power-circuit barrels of varying lengths. Further work is in progress which will extend this system to a full eighty-wire lead.

This system is known as the "exposed line system". It is comprised of two types of sections as follows:

1. Exposed line *A* section.
2. Exposed line *X* section.

Additional short sections, whose characteristics have not, as yet, been determined, are in the process of development; namely, the exposed line *Y* and *Z* sections.

The exposed line *A* section is nominally eight miles in length with 32 transposition points for the circuits most commonly used, and has been designed to give high crosstalk-balance together with induction balance to power lines transposed:

1. Opposite any mile-points of the telephone transposition system.

2. With two complete barrels (five transpositions of the power line) between mile-points of the telephone transposition system.

Thus, for a uniform parallel, this section gives balance to induction from power lines transposed with six-mile, three-mile or one-half mile barrels. It is possible to adjust the length of this nominal eight-mile section to any value less than eight miles, and this is frequently done in adjusting the sections or mile-points to correspond with discontinuities in the parallel. Transverse balance of all circuits to induction is accomplished in every mile.

The exposed line *X* section is nominally one-half mile in length with four transposition points, and is so designed that any number of units may be installed end to end. The *X* section unit does not balance to power lines transposed within any one unit, but is designed to be so used that transpositions of the power line and discontinuties of the exposure occur at junction points between successive units. Thus balance to induction is obtained in three successive sections if power transpositions are located opposite their junction points. Nominally this would give a power circuit barrel of one and one-half miles. The *X* section can be made of any length less than one-half mile per unit where required.

Short exposed line sections may be used in any part of an eight-mile loading section, and the remainder transposed according to some other transposition system.

By "other transposition systems," reference is made to the "standard system" which involves the use of four sections, *A*, *X*, *Y*, and *Z*, whose nominal lengths are 8, ½, 1½ and 4 miles respectively. In the standard system, however, balance to induction from outside sources, such as power lines, is not obtainable except by modification of certain of the transpositions involved. Also, the use of the *X*, *Y*, or *Z* sections consecutively is not permissible without modification.

Another method sometimes used is to superimpose on the crosstalk transposition systems, already in the line, special transpositions of all the telephone circuits on poles between the regular transpositions poles. That is, their function is to transpose all circuits with reference to outside circuits so as to give a minimum of disturbance to the crosstalk balance of the telephone circuits themselves. The prime purpose of "whole-line" transposition is, therefore, to make possible the retention of systems of transposition involved in parallelism which do not provide balance to induction in themselves. The use of whole-line transpositions is limited by crosstalk considerations to some extent where phantom or loaded circuits are involved. Their chief application is to very short parallelisms.

There are two types of whole-line transpositions; namely, the quarter-mile unit and half-mile unit. These are shown in Fig. 5.

The use of short sections or whole-line transpositions is dele-

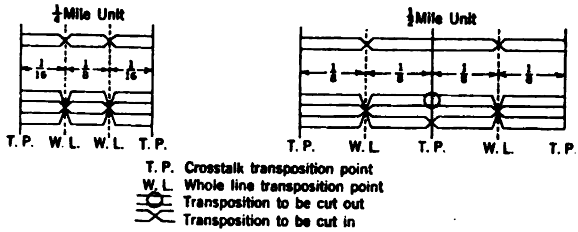


FIG. 5.

terious to the telephone service in that it is impossible with these arrangements of transpositions to reduce cross-talk as effectively as with eight-mile sections. Moreover, the difficulty of maintenance of telephone service is increased.

In order to illustrate in a more comprehensive manner the application of remedial measures, such as have been described and discussed in the previous sections of this paper, a few concrete examples will be cited and their solutions discussed. Before doing this, however, we believe it well to call attention to the fact that the successful design of remedial measures necessitates an exact knowledge, on the part of the engineer, of many details of the particular case. Not only must he be thoroughly conversant with the telephone circuits involved, but he must also be conversant with the characteristics of the power system involved. It is highly desirable that a personal inspection be made and copious notes taken in order that all practical difficulties be observed in advance of the design of remedial measures. That it is not possible for the engineer to personally inspect every case is recognized, hence the data must ofttimes be collected by some other person, and it is, therefore, necessary that a procedure be devised for presenting an accurate and detailed report to the engineer for his guidance.

Through the courtesy of The Pacific Telephone and Telegraph Company, we present in Appendix I of this paper the pertinent part of an engineering circular, describing a procedure for surveying a case of parallelism and for transmitting an accurate account of the essential facts, which we have found exceedingly satisfactory.

In the examples which follow, the symbolic representations described in Appendix I are used, and the reader is referred to this Appendix for their explanation.

The foregoing text has emphasized the fact that the severity of requirements of transpositions and balance which must be imposed on the circuits in a parallel depends largely on the wave shape of the generating apparatus as well as on the fundamental frequency of the power system and on other local conditions. This fact has been taken into account in the examples given below. In cases II and III the number of transpositions in the power circuits is less than would in many cases give satisfactory results, but case II represents an arrangement which was applied with success, and case III, one which it seems reasonable to install, in a particular case which has arisen.

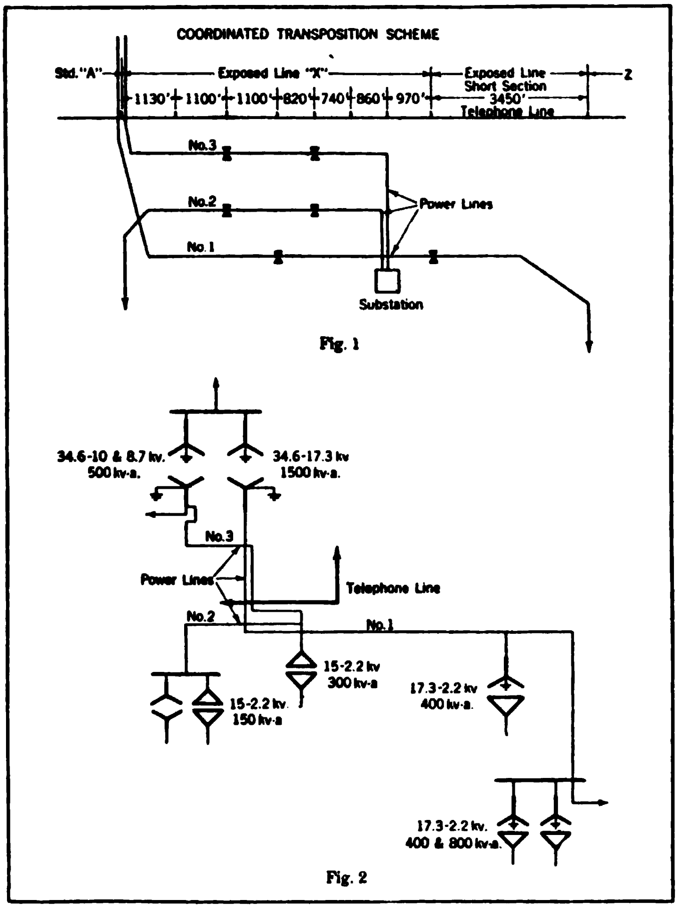
Case I

Case I presents an example of a uniform parallel involving three power circuits (see illustration) whose parallelism is coincident for a little over half of the total parallel. The case was presented for solution as a practical problem in the field, and the remedial measures to be described have been installed in part and found effective. The details of the parallel and characteristics of the power lines and telephone system are as follows:

Power Systems No. 1. 30,000 volts, three-phase, 50 cycles, vertical configuration; tower construction; star-star connected and star-delta connected transformer banks employing a ground connection. No transpositions.

No. 2. 15,000 volts, three-phase, 50 cycles. Flat configuration; pole construction; star-star connected transformer bank supply with grounded neutral and delta-delta and star-star (isolated neutrals) connected load banks. No transpositions.

No. 3. 15,000 volts, three-phase, 50 cycles. Triangular configuration; pole construction; star-star connected trans-



CASE I.

former bank supply with grounded neutral and delta-delta connected load banks. No transpositions.

Telephone System. High-grade loaded physical and phantom long distance circuits; ultimate capacity of lead 40 physical and 20 phantom circuits. Standard system of transpositions.

Parallel. 10,170 feet in length; separation of power and telephone leads: No. 1, 75 feet; No. 2, 49 feet; No. 3, 18 feet. Crossover at beginning of parallel circuits No. 1 and No. 3.

Co-ordinated Transposition Scheme. The variation in length of parallelism of the three power lines, different separations from the telephone line, difference in voltages, configuration and transformer connections as indicated above and on Case I, coupled with the added fact that the parallel is short and located in the middle of a telephone loading section which could not be disturbed as to length, makes this case a very interesting example of transposition-coordination and residual-mitigation.

Short transposition sections of the exposed-line type offer the most feasible solution and the coordination was accomplished as follows.

Considering power circuit No. 1, one barrel within the exposure was deemed sufficient to accomplish satisfactory longitudinal balance to the balanced voltages and currents. Hence the section of power line involved within the parallel is divided into three equal sections by the installation of transpositions therein at the towers adjacent to the one-third and two-thirds points.

Circuits No. 2 and No. 3 are operated in parallel and their exposures to the telephone line are coincident, hence accomplishing longitudinal balance by means of one barrel in each circuit within their exposure is feasible. Therefore, the length of parallel involving these circuits is divided into three equal sections by transpositions installed in the two power circuits at the one-third and two-thirds points.

Transverse balance to induction from both the balanced and residual voltages and currents is accomplished by using exposed line X sections of such length that their junction points fall opposite the power-circuit transpositions as depicted in Fig. 1 of Case I. From a point opposite the second transposition in power circuit No. 1 to the end of the parallel, a Y section is used since no discontinuities intervene to require shorter sections.

Mitigation of Residuals. The mitigation of residuals for this case brings out some interesting features. Considering Circuit No. 1 (see Fig. 2, Case I), a combination of star-star and star-delta connected transformer banks, with grounded neutrals is employed. As pointed out in a previous section of this paper, a condition is here established which is conducive to the passage of large triple-harmonic residual currents over the power line past the exposure with consequent heavy longitudinal induction on the telephone circuits. The obvious measure for reducing such effect was to remove the low-impedance path of such currents. Accordingly, it was suggested that the neutral on the low side of the star-star connected supply bank of transformers be ungrounded. This request was acceded to and the residual current was thereby reduced to a value small enough to have no appreciable inductive effect on the telephone circuits.

With the neutral of the No. 1 circuit supply bank grounded on the low-voltage side, some transient disturbances on the 60,000-volt line feeding the bank were transformed and caused severe trouble on the telephone circuits. The ungrounding of the neutral eliminated this trouble.

Circuits No. 2 and No. 3 are supplied from a star-star connected bank employing a grounded neutral, but all other transformers on the two lines are isolated. The star-connected supply bank has two taps on the low side so that power may be supplied at star voltages of 10,000 and 8,700 volts. From the 10,000-volt tap energy is supplied over a third circuit not involved in the parallel. Hence a shunt path is provided for the third-harmonic residuals, thus reducing the magnitude of such current in the line involved in the parallel. This condition, coupled with the fact that a high-impedance path is offered to residual currents via the earth due to the presence of a ground at but one end of the circuit, sufficiently reduces the magnitude of residual current in this short parallel so that its inductive effect can be tolerated.

Case II

Case II presents an example of a parallel with a power circuit employing a grounded neutral at one point only. (See illustration, Case II). It is of interest to state at the outset that this parallel is one which has recently been studied, the remedial measures outlined below installed in part and elaborate tests made to determine their efficacy. The details of the parallel and characteristics of power and telephone systems are as follows:

Power System. 60,000 volts, three-phase, 60 cycles, triangular configuration; 6-foot spacing; delta-delta connected transformer banks throughout the system with one exception; a star-connected bank with grounded neutral at one end of the line (see Case II.) Three existing transpositions; two within parallel and one outside.

Telephone System. One long-distance telephone circuit and several long suburban circuits. Standard system of transpositions.

Parallel. 75,090 feet in length; separation between power and telephone leads, 45 feet. Two crossovers, one of which is at the end of the parallel.

Co-ordinated Transposition Scheme. In this case a long uniform parallel is presented which offers an excellent opportunity for the use of the exposed line *A* section.

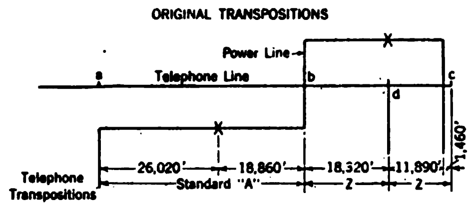


Fig. 1

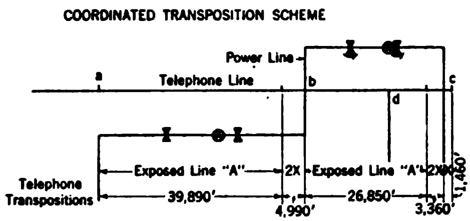


Fig. 2

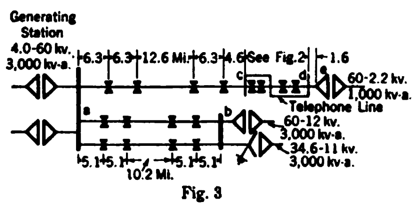


Fig. 3

CASE II.

The method was adopted of installing first a very small number of transpositions in the power circuit to determine the extent to which the induction was reduced. The design is such that additional power transpositions can be economically installed if later found desirable.

Referring to Fig. 2, Case II, beginning at point *a* (the commencement of parallelism) an exposed line *A* section is installed of such length that it occupies eight-ninths the total distance from point *a* to the crossover at point *b*. Thence, two *X* sections of equal length extend to the crossover point *b*. Transverse balance is obtained when the existing power transposition is removed. Longitudinal balance to induction from the balanced voltages and currents of the power system is accomplished by installing a barrel in the power circuit between points *a*, *b*, with two transpositions opposite the three-ninths and six-ninths points of the telephone transposition system.

From the crossover at point *b*, another exposed line *A* section is installed of such length that it occupies eight-ninths the total distance from point *b* to the end of the parallel at point *c*. Thence two *X* sections of equal lengths are installed, extending to the end of the parallel, at *c*.

Transverse balance is obtained when the existing power transposition in this section is removed. Longitudinal balance is obtained in the same manner as outlined for section *a*, *b*, but with reversed rotation of power transpositions, the purpose of which will be explained below.

Thus, coordination of the power and telephone systems is obtained within the parallel in so far as induction from balanced voltages and currents of the power system are concerned, and also transverse induction balance from the residual voltages and currents.

It will be noted by referring to Figs. 1 and 2 that a junction occurs in the telephone line at a point *d* which would ordinarily be treated as a point of discontinuity, and, therefore, balance to induction should be obtained on either side of it. In this case, such balance is unnecessary since the junction point shown represents a tap off the long distance circuit under consideration. Had one or more circuits branched from the lead or terminated at this point, the others running through, it would have been necessary to make the junction a neutral point and obtain balance independently on each side. This would probably have required the use of short sections in the telephone line and two additional transpositions in the power line.

Mitigation of Residuals. Due to the presence of the grounded-neutral bank at one station and the triangular configuration used in most of the system the effect of capacitance unbalance of the lines in causing residual voltage will be very small. Hence under the operating condition shown in Fig. 3 transpositions outside the parallel were not in this case necessary. The manner of locating such power transpositions for capacitance balance is however shown in Fig. 3. When the grounded-neutral bank is disconnected from the system there is a considerable residual voltage due to the vertical configuration of the two lines *a b*. The line *a e* being triangular has a much lower capacitance unbalance. Moreover the ultimate replacement of the grounded-neutral bank by a delta-delta bank is contemplated. An attendant advantage of transposing this line throughout its length is the improvement of the power-system telephone circuit which is located on the power-circuit poles.

In view of these considerations it was deemed desirable to rely upon the efficacy of the coordinated transposition system and balance of telephone circuits to avoid interference from the triple-harmonic residuals due to the grounded-star transformer bank.

The plan devised for obtaining an approximate capacitance balance is outlined below. If the transpositions according to this scheme prove to be insufficient others can economically be added.

Considering first the two power circuits *a b* (see Fig. 3 Case II) operating in parallel, two 15-mile barrels are installed in each line.

The section involving the parallel *c,d,* is already balanced by virtue of the two barrels installed to co-ordinate with the telephone transposition system and provide longitudinal induction balance within the parallel. Hence one section, *a,c,*and a second section on the other side of the parallel, *d,e,* remain unbalanced. In the section *a,c,* there is an existing transposition, to be retained if possible. Therefore, two barrels of unequal length were installed in the section *a,c,* utilizing in one of them the existing transposition; by reversal of the two transpositions within the section of parallel *b,c,* Fig. 2, the proper type of exposure occurs in the section *d,e,* Fig. 3, which, considered with the section from the existing transposition to point *c* makes up the deficiency in length of the barrel. Hence capacitance balance is obtained by the use of two 19-mile barrels, although using a detached section of power line for balance. This case again illustrates the use of the reversed rotation of power-circuit transpositions.

It may be stated in connection with this case that the transpositions for capacitance balance and reduction of residual voltage in the power system have not, as yet, been installed. The reason that they were not installed, is that under the present conditions of operation the coordinated transposition system within the parallel was determined by test to be sufficient to provide the requisite relief and that the longitudinal effect of the present existing residual currents and voltages was sufficiently small not to warrant greater refinement at this time.

Case III

In Case III (see illustration Case III) is given a typical example of parallelism between a telephone line and a power line operated isolated from ground. The details of this case are as follows:

Power System. 22,000 volts, three-phase, 60 cycles. All three conductors in same horizontal plane, spacings 35 and 65 inches. Delta-delta transformer connections at three stations. Three existing transpositions within the parallel.

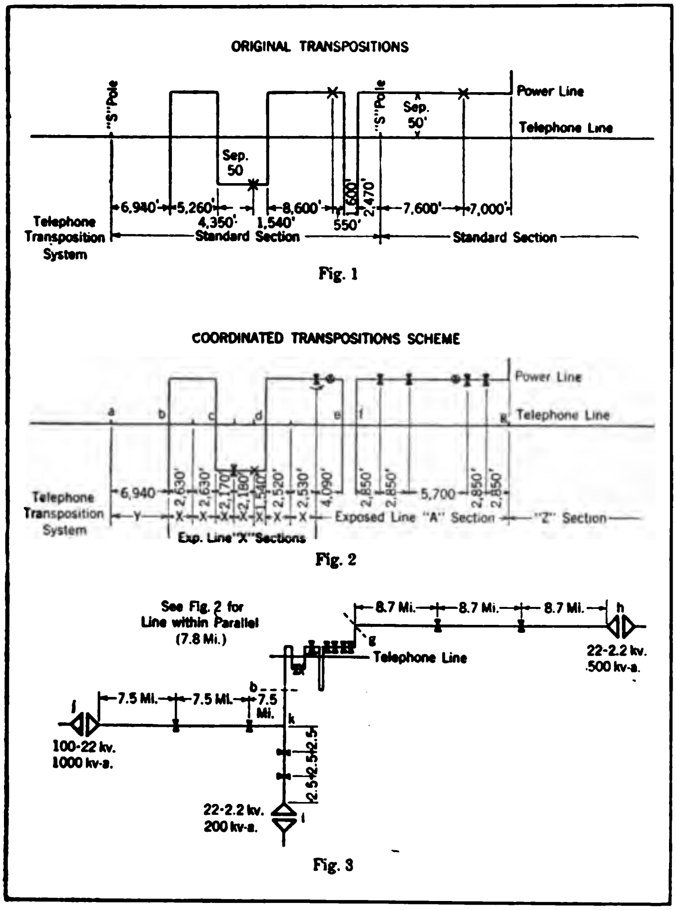
Telephone System. Long-distance telephone circuits; 10 physicals and four phantoms. Standard system of transposition.

Parallel. 38,970 feet in length; separation between power and telephone pole leads, 50 feet. Five crossovers.

Coordinated Transposition Scheme. Owing to the number of points of discontinuity in this case (crossovers) short telephone transposition sections (*X* sections) in combination with an *A* section, all of the exposed-line type, together with power-circuit transpositions as shown in Fig. 2 of Case III, give the best arrangement.

From the first neutral point of the telephone transposition system *a* (end of an existing section) adjacent to the beginning of the parallel, a *Y* section is installed, terminating at the first crossover *b* (beginning of the parallel). Thence, two exposed line *X* sections of equal length to the second crossover *c*, thus obtaining transverse induction balance of all telephone circuits in the section of parallel *b*,*c*, from both the balanced and residual currents and voltages of the power system. From the second crossover *c* to the third crossover *d*, three *X* sections are installed two of which are of equal length inserted between the crossover and the existing transposition in the power circuit. A transposition is installed in the power circuit opposite the junction point of the first two *X* sections. Transverse balance and approximate longitudinal balance to induction are accomplished by this arrangement in section *c*,*d*. If the existing transposition in the power circuit had been at one of the third-points of $c\,d$, exact longitudinal balance would have been obtained. It will be seen that here a sacrifice in longitudinal balance was made in order to retain an existing power transposition.

From the third crossover d to point g, the end of the parallel,



CASE III.

two X sections and one A section are installed. The exposed line A section is of such length that the pole at two-eighths of its length falls at the crossover point f. The two X sections are installed between the point d and the first pole in the A section and are of equal length. A power circuit transposition of reversed rotation is installed opposite the junction of the *A* and *X* sections, thus giving in combination with the section *b,c*, approximate longitudinal balance in the total section *b,c*, and *d,e*. The existing power transposition in section *d,e*, is removed. Whole-line transpositions are installed in the *A* section between the one-eighth and two-eighth points in order to reduce the transverse unbalance incurred due to the interruption in parallel from *e,f*. Thus, transverse balance has been obtained in the section of parallel *d,e*.

In section *f, g*, power transpositions are installed opposite the three-eighth, four-eighth, six-eighth and seven-eighth points of the *A* section, thus accomplishing longitudinal and transverse balance to induction in this section. The existing power transposition in the section *f, g*, is removed.

It will be seen that a coordinated system of power and telephone transpositions has been applied which balances to both transverse and longitudinal induction from the balanced voltages and currents of the power system, and transverse induction from the residuals of the power system.

Mitigation of Residuals. Since in this case an isolated system is involved and the flat configuration causes a large residual voltage, the remedial measure required is transposition of the power circuit outside the parallel in such a manner as to balance the capacitance to ground of the several phases.

In order to determine how small a number of transpositions would give relief in this case, it is proposed to install very long barrels in the sections of power line beyond the exposure, as indicated in Fig. 3. These will not be entirely effective if high-frequency components in the power circuit are prominent. The method of laying out these transpositions is as follows:

The transpositions of the power circuit within the parallel for longitudinal induction balance from the balanced voltages and currents also provide capacitance balance for this section of power line. It remains to transpose the section of line outside the parallel so that capacitance balance is obtained throughout.

In the section between one limit of the parallel *g* and the substation *h* (26 miles), one barrel is cut in the power line by installing two transpositions of normal rotation at the one-third and two-third points.

In the section between the other limit of the parallel *b* and substation *j* (22.5 miles), a barrel is cut in the power line by installing two transpositions of normal rotation at the one-hird and two third points.

The section from the power line junction point *k* to substation *i* (7.5 miles) is cared for in a like manner.

Thus, in each of the four sections cited, capacitance balance is obtained. Attention is called to the manner in which the practical considerations such as length of line and location of discontinuities arbitrarily determine the length (maximum) of power circuit barrel both from the standpoint of coordination of transpositions and measures for capacitance balance.

This case is one which was presented for solution in the field. However, for the purpose of simplifying the discussion, the extent of power system beyond either end of the parallel has been greatly reduced.

The above cases, it is thought, will serve to give a general idea of the practical methods pursued in the field for the solution of inductive interference problems. It must be remembered that the remedial measures set forth in the above cases are not necessarily applicable to other cases, and that each case requires a consideration of its particular conditions in order that adequate remedial measures may be provided.

In conclusion, we can say with conviction, based upon the facts cited in this paper and our actual experience, that the general problem of inductive interference involving three-phase circuits, while seemingly difficult of solution, is in fact, when fairly and reasonably approached, usually simple and inexpensive. The remedial measures employed, when properly designed and installed, are very effective. It is true that occasionally a problem will arise, the solution for which will impose some burden on one or both interests involved. When such a problem does arise, it is capable of solution only through a broad co-operative spirit between the two parties and their mutual willingness to bear such burden for the welfare of the community.

APPENDIX I

DATA REQUIRED IN CASES OF PARALLELISM

TO FACILITATE THE DETERMINATION OF REMEDIAL MEASURES FOR THE MITIGATION OF INDUCTIVE INTERFERENCE

The severity of the inductive interference with telephone service caused by any given parallel is dependent upon the physical characteristics of the parallel, the electrical characteristics and method of operation of the power system, and the condition of the telephone circuits. The following pages describe the data necessary for a study of a parallel to devise means for the prevention or reduction of inductive interference arising therefrom. In order that the best results may be secured, the instructions given herein concerning the preparation of the report transmitting the required data should be very carefully followed.

In the case of a proposed parallel, or general reconstruction of an existing parallel, a study shall be made to determine whether or not other routes are available, for either the telephone or power lines involved, which will avoid the parallel. A report on possible alternatives shall be presented in connection with the transmittal of other data concerning the parallel.

The forms and instruction of this circular have been devised to facilitate a complete report on parallels already in existence; the same general plan can be followed, however, for proposed parallels.

If any of the data are doubtful the best obtainable information shall be given and its degree of reliability stated.

A—Telephone and Power Line Data. A form for reporting the data regarding the power and telephone line is given. The form should be typed or mimeographed as convenience dictates. It is self-explanatory as to information required.

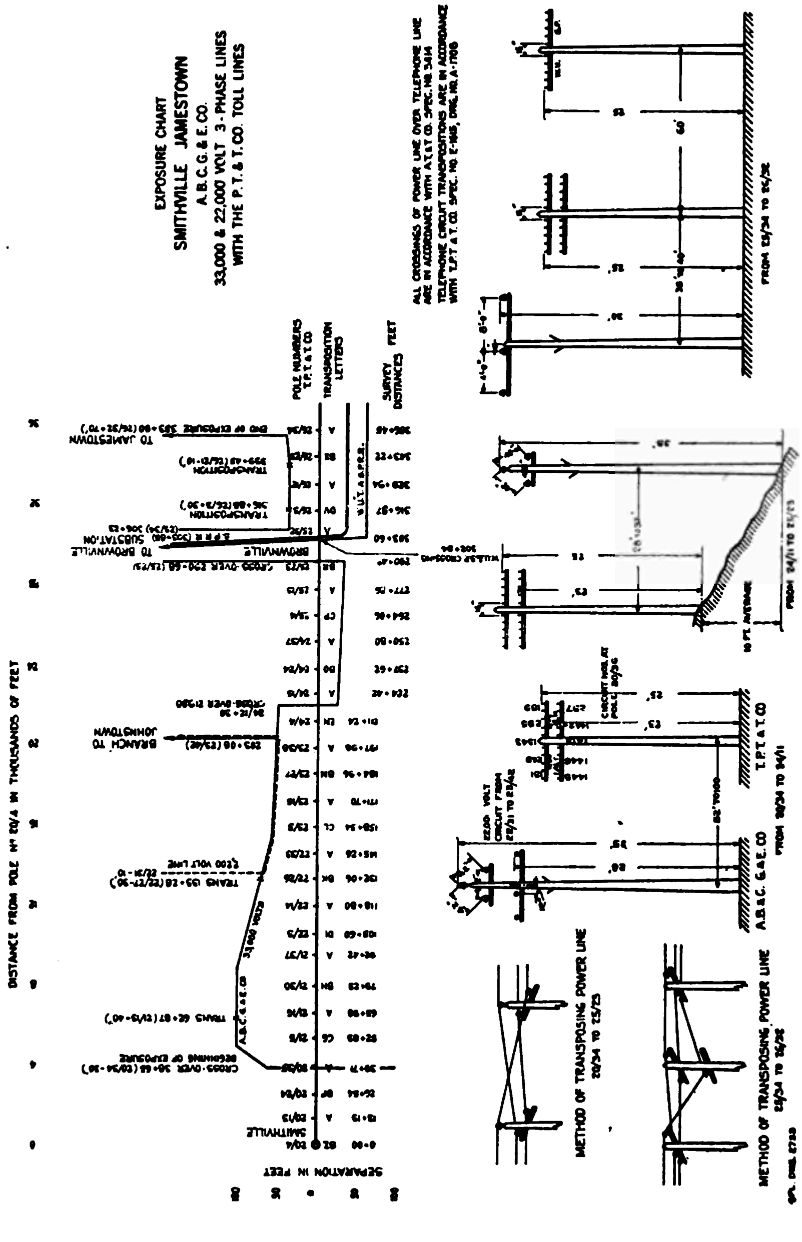
B—Exposure Chart. The telephone pole line involved in a parallel shall be plotted as a *straight line,* from left to right in the direction of transposition. The scale should be 4000 feet per inch, or 2000 feet per inch for short parallels and any case where complications render a smaller scale undesirable.

The power line *and all arc circuits, distribution circuits of* 2200 *volts or over, telephone, telegraph and signaling lines of other companies,* shall be plotted so as to indicate continuously along the telephone line the horizontal separation between the telephone pole line and the pole or tower lines supporting such other circuits. *These are to be plotted only within the exposure to the high-voltage power line.*

The scale for plotting separation will depend on the average separation; 50 feet per inch is usually convenient. The accompanying exposure chart, shows an example of a parallel and how the chart is to be plotted.

Distances measured along the telephone line from a given reference point, (and corresponding telephone pole numbers) shall be shown for:

a. Each telephone transposition pole, with transposition lettering.


EXPOSURE CHART
SMITHVILLE JAMESTOWN
A.B.C.G.& E.CO.
33,000 & 22,000 VOLT 3-PHASE LINES
WITH THE P.T.& T.CO. TOLL LINES
DISTANCE FROM POLE No 20/4 IN THOUSANDS OF FEET
SEPARATION IN FEET
METHOD OF TRANSPOSING POWER LINE
METHOD OF TRANSPOSING POWER LINE

b. Loading points.

c. Beginnings and ends of parallels.

d. Points where power lines cross over telephone lines.

e. Points where abrupt changes in separation occur.

f. Points where changes in configuration of power or telephone circuits occur.

g. Location of bridged stations and sections of cable in the telephone line.

h. Power-circuit transpositions.

i. Points where load or feeder branches connect with power line.

j. Places where there are spans of excessive length; river crossings, R. R. crossings, etc.

k. Each tower in case power circuit is supported on towers.

The chart shall contain as many sketches of the cross-section of the exposure as are needed to show the several types of construction, configuration and relative location of lines. A note under these shall specify the point at which each type begins and ends. These diagrams should show:

a. Average pole or tower heights.

b. Difference in elevation of ground under the two lines.

c. Dimensions to locate points of support and spacing of all wires on poles or towers.

d. Traffic numbers of telephone circuits with the number of the pole to which they apply.

A sketch shall be given showing the method employed in transposing the power line and number of poles involved in a transposition.

If special construction is employed at power line crossings, the details shall be given in the report.

Any special construction in the telephone line, such as at river crossing, shall be described in the report.

The chart shall contain a title including the number of the parallel, location, companies involved, voltage of power lines, and date.

The survey of the telephone line shall determine the location of telephone transposition poles, crossovers, power-circuit transposition poles, and other features to at least the nearest 10 feet. This distance should be the "wire distance", where obtainable from the records.

Horizontal separation of pole lines shall be measured within 2½ per cent (thus, where the separation is 20 feet, it shall be obtained to the nearest foot, if 100 feet, to the nearest five feet). The heights of wires above the ground shall be given to the nearest foot. The horizontal and vertical distances between wires of a power circuit and wire spacing on the telephone line shall be given to the nearest inch.

Many minor irregularities must be neglected, but the purpose should be to present the average conditions as faithfully as practicable, and to give data of all pronounced changes in the character of construction.

C—Circuit Diagram of Power System. Much of the required information concerning the power circuit can be shown diagrammatically as indicated in accompanying illustration. This diagram shall show:

a. All lines or apparatus *metallically* connected to the power circuits involved. Auto-transformers constitute metallic connections between lines of different voltages, hence the circuit diagram should not terminate in such transformers. Lines or apparatus which are connected to the circuit involved in the parallel by two-coil transformers are not required to be shown.

b. Method of connection of both primary and secondary sides of all transformer banks connected to the circuits. Indicate particularly the condition of all neutrals, whether grounded or not. Where single-phase, open delta or Scott connections occur, the particular phase, to which each wire is connected shall be shown.

c. Type and location of air and oil switches.

d. Type, location and connections of lightning arresters.

e. Location and ratio of potential and current transformers; location and range of ammeters in neutral ground connections.

f. Transpositions in the power circuits.

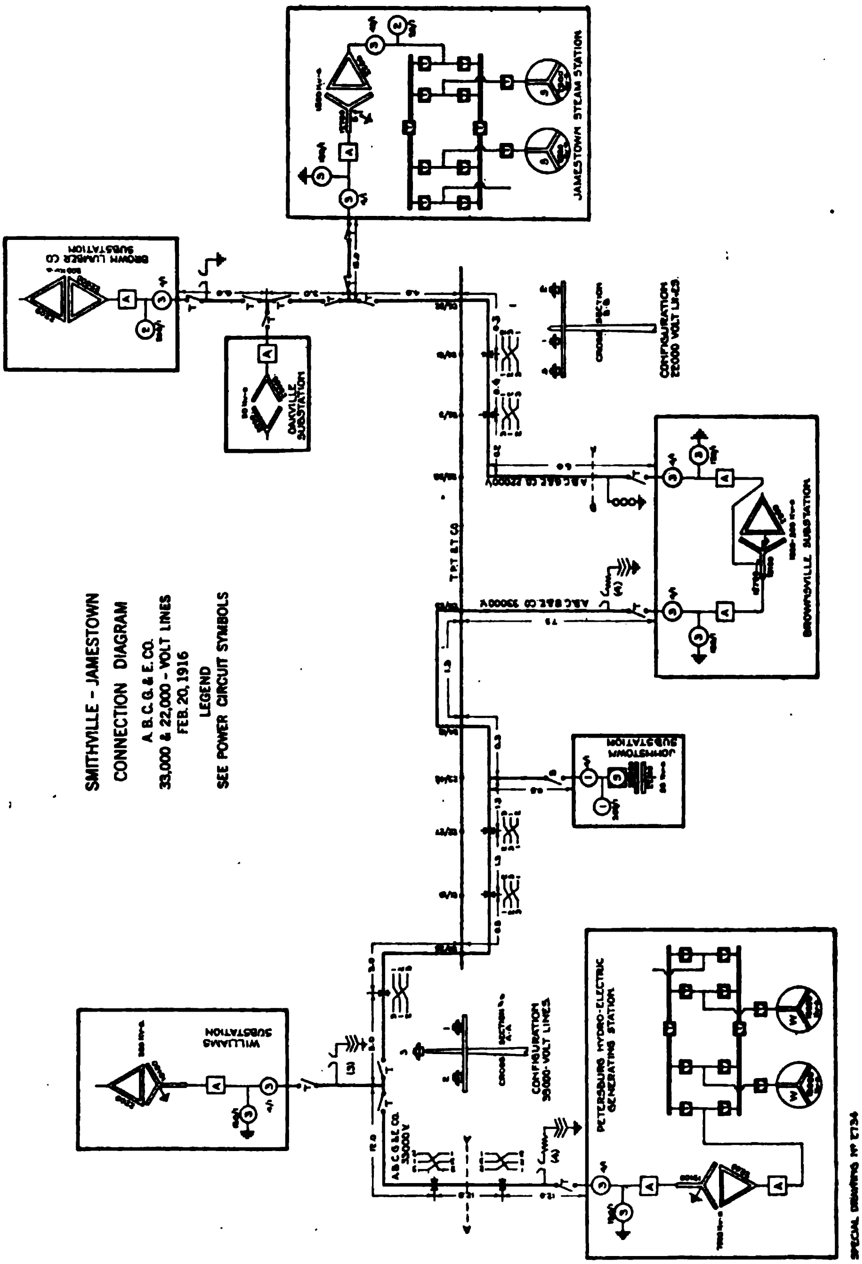
g. The length of power circuit between all points of importance, such as stations, branch points, transposition points, and points where configuration changes, to the nearest 0.1 mile.

h. Voltages and capacities of transformers or other apparatus connected to the circuit.

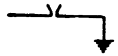
i. A cross-section of the power circuit at some one point with the conductors numbered to show their respective positions. If there are two or more circuits, the wires composing each shall be designated.

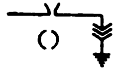
The title should include name of power company, number of the parallel, location, voltage of power circuits, date and legend.

A list of symbols for use in making up power-circuit connection

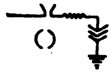

SMITHVILLE - JAMESTOWN
CONNECTION DIAGRAM
A.B.C.G.& E.CO.
33,000 & 22,000 - VOLT LINES
FEB. 20, 1916
LEGEND
SEE POWER CIRCUIT SYMBOLS
JAMESTOWN STEAM STATION
BROWN LUMBER CO SUBSTATION
OAKVILLE SUBSTATION
BROWNSVILLE SUBSTATION
JOHNSTOWN SUBSTATION
WILLIAMS SUBSTATION
PETERSBURG HYDRO-ELECTRIC GENERATING STATION
CONFIGURATION 22000 VOLT LINES
CONFIGURATION 33000-VOLT LINES
T.P.T. & T. CO.

SYMBOLS—Power Circuits—E. C. 134

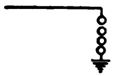

Horn-gap lightning arrester.

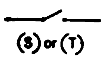


Aluminum-cell lightning arrester state in parentheses the number of units.

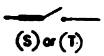


Same as above except with charging resistances.


Multigap lightning arrester.



Air Switch S-single poles independently operated. T-three pole interconnected.



Same as above with the addition of fuses.

Oil switch automatic all poles mechanically interconnected.

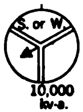
Oil switch non-automatic all poles mechanically interconnected Use "S" in place of "T" if poles are not interconnected.

Current transformers place figure inside circle indicating number of units.

Potential transformers connected between phases. Place figure inside circle indicating number of units.

Same as above—connected between phases and ground.

Generator—three-phase delta-connected 7500-kv-a. S-steam driven W-water wheel driven



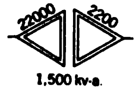
Generator—three-phase star-connected, neutral grounded, (if neutral is isolated omit indication of ground) 10,000 kv-a. (S and W same as above.)


Miscellaneous apparatus write description in rectangle or reference to descriptive note.

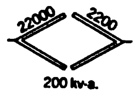
Transformer—single-phase connection 22,000/2200 volts 50 kv-a.


Power circuit transposition.

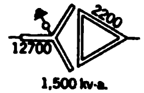
Transformers. Unless otherwise stated on the connection diagram single-phase units are assumed.



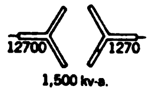
Delta-delta connection 22,000/2200 volts, 1500 kv-a. per unit.



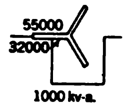
Open-delta connection 22,000/2200 volts, 200 kv-a. per unit.



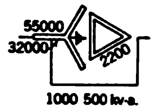
Star-delta connection neutral grounded, ammeter in neutral 12,700/2200 volts, 150 kv-a. per unit.



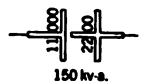
Star-star connection neutral isolated 12,700/1270 volts, 1500 kv-a. per unit.



Star-connected auto-transformers neutral isolated. 55,000/32,000 volts. 1000 k-va. per unit.



Star-connected auto transformers neutral grounded, 55,000/32,000 volts, 1000 kv-a. per unit. Tertiary delta 2200 volts, 500 kv-a. per unit.



Scott-connection 2 to 3 phase 2200/11,000 volts, 150 kv-a. per unit.

Note—Other transformer connections should be indicated in an analogous manner.

diagrams, in the manner shown in the illustration, is given herewith.

D. General Route-Map. The power and telephone lines shall be plotted on a map whose scale may be several miles per inch. Where available, the U. S. Geological Survey topographical maps are very convenient for this purpose. The toll route-maps of the telephone company can sometimes be advantageously used as a basis. The telephone line shall be indicated as far as the adjacent *S* poles outside of the parallel. The power circuit and substations shall be shown to an extent corresponding to the diagram of connections. In case the extent of the power system makes this impractical, a separate geographical map of the system shall, if possible, be obtained from the power company. Possible routes for either line to avoid the parallel shall also be indicated on this map.

DATA CONCERNING TELEPHONE AND POWER LINES INVOLVED IN A PARALLEL

....Division Parallel No.......

....191........

I. General

1. Location of parallel...
   (Between what towns?) (State)
2. Length, along telephone line..miles.
   (distance between limits)
3. Name of power company...
4. Number of power circuits...
5. Is the parallel existent or proposed?..
6. Which is the senior company?...

II. Telephone Line

1. If parallel is existent, state in detail the nature of the observed trouble...
   ....
2. What other parallels are there involving these telephone lines?
   ....
3. Is there trouble from secondary induction?......................................
4. State the present physical condition of the telephone line. How soon will it require general reconstruction? ....
   ....
5. Insulation of telephone circuits
   Relative noise on telephone circuits

Circuit No.	Insulation-Megohms per mile Tip	Ring	Mutual	Relative* Noise %
....	....	....	....	....

*Estimate noise in per cent of noise on noisest circuit rated at 100 per cent.

6. What is the ultimate capacity of the telephone line?

....

7. State specification and drawing numbers of telephone transposition system..

....

8. If any circuits are loaded, state the location of loading points, give pole numbers within the parallel and at the adjacent loading points outside of the exposure, and state whether or not loading point is an **H** fixture..

....

9. What types of insulators are used on the telephone line?..........

....

What types of insulators are used at loading points?..............

....

10. If the apparatus connected to any circuit is not standard T. P. T. & T. Co. equipment, describe it..................................

....

11. State location of any points within the parallel at which circuits enter cable (*e.g.*, river-crossings). Give specification number of cable..

....

12. Do any circuits branch from the telephone line within the exposure? If so, state traffic numbers and points of branching. If local circuits are also involved in the parallel, give their points of branching..

....

13. Telephone Circuits involved in the Parallel

Traffic No.	Physical or phantom	Size & material of wire	Loaded or non-loaded	Terminals
....	....	....	....	....

14. Describe special construction in telephone line at river crossings, etc..

....

15. State any other pertinent information.......................................

....

III. Power Circuit No..............................*)

1. Voltage..

(actual operating voltage between wires)

2. Number of phases...................., Frequency................cycles per sec.
3. Power circuit supplied from.......................................Station.....
4. Power circuit supplies energy to..

....

5. Character of load, motor, lighting or both.................................

....

6. Average current per phase...amperes.
7. Average daily maximum current...................................amperes.

*If there are two or more power circuits they should be reported separately and every sheet marked to indicate (by number) the particular circuit reported thereon.

8. Hour at which peak load occurs..
9. If the neutral points are grounded, are there ammeters in the neutral connections?..
10. State their range..
11. Are they connected directly or through current transformers?
....
12. Give ratio of transformation..
....
What is the average neutral current?........................amperes.
13. Size of conductors..ga.
Material of conductors..
14. In case the power line is existent, state its present physical condition. How soon will it require general reconstruction?
....
15. Type of insulators..
Are the insulator pins grounded?..
If suspension insulators, state number of discs..........................
16. Lightning arresters.

Location	Type	Connections	Frequency and time of day of charging	Charging current-amperes per phase
....	....	....	....	....

What is the method of charging?..
....
17. Switches

Location	Type	Mechanically interconnected for simultaneous action?	What devices are there for automatic operation of switches?
....	....	....	....

18. Transformers

Location	No. of units	Mfr.	Kv-a. rating	Voltage rating	Form No. etc.	Single or three-phase	If three-phase, shell or core type
....	....	....	....	....	....	....	....

19. Rotating apparatus. If generators, motors or converters, etc., are metallically connected to a circuit involved in a parallel or if such circuit connects directly to a generating station, give data as to

Kind of Apparatus	Location	No. of units	Mfr.	Type	Kv-a. rating	Voltage rating	Electrical connection
....	....	....	....	....	....	....	....

20. State other pertinent information..
....

DISCUSSION ON "INDUCTIVE INTERFERENCE AS A PRACTICAL PROBLEM" (GRISWOLD AND MASTICK), SEATTLE, WASH., SEPTEMBER 6, 1916.

Frederick Bedell: Remedial measures for inductive disturbances are necessary because we do not have perfect telephone circuits, nor perfect power circuits, nor perfect power generators. By improving the wave-form of the power generators—that is, by making the wave-form more nearly a pure sine wave—inductive disturbance and the necessity of remedial measures can be reduced, as is pointed out in the paper; but in all probability the best that can be done in the design of machinery, without prohibitive expense, will only reduce, but not eliminate the disturbance. The problem of remedial measures will still remain, but it will be an easier problem. A standard of wave-form, in this connection, is seen to be desirable.

L. T. Merwin: The authors' paper presents one consistent scheme only for overcoming the troubles of inductive interference Unquestionably, the telephone companies have made elaborate experiments as to the possibility of developing other means of overcoming the troubles. So far as I know, the power companies have done little or nothing along this line. It would be extremely interesting to us, as power men, to know what other remedial measures were tried, and, if tried, why they were abandoned. I would like to ask Mr. Mastick if the telephone companies have tried, for instance a scheme that appears to me to have some value, and, if they have, what were the results: For example, is it possible to so modify the Thompson system of telephone line loading with inductive shunts, that those shunts instead of giving a straight line function, for the *j* component of the impedance which would be obtained with inductive character only—would give an approximate straight line function for all frequencies above, for instance, the 5th or the 7th harmonic of a 60-cycle system, and a sharply divergent or logarithmic function for all frequencies below? In other words, that the shunts would perform two functions, namely, that of providing a short-circuit path for low frequencies; and, on the other hand, perform the same service as the inductive shunts of the Thompson system of loading for the higher frequencies, namely, that of producing a distortionless line—laying aside the matter of attenuation for the present—for frequencies within the usual range of voice currents, but producing short-circuit paths for these troublesome 3d, 7th and 9th harmonics of the 60-cycle system. Have the telephone companies experimented with series impedances in their lines of such a nature that the series impedances if judiciously placed, would produce a high resultant impedance for all low frequencies, and yet produce a straight line function of the Pupin type of loading for all frequencies say from the 9th harmonic of the 60-cycle system up through the range of the voice frequencies? If methods of this sort, or of any similar sort have been tried, it would be extremely interesting to us to know what were the difficulties encountered, and why they were abandoned. Any scheme of transposition, that is laid out, involves the expenditure of money, and it is only natural that when the power companies, themselves, are only concerned, in so far as the reaction of the trouble may lead to force expenditure, it is only right, I say, that we should ask of those who are fitted to answer—the telephone engineers themselves—as to the possibilities of other methods of overcoming the troubles.

J. B. Fisken: Two years ago the power engineers were pretty much alarmed at what they learned regarding the California order, and it looked as if we might possibly have to go into the hands of receivers or go out of business. It does not look as bad to me now as it did then. It looks as if a good many cases could be taken care of without prohibitory expense. One question I want to ask Mr. Mastick is whether I am right in supposing that the flat construction of a line is more detrimental, in that it produces more residual voltages than the triangular construction? I have had some experience with a line of flat construction 65 miles in length, and this line was built to avoid, as far as possible, paralleling the telephone toll lines, although, to some extent, it does parallel them, and we had nothing brought to our attention to lead us to believe that the flat construction was objectionable. Of course, it is transposed, just the same as a triangular construction, and we have had nothing to indicate that the residuals are serious on that line. It begins to look as if we had to take care of two features of construction, or, rather, one feature of construction and one feature of design of apparatus; the feature of construction being the location of transpositions, which, to my mind, unless our telephone friends insist on putting them in too frequently, are not objectionable; and the other of getting rid of the higher frequencies, which, I think, are just about as objectionable to the power men as they are to telephone engineers.

W. D. Peaslee: There is another feature that has not been mentioned in the paper, that is of considerable importance, I think, in the interference of a power line with a telephone line, and that is the effect of the continual corona discharge on a defective insulator, and also the effect, which I have seen on a great many of the lines, in the northwest, especially when they have taken to grounding the insulator pins on wooden poles. On a great many of those lines, you will see the ground wire connection to the insulator pin, loose, and at night, you will see a continuous discharge from the line into the condenser of the insulator from this loose connection. In a short study of that, I took an insulator—a standard, 60,000-volt, pin-type insulator—and putting on an artificial line with loose connection to a pin of that nature, with an ordinary coil of wire containing 300 feet and a telephone receiver, I have succeeded in getting considerable disturbance into the coil of wire. I would like to know if Mr. Mastick has encountered any situation of that kind, wherein the transmission of such disturbance on the transmission line into the telephone circuit occurs. Being of high frequency, and oscillatory in character, it would be a very difficult thing to get rid of, and also, a defective insulator, always produces a high-frequency discharge or oscillation in the power line. These discharges are very troublesome to the power people, and I would like to know in that connection, also, if interference has been encountered with this static inductance, with these ground connections showing up in the telephone line, either as a bat in the telephone receiver, or as a continuous high-frequency disturbance.

R. F. Robinson: In answer to that last question, I had something to do a few years ago with a line, where there was a great deal of trouble with the charging of the electrolytic lightning arresters. We made some tests with the power man, and had him vary the way in which he charged the arrester. He drew, for instance a very short, quick arc, that made very much less disturbance in the telephone line that when he drew out a long arc and held it for a long time. In drawing that long arc, it seemed to put the telephone line out of business all the time that the arc was held. The results on that line on account of the trouble were rather serious. There had been two or three cases of persons being injured while using the telephone line at the time the charging operation was taking place. In one case, a lady who was using the public telephone in a booth, was rendered unconscious during the time of this electrolytic charging. The answer seems to be indicated in this paper, that it is a matter for co-operation of the telephone companies and the power companies. The telephone people have probably done more studying on these questions, and in many cases, they have come to the conclusion, "Well, it is up to the power people. We can't do anything more." The power people on the other hand, say "It is not our trouble. Let us leave it .to the telephone people. They have got to figure out some way to get around it." But this paper very clearly indicates, I think, that it is impossible for either the telephone companies or the power companies to do all the work to overcome this induction trouble, but they must work together, and design the necessary means to get around the trouble at the least expense to both companies. Apparently, that consideration was one of importance in designing these transpositions which have been brought out here—that neither the telephone nor the power company should be put to any unnecessary expense or any unnecessary work on their lines, which could be avoided by co-operation on the part of the other company.

L. J. Corbett: Two years ago the investigations on inductive interference had just been started and a working rule was inaugurated and adopted in California. Only the simplest circuits, if I remember rightly, were taken up. At the present time, we have a great many different types of lines and interference cases analyzed. In time I presume all possible cases will be worked out, or we will be able to analyze all cases as combinations of certain cases which can be classified properly. I wish to call up the matter of the transmission line which crosses the telephone line at an angle of 20 degrees. I would like to ask Mr. Mastick if any investigations have been made upon such cases, because it seems to me that the effect would be greatest at the point where the line crosses, and as the departure becomes greater and greater, the influence, of course, would become less and less. In that case the interference would not be a true cosine function. I would like to ask also if they have investigated cases containing phantom circuits as applied to these schemes. That undoubtedly will have to be taken up, and I presume that in some of these complicated cases the addition of phantom circuits will complicate the matter even more, where a great many lines cross the power line.

C. A. Whipple: I have had occasion to investigate a number of cases of telephone troubles in connection with their proximity to power lines, and in all cases, I have found that the difficulties arising from the application of these rules, as set forth in the paper, have arisen from one of two conditions: Either the construction of the transpositions was not done in accordance with the instructions of the engineers, or there were defective insulators or other apparatus which caused these difficulties. In many cases the engineers relied upon those in the field to accurately place the transpositions where indicated. Investigation showed that in almost all cases the field work inaccurately done, sometimes the transposition points being but a few feet off, but the accumulation of a few feet on various sections of transposition lengths was cumulative, thus making quite a distinct disturbance upon the telephone line as a whole. In other cases, the discharge from defective insulators or the static effect of other apparatus in the near vicinity produced the effect upon the telephone system. These defects threw considerable disrepute upon the method. But it was not the method that was at fault, it was the execution of the method in the field.

J. B. Fisken: Mr. Mastick in his paper recommends that the neutral grounds be applied only at the power stations and important switching stations. Apart, altogether, from the question of inductive interference, I thoroughly approve of that recommendation. I have had some experience both ways. When we first installed our 60,000-volt distribution line, we grounded the neutrals of all our transformers, but after a few years experience with that method, we removed those grounds except at the power stations just as fast as we could. There was one experience we had, where a line switch was dead-ended, on insulators with very short connections, with solid wire to the switch itself. One of those connections broke, and before we found it the railroad in that vicinity was operating trains with flag signals; they had no apparatus left; and the telephones, of course were entirely out of business. It took us some time to find the break, because it was only about half an inch, and could hardly be seen from the ground. We found it by repeated experiments in trying the line and finally one man saw a flash, examined it, and found the wire broken. In many cases, the transformer itself does not give an absolutely true neutral, and if the transformers have neutrals grounded all over, there will be a slight interchange of current between them, which is not serious from the power man's standpoint, but I conceive might be quite serious from the telephone man's standpoint.

L. T. Merwin: If the telephone companies have experimented along other lines of remedial measures, as suggested in my previous remarks, I would like to ask, if a distortionless line was obtained at the expense of great attenuation, what percentage attenuation would be considered the limit that could be utilized and yet be not objectionable, by reason of modern methods of amplification in use by the telephone companies, either mechanical or of the audion bulb type.

R. W. Mastick: It seems desirable before replying to specific questions to discuss briefly the subject of "Noise" in telephone circuits which are exposed to high-tension power circuits, since in the main the discussions have borne directly on the elimination of noise by means other than those described in the paper.

The noise induced in a telephone circuit by the paralleling power circuit is usually due to several currents of various frequencies, viz., the fundamental, third, fifth, seventh, ninth, etc., harmonics. The fundamental is, however, from the standpoint of noise production, practically unimportant as compared with currents of higher frequencies. Analyses of noise currents have indicated the presence of frequencies from 50 cycles up to 2000 cycles and more.

The telephone speech current is of a very complex character, being a combination of a large number of waves of different frequencies, of which the most important waves lie within the range of the noise-current frequencies, that is, between 200 and 2000 cycles.

The detrimental effect of noise currents on telephone conversations increases very rapidly with the frequency up to a point near 800 cycles (which represents roughly the average frequency of voice currents and at which point therefore telephone apparatus is of maximum sensitiveness). For higher frequencies, the effect is gradually reduced. Since the frequencies present in noise are also those present in speech within the most important range of the latter, it can be seen that the application of a device in the telephone circuit whose successful action is based on the short-circuiting of the noise currents to the exclusion of speech currents is not generally feasible.

Mr. Merwin has suggested the possibility of modifying the Thompson shunt method of loading so as to short-circuit the noise currents below a certain frequency, and yet obtain the advantages of loading for all higher frequencies. The studies of this method of loading by telephone engineers have shown it to be generally unsatisfactory, because it is not possible to obtain sensibly uniform attenuation of all frequencies within the range of speech. In other words, the Thompson method of loading is inherently inefficient except for a small range of frequencies near the particular frequency of maximum efficiency for which the loading is designed. This method has also the disadvantage that it is not adapted to the use of superimposed telegraph on the telephone circuit, which practise is used to a large extent by the telephone companies.

The application of series impedances that Mr. Merwin has mentioned, is, of course, the principle of the present method of telephone circuit loading. Such arrangement gives a sensibly uniform attenuation of all frequencies up to a frequency determined by the coil design and spacing. Above this frequency which is always the upper limit of voice frequencies, the attenuation rapidly increases. Hence it is not possible to use this system of loading to exclude the lower frequencies in the range of noise currents.

Commenting further on both of Mr. Merwin's suggestions, it should be pointed out that it is not sufficient to exclude the noise frequencies below the ninth harmonic, but also those above must be eliminated since the detrimental effect of higher frequencies particularly in the vicinity of 800 cycles is far greater than the low frequencies. The 11th, 13th, 15th and 17th harmonics occur in present-day power-circuit waves in sufficient amount to require serious consideration in any attempt to mitigate inductive interference.

Configuration of the power circuit and its bearing on magnitude of induction and the residual voltage of an isolated system as mentioned by Mr. Fisken are of great importance. Studies have shown that the residual voltage of triangular lines is less than that of horizontal or vertical lines and that the horizontal configuration with unequal spacing of conductors is productive of the largest residual voltage found in practical cases. With respect to magnitude of induction from various configurations, the triangular configuration is generally to be preferred. However, the severity of the induction is governed by the relative location of the two lines with respect to separation, height of wires above ground, depth of ground plane for magnetic and electric phenomena, etc. For specific cases computations can be made which will indicate the best type of configuration to use.

The matter of discharges over defective insulators, mentioned by Mr. Peaselee, is a source of much concern to telephone companies. They are manifest in the telephone circuit as disagreeable cracklings, if intermittent, and in the event of total failure of the insulator, as very severe noises sufficient sometimes to temporarily deafen the telephone user. Total failure of an insulator generally creates a bad unbalance of the power circuit producing large residual voltages or currents which, of course, induce harmful voltages on paralleling telephone circuits. These induced voltages are frequently of sufficient magnitude to operate the telephone line protectors.

From the standpoint of inductive interference, angular crossings, as mentioned by Mr. Corbett if of fairly large angles, are usually not serious enough to require remedial measures. Some work of a mathematical nature has been carried out for a case in which a power line of high voltage crossed a telephone line at an angle of 30 degrees, and the results therefrom bear out the above assertion. However, if the angle of crossing is so small that quite an appreciable distance is required from the crossover to obtain a large separation between the two lines, some measures would generally be required.

Presented at the Pacific Coast Convention of the American Institute of Electrical Engineers, Seattle, Wash., September 6, 1916.

TESTING FOR DEFECTIVE INSULATORS ON HIGH-TENSION TRANSMISSION LINES

BY B. G. FLAHERTY

ABSTRACT OF PAPER

This paper discusses the importance and necessity of field tests on high-tension insulators and three methods of making such tests, viz.; with the oscillator, the megger, and the telephone receiver. The latter is described in detail, and some data given on its development and use on a 60,000-volt line in western Washington, covering a period of 2.5 years. Laboratory checks on 13 of the defective insulators located, are given, and an approximate relation established between the telephone receiver test and the break-down value at 60 cycles. Success of test is shown in note on its effect on operation.

Figures from regular routine tests show percentage defect on various lines, and cost of locating and replacing defective units is given at $1.13 each (labor only), and cost of testing only was 2.3 cents per insulator on the line.

A method of studying the rate of depreciation is outlined and some data given in illustration.

INTRODUCTION

MOST of the literature dealing with the failure of insulators on high-tension lines, treats almost entirely with the question from the point of view of improving the quality of the future insulator by various means of manufacturing improvements and specifications for testing before putting into use on the line. It does not deal to any considerable extent with methods of locating defective insulators among the great number already in service. While it may be admitted, without question, that the evolution of better insulation for future use is the most important need, the treatment and handling of the large quantity of insulators already installed should not be neglected. In fact this problem becomes the most serious one to the operating man, both from the standpoint of preserving the continuity of service, and of conserving as much as possible the large investment in the stock of the insulators in use.

Formerly, there was considerable discussion and argument about the depreciation of the porcelain in line insulators, though the majority of recent opinion seems to deny the depreciation *per se* and attributes failures after a period of service to various causes; such as inherent faults in the part as it comes from the firing, troubles due to improper cementing together of parts, or the use of cemented-in iron pins, causing unequal expansion. There is, however, no denial of the fact of deterioration of the insulator considered as a unit, *i.e.*, failure after a period of service. Undoubtedly a great deal can be, and has already been done to improve the quality of the porcelain; and by laboratory tests, to weed out the defective units in the process of manufacture and distribution. To this end the Transmission Committee has evolved the " Specifications for Insulator Testing ", dealing almost entirely with factory tests.

More important to the man now operating high-tension lines is some means of locating the defective insulators he already has on the line, thus affording him an opportunity to improve his factor of safety, and to preserve continuity of service, to which insulator failures have been in the past such a menace. Such a device, or devices, should be cheap, both as to first cost and as to methods of use; and should be reliable within practical limits. Too much expense either in first cost, or labor involved, could not be put into this class of work without approaching the point where it would be more economical to put in new insulation throughout. As yet, only three methods of testing insulators already in use on the line have been suggested; the oscillation transformer, the megger system, and the use directly of the telephone receiver.

The use of the oscillation transformer is recommended by Prof. E. E. F. Creighton and clearly outlined as to connections and adaptation in the TRANSACTIONS of the A. I. E. E. (Vol. XXXIII, 1914, p. 1122). The data given in the discussion indicate that it is very satisfactory as a high-frequency test and capable of being made very severe. Its availability and simplicity as a laboratory method for new insulators or those that have been removed from the line is evident; but its adaptability to service in the field is not so evident, presenting many difficulties. In the first place, in testing insulators on a line in actual service, it would be necessary to take the line out of service during the period of test; or to remove a quantity of insulators from the line, crate, transport, uncrate, test and replace on system, making the test prohibitive in cost. Also in attempting field work, a considerable crew would be required to handle and operate the apparatus and to make connections to each individual insulator, removing the line wire for the test. Another difficulty would be the source of current for the testing apparatus at all points of the line. These difficulties make the method impracticable for field work.

The megger test has become so commonly used throughout the country, especially on suspension insulator work, that it needs no description here. Mr. T. A. Worcester (*General Electric Review*, June, 1914, page 600) gives a thorough statement of the uses and limitations of this means of locating defective insulators. His main deduction is that it is not unconditionally reliable, being primarily a measure of the resistance, which may be practically "infinity" on a broken or punctured insulator unless contact is made directly with the defect and the latter is made conducting by the application of moisture. Another objection to the use of the megger for this purpose, is the necessity of "killing" the line under test for considerable periods and the use of a crew of men to make connections and remove the line wires from the insulators. It seems more particularly adaptable to testing the separate units of suspension-type insulators.

The use of the telephone receiver in the detection of defective insulators is mentioned by Mr. M. T. Crawford (TRANS. A.I.E.E., Vol. XXXIII, 1914, p. 1433), and it is with the development and use of this method that the present paper has to deal. Mr. P. H. Thomas (page 143, same volume) says, "We must find some way of detecting bad insulators. That can partly be done by tests, but we need a few new tests." If it can be shown that the test is reliable to a reasonable degree, it is evidently the most ideal method yet suggested, in that the actual testing can all be done by one lineman of reasonably good judgment and hearing, and also without any interference with the operation of the line, *i.e.*, the test is made at line voltage and frequency.

APPARATUS AND USE

The apparatus as developed for use on wooden poles is shown in Fig. 1. The double head set receiver is used to the best advantage as it aids in excluding foreign sounds, and focuses the observer's attention more closely on the work in hand. Almost any telephone receiver is found to be serviceable so that patrolmen in their routine work may use the receiver in the portable test set which they carry with them to locate the worst cases of defect. Where greater sensitiveness is required, the two thousand ohm wireless set shown in the illustration is found to give the best results, with the two units connected in parallel. The flexible cord used for connections is fastened by a small nut to the lineman's spur at one end, this serving as the ground terminal; and by a double connector to the large stiff wire run through the bamboo stick and sharpened to a point for contacting to the pole; *i.e.*, shunting a portion of the current flowing in the pole, through the receivers to ground. This, with the lineman's spurs and belt and proper notebook constitutes all the equipment necessary for locating defective insulators on pole lines using pin-type insulators. For use on steel tower lines using pin-type or suspension insulators the modifications are slight, looking more toward the safety and protection of the observer than anything else. The upper terminal is extended to a miniature wireless antennae, either in the form of radial spokes of a wheel, or a circular plate, and is used to explore the electrostatic field in the neighborhood of the insulator instead of measuring the actual current flowing over and through the insulator. Slightly greater sensitiveness is necessary for these cases and a higher resistance receiver with the units connected in series is recommended. The principal difficulty with this method is in protecting the operator from accidental contact with the high-tension wires. This is accomplished by covering the terminal with an inverted basket of wooden strips of dimensions sufficient to give proper clearance of four times the needle-gap spark value for line voltage to ground.

Two qualifications are necessary to the successful observer at this work; first, that he should be a good lineman, capable of going up and down, and working on the pole or tower near high-tension lines with quickness, steadiness, and assurance; and second, he should have good hearing. It is not especially important that he should be a technically trained man, although a little laboratory training and knowledge of electrical phenomena will help him considerably in the interpretations of the various sounds he will find throughout his experience of this work. The ordinary first class lineman of average intelligence can be taught by example to use the set and give a first rate judgment of defects indicated, in a few minutes time. Scientific truthfulness, *i.e.*, the faculty of setting down results as they actually come to him rather than as he believes he should get them, is also an important requisite. Absolute accuracy in

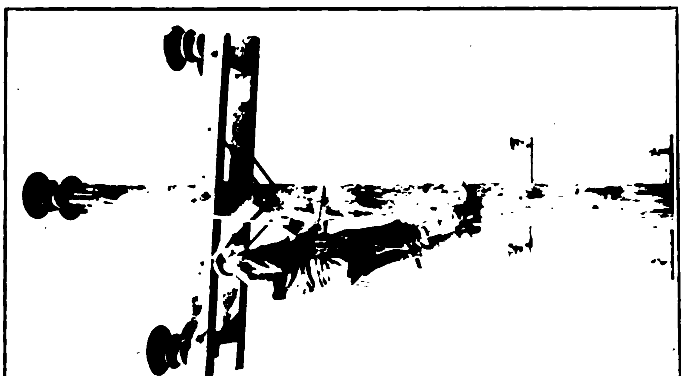


FIG. 1 [FLAHERTY]

FIG. 1a [FLAHERTY]

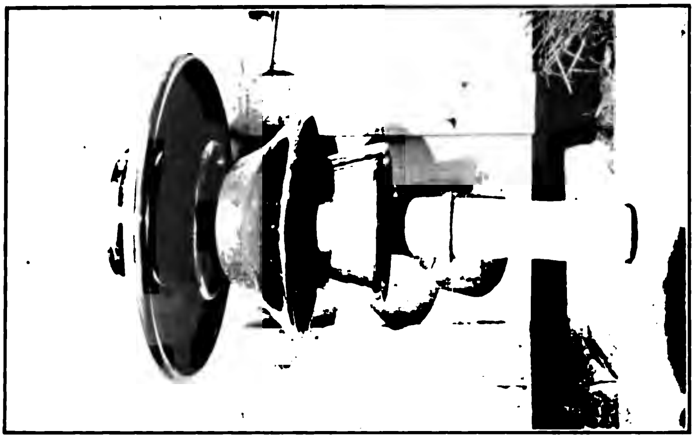


FIG. 4 [FLAHERTY]

keeping the records of the test is imperative if it is to be of any value in eliminating the defective insulators afterwards. Ordinary surveyor's field books are found to be most serviceable in use over the varied country which most transmission lines follow. The inspector in traveling along the line sets down the pole number and the result of the test on the ground. Four degrees of defect or leakage are arbitrarily assumed, namely, zero, first, second and third. The judgment of the observer must be depended upon to place properly the sounds heard. If the pole test indicates zero leakage it is not necessary to deal

INSULATOR TEST TACOMA No. 1 LINE

Pole No.	Pole test	No. 1	No. 2	No. 3	Remarks
2585	0				Fife, Station, P. S. E. Ry.
87	3	3	3	1	Date: 4-10-16
89	0				Observer: McGandy
91	1	0	1	0	Weather: Fair, clear
93	0				Ground: Moist, tide
95	0				flat level.
97	2	1	1	2	
99	3	3	0	0	
2601	3	0	3	0	
03	0				
05	0				
07	0				
09	0				
11	3	0	1	3	
13	0				
15	3	3	2	1	
17	0				
19	0				
21	0				
23	0	0	0	0	Climbed as check on former test
25	0				
27	0				
29	0				
31	0				
33	0				Gardenville Station.

FIG. 2

further with that one. If any leakage is heard, the inspector proceeds up the pole and tests to each insulator pin, or slides the point out along the crossarm or up the pole top if apprehensive of danger from too bad an insulator. Beginning at the left hand crossarm position, and looking in the direction in which the line is numbered, the insulators are numbered clockwise over the pole top in the case of equilateral construction. In vertical construction they are numbered from bottom to top. If more than one insulator supports the wire in each position on the pole or tower, the respective units are given sub-letter designations, as 1-a. 1-b, for double construction. Fig. 2 shows a sample page from the standard note book used. Only one man is necessary for this work, but the practise so far has been to send along a helper who is ready to climb to the other's assistance in an emergency, and this man can expedite the work considerably by keeping the record.

Weather conditions have considerable influence on the testing work through their effect, both on the insulator itself, and the working conditions of the test apparatus. Rainy or foggy weather increases the leakage over the insulators, especially if there is a deposit of dust, smoke, or other foreign matter, to such an extent that the exercise of a good deal of judgment on these effects is necessary in testing to keep from condemning a great many good insulator units. If rain is falling it is impossible to use the testing set, as the drops about the head and receivers shut out all other sounds effectually; and work on "bad" insulators on the pole top becomes literally "hair-raising". The ideal time to make this sort of test is when the sky is clear and the ground slightly moist underfoot to afford a good ground connection.

Theory of Action

The discussion of the theory of action here advanced is based on the pin-type insulator on wooden poles, but may be adapted to the other cases. The pin-type line insulator may be considered as a resistance shunted by a number of small condensers connected between the line wire and ground, and some idea of the magnitude of the currents flowing in such circuit may be obtained from measurements already published. Just to show that the resistance component of the current over the insulator from line to ground is of an appreciable value for measurement in the telephone receiver, Mr. Ralph D. Mershon may be cited (Vol. XXVII, TRANS. A. I. E. E.) as giving the power loss per insulator as between 40 and 75 watts at 50 kilovolts. From this it is readily seen that the effective value is sufficiently large to give considerable indication at 60 cycles, a-c., in an ordinary receiver, which is sensitive to a millionth of an ampere. Some idea of the relative magnitude of the capacity component may be obtained from Mr. Edward Bennett's statement (A. I. E. E. TRANS. Vol. XXXIII, p. 1127) of the capacity of a 40-kv., three-petticoat insulator at about 2×10^{-11} farads, giving a current on a three-phase, 40-kv. system of the order of 2×10^{-4} amperes effective.

Thus by shunting a portion of the high-resistance path of the resultant current through the crossarm and pole to ground, it is seen that an effective current of the order of 3×10^{-4} amperes is obtained through the comparatively low resistance receiver. This means a maximum variation of current, positive to negative, of $2\sqrt{2} \times 3 \times 10^{-4}$ or 8.5×10^{-4} amperes in the complete sine-wave cycle.

Over the perfectly good insulator this current is audible in the telephone receiver as a clear musical tone of the same pitch as the line frequency. If however, there is any defect, such as a crack, or a punctured petticoat, the leakage path is shortened, the capacity is changed, and the volume of sound increased considerably. If the defect is at all serious at the impressed voltage, a brush discharge effect becomes audible in the receiver as a scratching, spitting sound characteristic of such phenomena, before any evidence of it is given to the unaided eye or ear. On an ungrounded delta system, this sound can be heard to fluctuate as the neutral shifts toward or from the wire on the insulator under test.

The range of sound and variations, from the perfect insulator to the dangerously defective one, is very considerable, and capable of being subdivided into many more than four degrees selected, though they seem sufficient for all practical work. If more than one petticoat of a 60,000-volt, four-part insulator is defective, the noise of the brush discharge becomes so intense that it is unmistakable, though perhaps inaudible to the ear alone.

Many curious phenomena will present themselves to the observer who spends any time at this work, which can only be mentioned here, but may be used in further development or use of this same test. For instance, definite knowledge of the exact time of " killing " or " making the line alive " may be had by simply listening in the usual way at the bottom of the pole. Any disturbance on the transmission line is clearly audible in the test set, and the charging of lightning arresters miles away, is heard as distinctly as though near by. If considerable capacity is present on the pole top, through a number of insulators in parallel, an overtone of a very much higher pitch than the fundamental becomes audible, which is probably due to the presence of a higher harmonic.

No difficulty seems to be encountered by various observers in grading the sounds as to leakage indicated, though there may be a difference of one degree set down in the record by different persons when near the dividing line between two degrees. This is dependent on the judgment of the individual, and experience is the most valuable instructor in grading the defects accurately.

Checks of Method

The origination, and institution on the Puget Sound Traction, Light & Power Company lines, of this system of testing, in the spring and summer of 1914, followed a series of particularly severe interruptions to service during the winter of 1913-14, due almost entirely to insulator failures on that portion of the system which had been operating at 60,000 volts for about ten years. The effects of the apparently increasing number of failures were so annoying and cumulatively destructive that some method of locating the dangerous units became imperative. A number of tests were made on the defective insulators with a megger, but no satisfactory results could be obtained as it was necessary to actually find the flaw in the porcelain and then moisten it before any indication of less than infinite resistance could be gotten. A great deal of preliminary experimentation was done with the telephone receiver also, before it was adopted as a routine testing apparatus.

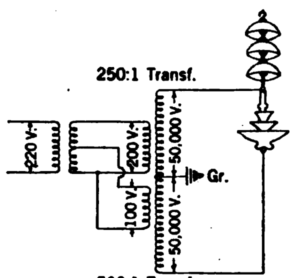


Fig. 3—High-Voltage Test

As a preliminary check on the accuracy, a pole was selected on one of the lines that had given most trouble during the previous winter, which carried insulators indicating in the test set all three degrees of leakage, as mentioned above. These three insulators were removed from the line and taken to the White River generating station, where a temporary high-voltage test set was rigged up out of the apparatus available. The insulators were kept as nearly as possible in the same condition as on removal from the line, and but a short time, perhaps a couple of hours, elapsed until the high voltage was applied to them.

The apparatus used consisted of a 50,000-volt oil-testing transformer and a 50,000-volt, 100-watt potential transformer connected in series on the high tension side, with the common terminal grounded. The secondary windings were energized from the local 220-volt service and regulation was obtained from the hand induction regulator on the oil-testing transformer.

A new three-part suspension insulator, hung from the ceiling, carried one terminal of the set and the insulator under test was suspended by the pin from this point. To a piece of line wire fastened to the test insulator head with fine copper wire, was carried the other high-tension lead. A diagram of the connections is shown in Fig. 3, and the results of the application of high voltage in Table 1.

TABLE I.

PRELIMINARY HIGH-VOLTAGE TEST AT WHITE RIVER, JULY 1, 1914.

Insulators taken from Pole No. 1739, Tacoma No. 1.

Ins. No.	Tel. test degree leakage	Volts at breakdown from trans. ratio
3a	3	63500
3b	2	84500
1a	1	Did not break down but showed distress at full voltage obtainable.

The maximum e.m.f. obtainable from the induction regulator for the secondaries of the transformer series, was 175 volts, giving 87,500 volts, (trans. ratio 500:1) on the high-tension side; if the effect of a possible phase-angle difference in the two transformers were neglected. While not regarded as a rigid check, this test was considered a practical demonstration of the utility of the telephone receiver for locating defective insulators. It was felt that the argument, that the chosen insulators failed at a voltage at least not any greater than the values given, would hold; and that while further use would give more data, the test would be sufficiently reliable to put into use at once in clearing the transmission lines of the worst cases of defective insulators. A complete test was therefore run on two of the older lines, Tacoma No. 1 and Seattle No. 1, and the poor insulators taken off immediately afterwards.

No other source of e.m.f. higher than 60,000 volts was available in this section, than the rough set-up described above, until the placing in service of the 20 kv-a., 200,000/220-volt testing transformer at the University of Washington, built by Messrs. Dodds & Dashley in 1915. Through the courtesy of Dr. C. E. Magnusson and the University of Washington, the use of this transformer and the facilities of the university laboratory were offered in checking up the results of the test.

A group of insulators, ten in number, was selected from those found leaking in a test with the telephone receiver on the afternoon of February 17, 1916. On February 18th, these were removed from the line, and on February 19th, were transported by automobile to the University of Washington laboratory and tested to complete breakdown. The comparative results of the two tests are given in Table 2. The current to energize the transformer was obtained from an alternating-current generator, whose voltage wave had previously been determined to be very close to the true sine curve. This machine was run by a 10-h.p. motor at a speed giving close to sixty cycles, and the voltage (generator) was controlled by varying the field of the d-c. dynamo used as an exciter for the a-c. generator. E.m.f. was measured from an instrument coil in the low-tension winding of the transformer and the high-tension voltage calculated from the turn ratio (10,000:1). Since the test the high-tension voltage has been checked by means of a sphere gap and found to be about 9200:1 in the neighborhood of 100,000 volts.

TABLE II
COMPARISON OF TESTS

Pole No.	Ins. No.	Tel. Rec. 3/17/16–Test, degree	Breakdown test, U. of W, 3/19/16.				Petticoats punctured
			Brush discharge		Breakdown		
			Volts		Volts		
			Turn ratio	Sphere gap	Turn ratio	Sphere gap	
2645	1	3rd	80,000	73,600	104,000	95,700	1st, 2nd, 3rd
2645	2	3rd	84,000	77,200	96,000	88,400	1st, 2nd, 3rd
2693	1	2nd	100,000	92,000	134,000	123,200	3rd
2693	2	2nd	80,000	73,600	116,000	106,800	4th
2709	3	3rd	80,000	73,600	100,000	92,000	1st, 2nd
2711	2	3rd	76,000	70,000	94,000	86,500	1st, 2nd, 3rd
2717	2	3rd	60,000	55,200	98,000	90,000	1st, 2nd, 3rds
2737	1	2nd	80,000	73,600	104,000	95,000	1st, 2nd, 3rd
2737	2	3rd	50,000	46,000	80,000	73,600	1st, 2nd, 3rd
2759	1	3rd	75,000	69,000	120,000	110,300	1st, 2nd, 3rd

NOTE: Petticoats are numbered from top to bottom. Those not noted as punctured are the only ones over which the flash of power arc was plainly visible at breakdown.

In considering the results of this test and comparing with those of the preliminary check, there are several changes in conditions to be taken into account, chiefly effects due to weather. The insulators removed for the latter were tested during damp weather in the winter time, February, 1916, and in a tide flat location where they were subject to salt water fogs. Two days afterwards they were transferred to a warm, dry laboratory room for the breakdown test. The preliminary test was made on a very warm, fair day in July and high voltage applied to the insulators soon afterwards. The searching out effect of the moisture on the insulator faults in the former case being so much greater in the receiver, a change being made in the observer, and the increasing severity of requirement in grading the leakage, all being taken into consideration, the apparent discrepancy between the two tests does not appear to be so great.

Three important points are to be noted in the results obtained; first, that all, except one, of the insulators rated at second and third degree leakage chosen for the test failed at double the rated insulator voltage (60,000 volts) or less; second, the effect of the location of the punctured petticoats, *i.e.*, whether top, middle or bottom; and third, that every one selected by the test set as of second or third degree leakage shows one or more defective parts. Evident distress, shown by the beginning of the brush discharge, at or near the rated voltage of the insulators should also be noted. If we accept the state law requirements, not one of the entire group would be considered a satisfactory insulator on test, as every one punctured or flashed over at less than two and one-quarter times line voltage.

By scrutiny of the results it is possible to place an approximate upper limit of puncture value for the third-degree leakage insulator near one hundred thousand volts; and a consequent like lower limit for the second degree insulator, though of course in the very nature of the test there is no sharp dividing line between any two consecutive degrees. It was not possible to test insulators of lower than second-degree leakage, on account of the temporary, makeshift nature of the terminals in use at that time on the testing transformer, rendering it impracticable to go above 135,000 volts. The installation of permanent condenser terminals will later render an extension of the check possible. Note should be taken also of the fact that all the second-degree and highest puncture value insulators were those one or more of whose widest flaring petticoats were not punctured, but flashed over. A view of the type of insulator discussed in this test is shown in Fig. 4, cemented on a 2½-in. (10 cm.) galvanized iron pin, as all were.

Results Accomplished

As mentioned before, a complete test was made July, 1914, on two of the lines giving most trouble during the winter 1913-14, namely, Seattle No. 1 from Sumner to the city limits of Seattle; and Tacoma No. 1 from Sumner to Tacoma city limits. Only the insulators recorded as third-degree leakage were replaced, although the record is kept for all degrees for further data on the rate of depreciation. In April and May, 1915, a second test was made on these lines, and the third annual test was made in May, 1916. In March, 1915, a test was also made on two pole lines from Sumner to Electron, a distance of eighteen miles. Following is a tabulated summation of above mentioned tests.

TABLE III

SUMMATION OF TESTS

TEST 1914

Line	No. of Ins.	3rd deg.		2nd deg.		1st deg.		Clear	
		No.	Per cent	No.	Per cent	No.	Per cent	No.	Per cent
Tacoma No. 1.......	1716	100	5.85	155	9.05	216	12.6	1245	72.5
Seattle No. 1........	3405	25*	0.735	49	1.44	29	0.89	3302	97.0
TEST 1915									
Seattle No. 1........	3405	82	2.4	68	2.0	45	13.2	3210	94.5
Tacoma No. 1.......	1716	85	4.96	60	3.5	17	1.0	1552	90.2
Elec. No. 1..........	2670	72	2.7	65	2.42	103	3.86	2430	91.0
Elec. No. 2..........	2670	224	8.4	75	2.8	105	3.94	2266	85.0
TOTALS									
1914...............	5121	125	2.44	204	4.0	245	4.8	4547	89
1915...............	10501	463	4.4	268	2.56	270	2.6	9458	90.2

588 removed from lines.

*First completely tested line.

NOTE: Decrease in first and second-degree insulators in 1915 test was due to skipping poles of lowest leakage in order to locate most defective ones first for removal from line.

A close check on the labor costs of the complete operation of locating and replacing the 85 defective insulators on Tacoma No. 1 on the second test was made, and is here presented.

COST OF TESTING AND REPLACING INSULATORS

Two men testing, 5 days time @ $7.90..................	$39.50
Number of poles..	558
Cost per pole..	7.1c.
Number of insulators included in test..................	1716
Cost per insulator.....................................	2.3c
Total number replaced..................................	85
Total cost locating and replacing......................	$96.35
Cost each..	$1.13

Of course as the line insulation becomes better the costs will somewhat decrease, and vice versa, but the average cost of testing runs less than ten cents per pole over all kinds of country, and most insulation conditions on lines in operation.

In conclusion should be given some data on the success attained in the elimination of troubles due to defective insulators, but this material is not in shape just now for presentation in definite form. The fact stands forth, however, that whereas in 1914 any ground on the system, arcing or otherwise, resulted in numerous insulator failures, burning off poles and crossarms, and even burning through No. 0000 copper line wires on the lines mentioned above; since that time there have been only two cases of destructive insulator breakdown on these lines. The first one of these was on Thanksgiving Day, 1915, and was apparently due to a direct stroke of lightning, which stripped every bit of porcelain out of a three-disk, dead-end insulator on a river crossing tower at Orting on Electron No. 1 Line, leaving the pole top wire connected directly to the pole by the inter-linking hardware; and broke down a pin-type insulator on the same wire four miles north of Orting, literally blowing the top of the insulator clear of the pin. Despite the fact that one line wire between Renton and Kent lay on the ground for some time until burned off above arcing distance, no other insulators on the tested line failed under the severe strain, although on other lines not tested quite a number did. The second case of failure was February 2, 1916, on Tacoma No. 1, during the very severe sleet storm of that period and was caused by trees growing near the line bending over under the sleet load and grounding one wire numerous times at short intervals. It is also to be taken into account that the last two years have been a period of more severe storms, especially of lightning and sleet, than have been known in this district for many years.

Depreciation Data

Some effort is being made to collect data on the rate of depreciation of porcelain insulators through annual tests over the same lines, but completeness along this line will require more time and more standardized methods than have been used in the past. Considerable study and latitude in reasoning are necessary to correct interpretation of the records obtained in order to get a clear idea of the facts as to the rate of depreciation. For instance, the testing so far in this work has been done with the sole idea in mind of locating the *worst* insulators and improving the line insulation at once by their removal, so that very little attention has been paid to those of second-degree leakage or less, and the records of them are not complete or exact. Another factor for which considerable allowance must be made is the personal equation of the observer, who in some cases is very liable to miss the indications of lower leakage, either intentionally as intimated above, or due to lack of keenness of observation. Then too, there is considerable chance for confusion of circuits of the leakage current, that is to say, if a pole top holds one very bad insulator, there may be some indication of leakage from the other ones, though the latter will show up as perfectly sound upon removal of the defective unit. All of these things are brought out in the accompanying depreciation list, which contains the results from three tests over the same line, each one being made by a different man, without any record of the previous survey.

TABLE IV

DEPRECIATION LIST TACOMA NO. 1 LINE

Tested	July, 1914			May, 1915			May, 1916		
Insulator Numbers	1	2	3	1	2	3	1	2	3
Pole Nos.									
2137	1	1	1	0	3*	0	1	1	3
2231	1	1	0	0	2	2	1	2	3
2333	1	1	1		Clear		1	3	3
2499	1	1	0	1	3*	0	1	0	1
2587	2	0	1				3	3	1
2609	3*	0	1	0	2	3*	0	0	0
2657	1	1	0	3*	3*	3*	0	0	0
2671	0	1	0	3*	3*	3*	0	0	0
2699	1	2	0	2*	3*	3*	0	0	0
2723	1	1	1	3*	3*	3*	0	0	0
2753	3*	1	1				0	2	1
2789	2	2	3*	3*	3*	0	0	0	0
2793	0	3*	0				3	0	3
2827	3*	3*	3*	0	0	0	0	0	0

*Insulators replaced immediately after the test was completed.

Pole No. 2137 serves as a good illustration of several of the points stated above. The first test, July, 1914, was made with more care than that of May, 1915, the lower leakage consequently being noted. In the latter test the depreciation and excessive leakage of insulator No. 2 so overshadowed that of the other two in the hearing of the observer, that, coupled with the main idea of locating the bad insulators only, the result was a record of zero leakage for insulators Nos. 1 and 3, although careful attention would probably have also designated them. The third test, May, 1916, after the replacement of No. 2 insulator, shows what is probably the effect of a confusion of the circuits, as it is conceivable that a portion at least of the leakage current from No. 3 insulator would flow along or through the crossarm to the pole, up the pole top to the receiver terminal and back through the receivers to the pole at a lower point.

Poles Nos. 2609 to 2827 show very clearly the improvement in insulation and the clearing up of the line from the replacement of the third-degree insulators, whether singly or all three on the pole top. No. 2753 exemplifies the perfect insulation of insulator No. 1 two years after the replacement of a defective one, and the gradual depreciation of the other two. No. 2793 is a like example, but with much more rapid depreciation of the clear ones. No. 2789 shows the increase to third-degree leakage from second in less than a year's time and the subsequent clear test a year after replacement. This table will give some idea of the method for studying the depreciation rate which is being planned on for the future.

DISCUSSION ON "TESTING FOR DEFECTIVE INSULATORS ON HIGH-TENSION TRANSMISSION LINES" (FLAHERTY), SEATTLE, WASH., SEPTEMBER 6, 1916.

Harris J. Ryan: The purpose of the author is primarily to lessen the operating troubles that are caused by the deterioration of insulators. The elimination of the deterioration of insulators will require much effort and time, and until it is accomplished, the transmission engineer must value highly a method that enables him to have a defective insulator located before it causes an interruption. In the meantime he has an intense interest in the discovery of the causes of such deterioration and their avoidance. Doubtless some deterioration of porcelain high-voltage line insulators may be due to defects in design or construction, though from the evidences at hand most of the deterioration that is going on is due to defective porcelain. From the ceramist we learn that it is difficult to make electrical porcelain which is altogether non-porous, and from the geologist, that earth products to be mechanically strong and durable under the action of the elements, must be highly refractory and impervious to moisture. In one instance the deterioration of more than a thousand suspension insulator units manufactured eight years ago was one and a half per cent for their first six and one half years of service on a 100-kv. line. In another case more than a thousand units were bought and stored in the open four years ago. By tests made on them during the past summer, five per cent were found by the megger to have failed, and fifteen per cent failed to withstand the one-minute flash-over potential test. It is reasonably certain that design and construction can account for but a small portion of the great difference in the number of failures that occurred in these two lots of insulators. It is also reasonably certain that the denser structure of the porcelain in the older insulator was largely responsible for their few failures.

Finally it appears that if such a material as fused quartz could be cast into insulator forms, a decided improvement in insulator practise should result. Fused quartz is a thoroughly vitrified material that is dense, tough and refractory, requiring no annealing.

L. T. Merwin: I would like to commend for experimentation a method that might lead to results possibly cheaper in some instances than this method outlined in the paper. A year ago I had occasion, in experimenting with a wireless receiving set which, as some of you know, we use regularly as a means of dispatching on our transmission line between the City of Portland and the power station on the White Salmon River, to find out whether it would have any application to the discovery of weak insulators. We noticed that intermittent discharges were coming in, that could not be attributed to any nearby wireless station. We believed that some of them came from defective insulators, and further tests proved that to be the fact. I have not had the time to continue the experiments, and I simply offer them for what I believe to be a very profitable line of experimentation. It is as follows: Take an ordinary audion receiver set of the De Forrest pattern, with a high resistance head set, and if the line is along a highway sit in your car with a wire fastened to a bamboo pole, say, of six or eight feet in length, with the bulb ready for action and the receivers at your ears. Drive along, and, as you do so, you will hear the characteristic hum of the transmission frequency with its harmonics, and if you pass any insulators that are defective in such a way that transient discharges are taking place, you will hear the characteristic scratch. I have not carried the experiment far enough to know how conclusive the determinations are, but when driving along a line at the rate of 15 miles an hour, you would not fail to hear any oscillatory discharge in an insulator. It would certainly be a much more rapid means of discovering broken down insulators than any other. Now, having once discovered a pole with a broken down insulator, whether the means that I am mentioning will be effective in definitely locating which insulator it is, I do not know. I talked with Mr. Crawford last year about it, and it is quite possible that he has made some experiments with this method. Whether it will be effective in finding defective insulators on steel tower lines, I do not know, but I belive it is a means that is well worth investigation. I might mention one little instance that came up in my experiment: In driving along at a rate of approximately 15 miles, I heard the scratch, and stopped the machine and got out to locate, as nearly as I could, the pole that had the defective insulator. By moving the antenna wire, which we will call this little wire fastened to the eight-foot pole, back and forth, I finally located the trouble on an adjacent power system some four blocks away, so I do believe that the method has merit.

E. A. Loew: Notwithstanding the fact that all insulators are reputed to be more or less "rotten," it is, nevetheless, evident that if the power companies are to continue to transmit power at all, until better insulators have been designed and manufactured, they will have to continue to use those which are now on the market, and, therefore, it seems to me that some method of testing insulators which are in use, while they are in use, is of exceedingly great value to the power companies, expecially if that method is a simple one. Therefore, in reading over Mr. Flaherty's paper, I have been impressed with the idea that some such method of conveniently testing insulators in service as therein described, is the kind of insulator test which operating companies have long needed. So far as insulator testing is concerned, there are two distinct circumstances under which tests are desired: First, there is the demand for a factory test or series of tests, which are made before insulators are accepted and installed by the purchasing company, in order to insure the delivery of units which will meet such specifications as are suited to the service for which the insulators are intended; secondly, there is the demand for tests on the installed insulators at regular intervals while they are in service, that is, without the expense and interruptions incident to their removal from the line, in order to determine the condition of insulators from time to time so that those which have developed defects and are liable to cause trouble may be detected and replaced by new ones before the trouble develops. As already pointed out by Mr. Flaherty, the first mentioned class of tests have in the past been the subject of considerable discussion and are now pretty well standardized. The methods there developed, however, have not been suitable to the testing of insulators under ordinary service conditions. The method outlined in Mr. Flaherty's paper and now in use by the Puget Sound Traction Light and Power Company on its lines is, so far as I know, the first method proposed by which a fairly reliable test of the serviceability of an installed insulator may be quickly and conveniently determined. Its simplicity and cheapness, accompanied by a fair degree of reliability will, no doubt, recommend this method, or some modification of it, to power companies generally, where a rough qualitative test of this kind is required. A modification of this method of testing, which seems to me to be highly desirable, is some arrangement whereby the personal equation of the operator may be either largely or wholly eliminated. How this test may best be brought about I am not prepared to say. Some of the obvious advantages of making qualitative tests of this kind on insulators in service may be enumerated as follows: First, the test may safely be made while the line is in service; it is a simple test easily made by the regular line force at a small cost, and it apparently gives indications which are sufficiently reliable for practical purposes. Secondly, by means of such tests made at regular intervals, line trouble is anticipated and thus often prevented. The loss resulting from damaged apparatus and shut-down should thus be greatly reduced. Thirdly, by keeping a suitable record from month to month, and from year to year, the points of greatest depreciation of line insulators and of greatest line trouble may be more definitely located. By increasing the insulation on such parts of the line, trouble should be further reduced, continuity of service better guaranteed and greater reliability of operation secured.

J. B. Taylor: If material that is weak, or has already partially failed, can be located and replaced before complete failure occurs, records for uninterrupted service may be improved. Mr. Flaherty's method for weeding out defective line insulators, using a telephone receiver to detect small leakage currents, is novel and worthy of extended cautious trial. Work among live 60,000-volt conductors with exploring wire in hand and testing circuit connected to head and feet calls for caution.

As described, the field for the method seems restricted to wooden poles with pin-type or single-unit insulators, though the author intimates that some study has been given the case of steel towers and chains of suspension insulator units.

No figures are given for break-down of insulators taken at random from the same line and giving zero indication in the telephone. If these can be added, the value of the telephone method may be made more convincing.

In Table IV the records of certain selected poles for three consecutive years are discussed as showing progressive increase in degree of leakage. This deduction may be questioned on the showing of Table III, where for example Tacoma Line No. 1 lists 371 first and second-degree insulators left on the line after 1914 test, though only 162 of all three grades are found on the same line in 1915 test. Data for the test in May of this year are not given.

Incidentally it appears more probable that the "clear musical tone" heard when testing a perfect insulator is of higher frequency than fundamental (assumed to be 60 cycles). Not only does the capacity connection favor the harmonics, but telephone receiver sensibility is relatively low at commercial frequencies. (See A. I. E. E. TRANS. XXVIII, 1909, page 1184)

C. E. Magnusson: Mr. Merwin's use of the audion is merely a method of magnifying the effect of the electromagnetic waves as they radiate from the damaged insulator. I would raise the question as to why the insulators are left so long on the line in a damaged condition. From the paper, I would judge that the operators take a keen delight in edging up as close as possible to the break-down point. It would appear as a more desirable plan to eliminate defective insulators before they reach the fourth stage, and thereby save the additional loss that necessarily follows when the break-down actually takes place. I understand that the continuity of service record for the P. S. T. L. & P. Co., has been vastly improved since the method described in Mr. Flaherty's paper was adopted, and if I understand correctly, the engineers in charge could guarantee uninterrupted operation if the insulators of the third degree or second degree were to be taken out, so that they would not have to wait until the insulators were so near the breakdown stage. I would like to ask Prof. Ryan this question: From his remarks, may we hope that some day, we shall have quartz insulators?

H. J. Ryan: We hope so. I have no other foundation for expressing that hope than that quartz has splendid qualities which render it adaptable for the purpose. There are quartz utensils made for the chemical laboratories, as we all know, that are not prohibitive in price, notwithstanding the fact that the laboratories do not use a great deal of product of that sort, and it would seem that if the matter were gone at in a large way, because of the fact that silica is a very abundant material in nature, it should be practicable to have quartz insulators.

M. T. Crawford: I would like to say just one word in defense of Mr. Flaherty's paper, after thinking over Mr. Buck's remarks this morning. Mr. Buck made a very good point, in stating that the insulation of our systems was poor, and that redesigning should be given attention, and replacement taken care of. But the re-designing of insulators is going to take considerable time and the replacement outright of many thousand of more or less defective insulators is going to take a sum of money which cannot be always obtained promptly. In the meantime, the system must be operated, and I believe the engineer is doing a real service when he takes what is available and makes it work, securing thereby reasonably good service from poor equipment, while the process of redesigning and replacement of equipment is in progress. I have received a great many letters from all over the country since this method was first brought out two years ago, inquiring for additional information, describing the results of using the method; and while in some cases, local conditions prevented its successful use, there have been a great many systems that have made very good practical use of this method, and reported good results. In our own systems, we have almost no trouble from interruption of service due to defective insulators, whereas, three years ago, it was one of our main sources of trouble.

W. D. Peaslee: I think that one point raised by Prof. Magnússon—that is, as to leaving slightly defective insulators in service—is simply a question of economy. The progressive deterioration of an insulator as it goes to No. 3 is very apparent. We all know that if we have a pole in a transimission line that begins to rot, we don't take the pole down at the first splinter of rot that appears in it, but we watch that pole very closely, and as it gradually deteriorates toward a condition of worthlessness, we remove it. I think the same rule applies to insulators. Mr. Flaherty has described a method whereby it is possible, at very reasonable expense to watch these individual insulators, and if an insulator is shown to be defective on No. 1 test, that is no reason for taking it off the line, because that costs money, and money has to be borrowed, and it is not always easy to get. Whereas, if we can go out and watch that insulator, and it gradually goes to No. 2 we can note it in our book. Then if it goes to No. 3, we can take it out, and in the meantime we have had probably two years use of that insulator. We have to face the fact that no matter how good an insulator is when we put it on the line, it has to be replaced sooner or later. Insulators will deteriorate, and the thing for the engineer to do is to take off the constantly deteriorating factor in his transmission line. I have taken off an insulator that has failed, and outside of the points of failure, the insulator was good; the porcelain was good. It was as good as you could expect, under present conditions, to be manufactured. There was no reason to suspect that that insulator when it went on the line, was not good, and gradually deteriorated, and I think that the practise of leaving these insulators on until the last moment is pretty good, economic engineering.

R. W. Pope: The old Boston and Albany line was insulated with what my brother called white flint insulators, and he considered those insulators very much better than glass. That was as far back as '58. They were abandoned I believe because glass was cheaper and served the purpose. I have never seen any reference to that material, but I remember how those insulators looked at that time, and I have had an idea that they might have been quartz, and their manufacture a lost art.

C. P. Osborne: I might say that we have just completed a test on our power line, equipped with suspension type insulators. Last year we made no changes in those insulators. Two years ago, we removed all insulators that tested less than 2000 megohms. Last year we made the megger test, and we found about 4 per cent of those insulators that would test below 2000 megohms and after discussing the proposition, we decided to let them go over and see what the result would be, without making any change. We did so, and had no failures at all. The test that has just been completed shows 15 per cent that tested below 1000 megohms. We have had no failures yet. We expect to change insulators this year. When the line was built, five years ago, we had considerable trouble. We had 14 shut-downs in six months from insulators breaking down. Three years ago we installed 12 insulators on the platform, six in a string, and on one of the strings, we put a 600-pound weight, and the other was without weight. The object of doing that was to determine i our trouble was mechanical. Those 12 insulators have been hanging there in the weather three years, and we have come to the conclusion that the electrical stress is what has been breaking down the insulators. We have no reason for believing that, except from our own observation.

The great objection we find, in testing with the megger is where you have a ground on the line, as we have in our tower line, there is one insulator that you can't test unless you disconnect it from the tower. Three months ago, we tested five miles of the line, and the test we just completed checked almost exactly with the test that was made three months ago. Some of them showed a little bit lower, but not very much. We are going to try to see if we can get the same results on the s eel tower line. We may be able to do that on our wood pole line, bu hardly on the steel tower line. We also have a line that we have been carrying 60,000 volts on for four years, and we have only had one insulator breakdown. You can walk along that line at night and see the fireworks almost any place. You don't need a telephone receiver to find those.

George Harding: It has been stated hat porosity is probably the cause of the breaking down of the insulators. I would like ask whether or not this has been tried: It has been s ated that you can expel the moisture by baking the insulator. Has this experiment ever been tried: Immersing the insulator, after the moisture has been expelled, in oil? In other words, impregnating the insulator with oil, and then putting it under the test.

H. J. Ryan: That idea occurred to some of the engineers of the power companies with whom we worked this summer. We have not, however, made any effort to carry out an undertaking such as you have suggested. Naturally, since porosity seems to be such an evil, impregnation with parffine or oil, or some other similar material was brought forward. However, there are so many evidences that a unit that you can treat in such fashion, and that you can make work very well for a time, when you leave it, and have forgotten it, in four or five years, the oil would go out of it, and it would again be in a bad class. A word of comment on one point that was brought out by Mr. Osborne, and that is in regard to the voltage duty that a defective unit will carry in a suspension insulator. You have spoken of units that are continued in service when they have a resistance of 1000 megohms. Surely, such units are capable of carrying a lot of duty—normal voltage duty. Mr. Osborne felt that they would like very much to know the capability of defective units in regard to voltage duty, and the voltage duty that they would carry or fail to carry in a string. So, in our laboratory, with a high-voltage potentiometer, we erected strings with as many as 12 units, and applied 75,000 volts to ground thereon. We employed, first of all, good units throughout, and then employed a bad unit or two bad units next to the line, and then employed a good unit mounted next to the line, and then a bad unit or two bad units, or arranged them in various other combinations that, of course, immediately suggest themselves to the mind. The bad units had been shorted through, were punctured, or they were units that were water-logged. In a string of 12 units, for example, each unit carrying an average of 8.3 per cent of the total, units would carry as much as six or seven per cent that had actually been shorted through on high-voltage tests, because they were defective and conductive. Nevertheless, it appears to me that units of that kind in a string would surely fail under the ordinary forms of high voltage. It seems to me that the danger from leaving units on a line, that show as low a resistivity as 1000 megohms, comes from the fact that one is manifestly leaving on a line an insulator that is pretty porous, and is engaging in a process of absorbing more and more water all the while. It must have absorbed quite a little, apparently, in order to be down so low. As long as certain accidental forces don't come along, laboratory studies indicate that those units will carry very nearly as much duty as if they were in perfect condition, thus not throwing an undue amount of duty on to the other units.

C. P. Osborne: I would like to cite one instance which happened last Saturday on our line. The Southern Pacific has a tap from one of our substations which operates their line. The lightning struck their line, burning the tie-wire off the insulator going to the ground plate on the pole, which the Commission, I believe, makes it necessary to install. That, no doubt, created some disturbance on that line. Now, the tower line which I spoke of, kicked out at the generating plant, at least thirty miles from that point. When I mention the insulators being 1000 megohms, I will state that we have three strings, and all of them showed 1000 megohms. This simply shows that here is a case where lightning did strike the line, and there is no question but what some undue strain was put on that line by the lightning striking it. It also burned up some of the instruments in the substation, right along side the line. We have been a litle bit skeptical in making the tests. As we look at it now, it is a case where we have to go through every two years and weed out the bad insulators, and put in new ones, and that is going to continue until we get better insulators. Were those insulators Mr. Pope spoke of, bullet proof?

R. W. Pope: The form I speak of was pretty nearly bullet proof, because bullets glanced off from them.

B. G. Flaherty: All our lines here have ungrounded neutrals. We have had no experience with the grounded neutral systems. In reply to Mr. Merwin's suggestion as to the audion testing set. We can use the telephone receiver in practically the same manner except that a grounded terminal is necessary—the same bamboo pole and the antenna. You can ride along the line and get practically the same results with just the telephone receiver alone. An incident comes to my mind where we were testing a line this summer. The linemen were testing the insulators on a pole line with a steel tower line paralleling it. They called my attention to two cases where the tower line had defective insulation on it, that they had discovered by walking along with the pole over their shoulder. Mr. Osborne, undoubtedly a number of your poles or towers would have no defective units on them.

C. P. Osborne: There are a lot of them that have no defective insulators on them.

B. G. Flaherty: That would avoid your going over them with the megger test, if you could locate the poles or towers with the telephone receiver set.

C. P. Osborne: Have you tried that method at all with lines with grounded neutrals? We operate a grounded neutral on all 60,000-volt lines.

B. G. Flaherty: No. We have no grounded neutrals here. As to Mr. Osborne's statement about the 45,000-volt insulators, and the ability to use the telephone receiver set, we have about 25 miles of line with 30,000-volt insulators, that we have tested. An old style insulator was put on, and it has been on a number of years. Our telephone receiver set seems to work all right in those cases. Of course, we get an excessive amount of noise, and it is not necessary to make contact with the pin on the insulator.

The lineman, in testing, simply starts out along the cross-arm and observes by the comparative intensity of the sound, and he can tell those insulators that are most defective.

Mr. Taylor referred to the discrepancy in the tables given, as to the number of insulators in the different tests, giving a larger number of the lower degree leakage in the first test of July, 1914. I have explained in the paper, that we were very much more careful in the first tests in 1914 to get the degrees of leakage. As a matter of fact, we almost neglected the lower degrees in the tests of 1915 and 1916 as the sole object of the test was to locate the dangerously defective units.

S. C. Lindsay: The insulators, Mr. Flaherty referred to as "30,000-volt insulators", were not designed for that voltage. They were designed for 55,000 volts and were first used on a 30,000-volt line with the idea of later changing the line to 55,000 volts, and in that way became known as 30,000-volt insulators. They are very much smaller than the 55,000-volt insulators used at this time, and although we used them for a short time at 55,000 volts, we found that they were an unsafe insulator for that voltage.

J. P. Jollyman and J. Mini, Jr.: Regarding the use of the telephone receiver for the detection of defective pin-type insulators on pole lines, the writers after the publication of Mr. Crawford's outline on this subject of August, 1914, gave the method, what they believe a fair trial. First in an experimental way as will be described later, and finally by actual application to several sections of existing 60-kv. lines on the Pacific Gas and Electric Co.'s system.

About this time it was decided that parts of several lines would be rebuilt for various reasons; this required the insulators to be completely removed from the poles during the reconstruction. This opportunity was taken advantage of and a number of "telephone surveys" were made of the same pieces of line, at different times of same day, and also on different days, by two independent men, who took new records on each survey, without reference to results of previous surveys or of each other's work. Here the first points against the telephone method showed up, in that records for the same pole often were far divergent for the several tests, while the voltage and load conditions of the circuit remained practically uniform.

In all but two cases, the lines carried 14-in. diameter tops 4-part pin-type insulators, and the poles and insulators as regards, spread, etc., were about the same as exist on the system on which Mr. Flaherty conducted his tests. The only point of difference of which we know is that his system operates with isolated neutral while our tests were on the solidly grounded neutral system. The comparison of climatic conditions also is not known.

As the insulators were removed from the poles they were carefully tagged and hauled to a central point, where each shell of each individual assembled insulator was given a careful test with the megger, and then by the application of 55 kv. from a 2000-watt testing transformer across each separate shell.

Referring to Fig. 3 and to the note under Table II of the paper, it is understood that the voltage tests were made by applying the test terminals to the shells over all. Owing to the relative lengths of striking distances due to design of certain insulators, this method of detecting punctured shells, is very often not reliable; since the spark will sometimes jump across two shells from the pin for instance, rather than jump down along one side of a long inner shell and out and up again on the opposite side of this shell. This leads one to believe that a shell was not punctured. This "over all" testing throws unbalanced stress on the inner shells as a rule (depending of course on the design), and often punctures them on a total test of say 110,000 whereas they will often stand 60 to 70 thousand volts or perhaps flash-over, if tested individually. It is perhaps (especially in making checks on the phone test), more proper to find what shells are already cracked, punctured, or so porous and full of moisture as to stand practically no voltage, rather than to puncture some of them at 50,000 volts per shell or over. An insulator having four such shells standing such a voltage per shell, would be expected and has proven in many cases to still be capable of giving considerable service, and it is doubtful if any phenomena it exhibits under normal operation, would give any phone detection and therefore should not be counted as a debit or a credit to the number the phone missed, or on the other hand detected.

Experimentally, various types and sizes were put on a pole on which the circuit connecting thereto, could be switched on or off at will. It was soon discovered that it was not necessary to connect one terminal to the pole, but that a regular wireless effect existed and an antennae held up brought the same results. Sound, four part insulators, every shell of which has passed a megger and severe voltage test, were put on the pole. One shell after another was shunted out by a wire, and the result in the phone receivers was an increasing disturbance after each such artificial shorting out of shells. Carrying out this procedure in the reverse order, the noise produced by the insulators became quieter, returning to the clear hum again as the short-circuiting wires were removed from across the shells. Again other sound insulators were dusted over and then sprayed with water from an atomizer; these got noisy but gradually returned to quiet again as the sun dried them off. The receivers used were of the wireless type, two of them having a resistance of 2000 ohms, and one set, 3000 ohms per pair. These different insulators of various degrees of defectiveness purposely put on the test pole, together with those temporarily made defective by artificial means as noted above, gave quite similar disturbing noises in the receivers. These tests gave the field men "ear training" before they actually did any testing on existing lines in regular operation. Various degrees of noises were found characteristic upon which the field men standardized for record purposes by coining describing words, such as: "light, medium, and heavy fry; light, medium and heavy continuous bombardment. Numerous attempts were made to locate the particular defective insulator purposely placed on the test pole, from the three total using the scheme outlined in Mr. Crawfords' paper, but with very little success. The nearest approach toward picking the correct defective insulator was perhaps by the use of a telephone transmitter, mounted on the end of a long light pole, by which it was held up close to the end of the insulator pin of the several insulators on the pole. The other end of the wire telephone circuit (including dry batteries and ordinary telephone receiver) was held by a man standing on a well insulated stool, located at the base of the pole. The scheme is dangerous and the results far from reliable as the number of incorrect detections far outnumbered the correct ones. It might be stated that whether the three metallic pins located at the two ends of the cross arm and at the pole top, were connected metalically or not, did not seem to effect the phone test results.

Tests made on lines in regular operation.

TEST No. 1

Each pole carried three 3-part 14-in. diameter insulators. Location about 90 miles inland from sea coast. Weather dry and relative humidity fairly low.

9 poles selected (which gave three consecutive checks on telephone survey) from out of a total of about 50.

Poles	Character of phone test.	Megger and high-voltage test of each separate shell of all insulators on pole.
2	Clear hum	O. K.
7	Medium to heavy bombardment.	At least one shell in one or more insulators of each pole group (3 insulators) found defective.

The phone test was checked correctly by megger and voltage tests on the insulators of all 9 poles, or 100 per cent.

It might be added that in the above, the tests were made with an antennae length of the phone circuit not over ten feet above the ground, same having a sharp point which was lightly driven into the pole butt. If the end of the antennae is held up near the cross arm, all the poles on this line give the "fry" sound in the receiver. Each shell of this type of insulator is of course carrying more voltage stress than the shells in other types of insulators used on the lines, where the remaining tests were conducted.

TEST No. 2

Three 4-part 14-in. diameter insulators per pole.

Location about 40 miles inland from sea coast.

17 poles selected at random.

Phone test clear	Phone test clear	Phone test bombardment	Phone test bombardment
Insulators found O. K. by megger and voltage test.	Insulators found defective by megger and voltage test.	Insulators found O. K. by megger and voltage test.	Insulators found defective by megger and voltage test.
0 poles	6 poles	5 poles	6 poles

Total phone tests which were checked correctly by other tests	6 = 35 per cent
Total phone tests which were not checked correctly by other tests	11 = 65 per cent

Test No. 3

Three 4-part 14-in. diameter insulators per pole.
Location about 20 miles inland from San Francisco Bay.
25 poles selected at random.

Phone test clear	Phone test clear	Phone test bombardment	Phone test bombardment
Insulators found O. K. by megger and voltage test	One or more shells of one or more insulators found defective by megger or voltage test.	All insulators tested O. K. by megger and voltage tests.	One or more shells of one or more insulators found defective by megger or voltage tests.
2 poles	0 poles	16 poles	7 poles

Total phone tests which were checked correctly by other tests	9 = 36 per cent
Total phone tests which were not checked correctly by other tests	16 = 64 per cent

Test No. 4

Six 4-part 14-in. diameter insulators per pole. (Twin three-phase circuits on a single-pole line, with the two circuits solidly connected in parallel at both ends.)

Location about 20 miles inland north of San Francisco bay.

209 poles tested; consisting of two pieces of line about 8 miles apart and of 70 and 139 poles respectively.

Phone test clear	Phone test clear	Phone test bombardment	Phone test bombardment
All shells of all insulators found O. K. by megger and voltage test.	One or more shells of one or more insulators found defective by megger and voltage test.	All shells of all insulators found O. K. by megger and voltage test.	One or more shells of one or more insulators found defective by megger and voltage tests.
48 poles	50 poles	46 poles	65 poles

Total phone tests checked by other tests	113 = 54 per cent
Total phone tests not checked by other tests	96 = 46 per cent

TEST No. 5

Three 4-part 16-in. diameter insulators per pole.
Location about 3 miles inland from San Francisco bay.
81 poles tested, all in a single continuous piece of line.

Phone test O. K.	Phone test O. K.	Phone test bombardment	Phone test bombardment
Insulators O. K.	Insulators Some shell defective on one or more insulators.	Insulators O. K.	Insulators Some shell defective on one or more insulators.
9 poles	8 poles	12 poles	52 poles

Total poles on which phone test was checked by other tests..................................	61 = 76 per cent
Total poles on which phone test was not checked by other tests..................................	20 = 24 per cent

The results show that a number of defective insulators can be detected and removed as a result of the phone test but at the great expense of taking down many times the number of sound insulators from the poles showing defective in order to get the few bad ones. Again, the expense of taking down the insulators from poles showing defective, only to find that no bad ones exist. And lastly perhaps the most unfavorable feature—trial tests demonstrate a large percentage of defective insulators are missed altogether in the field survey. While the probability of future line trouble is no doubt decreased in direct proportion to the number of defective insulators removed, it was this last feature which led to the abandonment of the telephone method for the trial of other schemes which it is hoped will show more perfect scores in the results obtained.

Current audible as a clear musical tone over good insulators is the same as that obtained by antennae effect in the vicinity of the circuit and is due to harmonics, since the fundamental at 60 cycles is a very low pitch tone too low to be at all noticeable in the telephone receivers. In a system with a grounded neutral the principal harmonic is usually the third and in a delta system the fifth or seventh.

We agree that brush discharge is the cause of the scratching or spitting noises heard as superimposed on the "clear" hum. Brush discharge is not necessarily due to a cracked shell or a shell of low megohm resistance. If the design of the insulator is such that the air is overstressed at any point, a brush discharge will be formed even though the insulator is perfectly good. A certain type of insulator with which we have experimented, all showed "bad" on the line but were found "good" when removed and tested.

We do not think that the neutral of an ungrounded delta system of any size and voltage shifts sufficiently to affect the voltage over the insulator on any one phase unless an actual ground has taken place. The displacement of the neutral can only be caused by the flow of a very considerable current to earth from one phase. The current which must flow to ground from one phase of a delta system to shift the neutral to that phase is equal to about 1.5 times the normal charging current. This current to ground would be about 18 times 1.5 or 27 amperes on a 60-kv. system with 100 miles of line. Certainly no current which would leak over one or several insulators would shift the neutral enough to affect the voltage over the insulators on that phase.

We suspect that the air in the vicinity of the second (short) shell of the insulator would become overstressed if the top was defective and frequently overstressed if the third or center was defective. This particular type of insulator appears to be one which lends itself very well to the application of the method of testing described. It should not be inferred that the method will be equally successful with other types of insulators or under the conditions existing on other systems.

E. E. F. Creighton: An experimental and theoretical study was made of the telephone method of testing insulators in an endeavor to bring out definite information on the factors involved

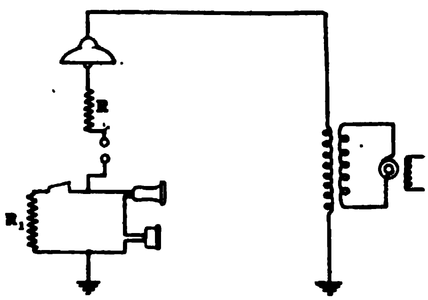


FIG. 1

and to determine the limitation of its successful use. The experimental work may be divided into two categories: namely, first, tests with gaps and resistance; and second, tests on defective insulators.

The apparatus for the experimental work (Fig. 1) consisted of a sine-wave alternator with a smooth core; a 50-kv. step-up transformer, three good suspension disks and seven defective pin-type insulators, a small sphere gap (2.5 cm. diameter), a water resistance tube giving a resistance of 60 megohms, telephone receivers (one of 5-ohms resistance and one of 70-ohms resistance), and a resistance box for shunting these telephones. The studies made can be designated under five categories:

1st, determine the point of brush discharge in the insulator when there is neither series resistance nor series gap in the circuit; 2nd, determine the effect of series resistance in diminishing the sound in the telephone receiver when there is no gap in series; 3rd, determine the effect in the receiver of introducing a continuously increasing series gap when there is series resistance in the circuit, and 4th, the same with no series resistance in the circuit; 5th, determine how much shunting resistance in parallel with the telephone receiver becomes undesirable.

Test With Good Insulators in Series

No attempt will be made to present the tests in detail but rather to give the deductions made from these tests, which will be designated as *A*, *B*, *C*, *D*, and *E*.

Conclusion A. When there is no gap in series with the insulator and the charging current of a single suspension disk insulator is carried through the telephone a pure sine wave gives a low, musical note. With a difference in sensibility of the telephone receiver and difference in attention the 60-cycle note becomes audible for different values of current. In a noisy room with a 70-ohm receiver in series with a single 10-in. suspension disk the sound becomes audible at 20 kv. applied. Since the capacitance of a single disk is about 34 times 10^{-12} farad, its reactance will be 85 megohms, and the current in the receiver 236 micro-amperes.

When the resistance of 68 megohms was placed in series with the insulator there was an appreciable decrease in the sound, due to the decrease in current. Since the reactance and resistance combine at right angles, the total resistance in the circuit was 110 megohms which allowed the passage of 182 micro-amperes (77 per cent of the previous value). The musical note was pure to start off with and went through no changes in timbre by the introduction of the resistance.

This leads to the conclusion that porous insulators which have absorbed moisture and have a measurable resistance in megohms or lower will give no indication in the telephone of their defectiveness. The same conclusion applies if the insulator is cracked and filled with moisture which makes a moisture contact with the cement. If the contact between the cement and the crack is made by means of a small spark, then the conditions are different and a discussion will follow under a later paragraph.

Conclusion B. By gradually raising the voltage on the suspension disk from 20 kv. the growth of the brush discharge in the insulator can be heard in the telephone. The brush discharge is also audible directly from the insulator. At 50 kv. there is considerable roughness in the musical note which can be attributed to the brush discharge from the various points on the surface of the Portland cement in the head of the insulator. Once familiar with this sound of the uniformly distributed brush discharge it can be distinguished from the other sounds which will be described later. This sound is somewhat diminished by the introduction of 68 megohms in series with the suspension disk.

Conclusion C. If the resistance is left in series and the voltage is maintained constant, say at 50 kv. and the sphere gap is gradually opened, a new sound of rather high pitch but not a musical note takes place. As the gap is gradually opened to 0.02 in. the pitch gradually decreases and the intensity of sound increases. Beyond this gap length the sound takes on gradually a different note. The sounds are full of different noises which gradually grow and fade in a way which baffles description in words. At small gaps there is a hissing noise like the escape of steam. As the gap increases there is superposed a disagreeable muscial note of decreasing pitch. Then there appears a rumble like the sound given off from the rails by a rapidly moving express train. This gradually passes into a disagreeable scratchy sound and at the larger gaps ending up with a distinct rattling sound as the sparks become less and less frequent per second. From the smallest gap to the largest gap the intensity of the noise, irrespective of its character, gradually increases, so long as the series resistance is left in place. The difference between the sound given out by the series spark and the sine wave current without series spark may be described as the difference between a noise and a musical note. It is just as distinct as the difference between multiple strokes on a bell and multiple strokes on the bottom of a dish-pan.

We may conclude from this that any spark in an insulator with the resistance of a wooden pole in series will cause a peculiar sound in the telephone receiver, the nature of the sound depending on the length of the spark in the insulator. If a single skirt of a pin-type insulator is cracked and the charging current is sparking into this crack, the sound will be distinctly heard on the telephone and it will have a note that can be distinguished from both the musical note and the evenly distributed brush discharges. The telephone receiver then is fitted to detect this kind of a fault in an insulator but the voltage must be such as to cause the spark. A spark may not necessarily be due to a defective porcelain and a cracked porcelain may be so full of moisture as not to spark.

Conclusion D If the series resistance is entirely eliminated and the charging current of the insulator is taken through the telephone with a series gap gradually increased, a result will be obtained quite contrary to the ones just described. When the resistance is not in series and with the tiniest spark playing, a very high pitch is obtained which is something more than a noise and may be described as a rather disagreeable musical note. For small gaps the sounds are somewhat similar to those with resistance in series. As the gap opens the pitch decreases and the noise becomes very scratchy beyond 0.02 in. Beyond this gap also, the noise begins to decrease in intensity until the maximum spark gap, about 0.35 in. is reached when the sound has very greatly decreased although it is still audible. It has very little resemblance to the sound given by the same spark length when the resistance is in series. It should be noted that the sound decreases rather than increases with the gap length after the first 0.01in. or 0.02 in. is passed. The high pitched noises at small gap lengths are due, partially at least, to many successive sparks jumping the gap for every cycle of the generator wave. Larger gaps require more voltage built up before the spark takes place and therefore there are a less number per cycle.

If this method then is applied to an insulator on a metal tower, quite different intensities of sound will be obtained from those on a wooden pole line.

It seems desirable to endeavor to point out the cause of the difference in the sound in the telephone receiver when the series resistance is used and when not. With a high resistance in series the condenser discharge from the insulator capacitance is so thoroughly damped that it passes through the telephone as a single impulse and we get the effect on the iron disk of a single blow on the bottom of a dish-pan. When there is no series resistance the discharge of this condenser is damped comparatively little and as a result the iron disk of the telephone will receive a blow first in one direction and then in the other direction as the logarithmic wave dies out. This frequency is so high that the inertia of the disk will not allow it to move in synchronism with the oscillation. Therefore each half-cycle of the oscillation counteracts the previous one, leaving the disk almost stationary. As a result there is a very little sound given out.

Conclusion E. It is found that when the resistance in parallel with the telephone has a value five times the resistance of the telephone there is an appreciable diminution in the sound. As the shunting resistance increases the sound gradually increases and above 20 to 50 times the resistance of the telephone, the sound in the telephone has approximately its full value.

Tests With Defective Pin-Type Insulators

These tests were made on seven defective insulators furnished the writer by Mr. P. M. Downing from the Pacific Gas & Electric Company's lines last fall. To avoid prejudicial information the tests with the telephone were carried out without any regard to the defects of the insulators and subsequently the insulators were tested up with the megger on each separate skirt and the defective ones listed. The data were then rearranged for the convenience of the reader, placing the insulators in the order of their defectiveness, the least defective being placed first.

These insulators were used on 60-kv. circuit and their Y voltage would therefore be about 35 kv. The record given here is for an application of 43 kv. which is 23 per cent above the Y voltage. The reasons for this choice were several-fold. In the first place the laboratory was noisier than the usual location of a transmission pole. Second, it was desired to make the laboratory test a little more severe than the usual conditions of the line to make up for high-voltage surges which would naturally occur on the line, and third, an endeavor to make the test voltage a little more severe than could be found in practise with the idea of determining the best results which might be obtained in actual service. No doubt with a more sensitive telephone receiver more noise could have been obtained but it is doubtful if the greater intensity of noise in the telephone receiver would have given any distinguishing effect. This conclusion is drawn from the fact that perfect insulators of the suspension type gave more noise by internal brush discharge than the defective insulators of the pin type.

The first test consisted in connecting up the pin to one terminal of the insulator and allowing the other connection to hang in the air parallel to the insulator about 8 in. away. A very considerable corona could be heard directly on this wire but no appreciable sounds could be detected in the telephone receiver. This shows that any noise obtained does not come from the distant points of the loads but must come from those more directly in contact with the porcelain.

Tests on Insulator No. 1. This insulator originally measured less than 10 megohms on skirts 3 and 4, counting the skirt next to the line as No. 1. However, it had dried out at the time the telephone test was made and all four skirts measured infinity. The voltage was raised on this insulator up to 50 kv. without giving any distinguishing sound in the telephone which would indicate that it was defective.

Tests on Insulator No. 2. The second skirt of this insulator measured 2000 megohms and the other three skirts infinity. This insulator also up to 50 kv. applied gave no distinguishing sound to indicate its defectiveness.

Tests on Insulator No. 3. This insulator originally meggered less than 10 megohms on skirts 2 and 3 but by drying out it measured 2000 megohms on skirt 2 and infinity on skirt 3, and subsequent to the last test, skirt 4 developed defectiveness and had a resistance of 10 megohms. As it stands at the present time then, skirt 4 measured 10 megohms and skirt 2, 2000 megohms. At 43 kv., 23 per cent above Y voltage, there was no audible sound to indicate defectiveness. However, at 50 kv. a distinct brush discharge could be heard. This sound of the brush discharge is sufficiently different from the spark of the gap in series to be distinguished but not described. The defect in this insulator could not be told by our telephone tests.

Tests on Insulator No. 4. This insulator was slightly worse than the previous one in that skirt 2 measured less than 10 megohms—how much less is not known since the megger needle went to its zero value. Skirt 4 gave 2000 megohms. With 68 megohms in series to represent the resistance of a transmission pole no distinguishing sound of fault could be heard in the telephone either at 43 kv. or at 50 kv. When the series resistance was cut out there was a sound such as a slight, distributed brush discharge in an insulator would give. At 50 kv. this sound of brush discharge was intensified but there were no indications of sparks taking place internally in the insulator. It should be noted that series resistance decreased the sound of the telephone and is just the contrary to the effect obtained with a long series gap where the spark could take place in concentrated form. Attention is called to this fact to show the various sounds that can be given out under the various conditions. The operator must learn these sounds that correspond to the different conditions by actual use. This experience has a bearing on how near to the insulator the lineman must be in order to obtain the desired degree of intensity. Again his personal judgment must be depended upon.

Tests on Insulator No. 5. This insulator originally meggered less than 10 megohms on both the 3rd and 4th skirts. However, at the time of test the third skirt had risen to 30 megohms With a series resistance of 68 megohms and the potential at 43 kv. there was no distinguishing sound of defectiveness.

With the series resistance cut out there was quite a distinct brush discharge audible at 43 kv. At 35 kv. it was proportionately less, although it is very probable that the noise of the brush discharge might be sufficient to throw this insulator under suspicion.

At 50 kv. applied an internal spark suddenly took place. The difference in the sound was unmistakable.

Tests on Insulator No. 6. This insulator was slightly more deteriorated than No. 5 in that both skirts 3 and 4 measure less than 10 megohms. The needle of the thousand-volt megger went against its zero spot.

The same sound of brush discharge could be heard on this insulator as on the previous one. At 50 kv., however, only the brush discharge was intensified without giving any sound of internal spark.

Tests on Insulator No. 7. This insulator was the worst of all, having the 2nd, 3rd, and 4th skirts all meggering too low to read on the thousand-volt megger. On this insulator very little sound of brush discharge could be heard at 43 kv. when 68 megohms of series resistance was used. Without the series resistance, however, distinct sounds of brush discharge could be heard at voltages as low as 15 kv. At 43 kv. and no series resistance, there was not only a loud noise of the brush discharge but also a superposed sound of higher pitch. There can be no doubt that by this method any operator with the slightest experience could detect this insulator as faulty.

General Conclusions. These data lead one to the following tentative conclusions regarding this method of test:

1st. The method apparently cannot give good results for porous insulators with either air or water in the pores although such porcelain is defective.

2nd. Insulators with three petticoats out of four defective showed up with great intensity. Insulators with two skirts out of four defective may apparently be distinguished in many cases provided series resistance is eliminated by making the telephone connection near the insulator pin.

3rd. Considerable difficulty will be encountered using the method on a metal tower with the pins grounded. A low resistance telephone will then be desirable and possibly a ground connection separate from the tower legs.

4th. Certain conditions on the line will make the method more favorable there than in the laboratory tests, such as quiet surroundings and more high-voltage surges. On the other hand, certain disadvantages may be encountered in the presence of the higher harmonics of the generator, especially the 11th, 13th, 17th and 19th harmonics which correspond to 12 teeth per pair of poles and 18 teeth per pair of poles. These harmonics will be more or less magnified by the capacitance of the line, depending upon how much the circuit is loaded. Such harmonics will give a different timbre to the sound in the telephone.

5th. The laboratory tests would indicate that roughness in the surface of the Portland cement, such as might be caused by the presence of an air bubble on the surface of the porcelain at the time the cement was set, might cause local brush discharge indistinguishable from the noise produced by a defective porcelain. Such a local spark can be easily reproduced experimentally by twisting a wire around the metal pin of a suspension insulator and extending it out a fraction of an inch, leaving the point not quite in contact with the porcelain.

6th. With all that has been said regarding the possible inaccuracies of this method, it still remains as a very cheap and simple method of detecting pin-type insulators which are in an advanced stage of deterioration.

Presented at the Pacific Coast Convention of the American Institute of Electrical Engineers, Seattle, Wash., September 6, 1916

THE HIGH-VOLTAGE POTENTIOMETER

BY HARRIS J. RYAN

ABSTRACT OF PAPER

The author describes a high-voltage potentiometer which may be made at reasonable expense consisting of a water resistance potential distributor and a sparking probe potential difference detector. The water resistance consists of a column of water moving slowly through an ample length of garden hose, and tapping in points through which to connect the probe are provided by breaking the hose at regular intervals and connecting it with any of the plain metal connectors found on the market as "hose menders." The results of an integrity trial are charted in Fig. 2. The device is intended for investigations in which the results are not required to be known within 2 or 3 per cent of their actual value.

THE potentimoter method for the determination of altering potentials or for the measurement of alternating-voltage duties requires: 1. A *distributor* of alternating potential, identical in phase and wave form with the alternating potential to be determined. 2. A satisfactory potential difference *detector* to determine when the known potential from the distributor matches the unknown potential to be measured. For a high-voltage potentiometer at reasonable expense the following types are feasible:

A source of synchronous variable voltage that matches the voltage to be measured in phase and wave form; requires a phase-shifting transformer and an induction regulator or a suitable multiple-tap transformer.

A condenser connected to the high-voltage source having a variable potential feature as follows: A fluid dielectric and a potential tapping plate electrode that may be moved to any position between the main electrodes of the condenser, or a series of electrode potential plates mounted in the dielectric between the main electrodes at uniform intervals.

A chain of equal water resistances connected across the same high-voltage source as the test specimen from which any required potential may be tapped.

There are two types of detector available:

The sparking probe.

The Bennet small current oscillograph.*

In the sparking probe detector advantage is taken of the fact that a spark occurs at a pointed electrode when used to connect two condensers charged to different potentials. This is true even when the capacitances and differences of potentials are small. In the Bennet detector an oscillograph with suitable auxiliary equipment is used to observe the charging current taken by the insulator system under observation, and to note when the potential applied to a conductor is such that it may be brought in contact with a metal part of the insulator system without disturbing the normal value of such charging current.

The author has had experience in the development and use of these several potential distributors and the sparking probe detector. He has had no experience with the Bennet detector, though he is convinced, from his own experience, that such detector will yield reliable results. Of the several expedients specified it has been found that the water resistance distributor and the probe detector constitute a convenient and reliable high-voltage potentiometer that may be constructed of common materials with ordinarily skilled labor at small cost. A column of water moving slowly through an ample length of garden hose constitutes the resistance. The length of hose required for a given over-all voltage may vary considerably. The author has used *one foot* (30.4 cm.) of hose *per one thousand* maximum range effective *volts*. Tapping-in points from which to connect the cable leading to the probe are provided by breaking the hose at regular intervals and connecting it with any of the plain metal connectors found on the market as "hose menders". The illustration in Fig. 1 was taken from a photograph of one of these water column potential distributors. The hose is of the common *three-quarter-inch* (1.9 cm.) variety, 75 ft. (22.8 m.) long, in 50 sections of 18 in. (45.6 cm.) each. It is formed into a cylindrical helix of twelve and one half turns on a diameter so as to use four sections per turn and so as to make corresponding metal connectors line up in four columns on the surface of the helix-cylinder. The turns are spaced, insulated and held together by strain insulators and light galvanized steel strands

*Distributing Potential over a String of Insulators. By J. L. Brenneman and Harold M. Crothers. *Electrical World*, Vol. 64, Dec. 5, 1914. p. 1095.

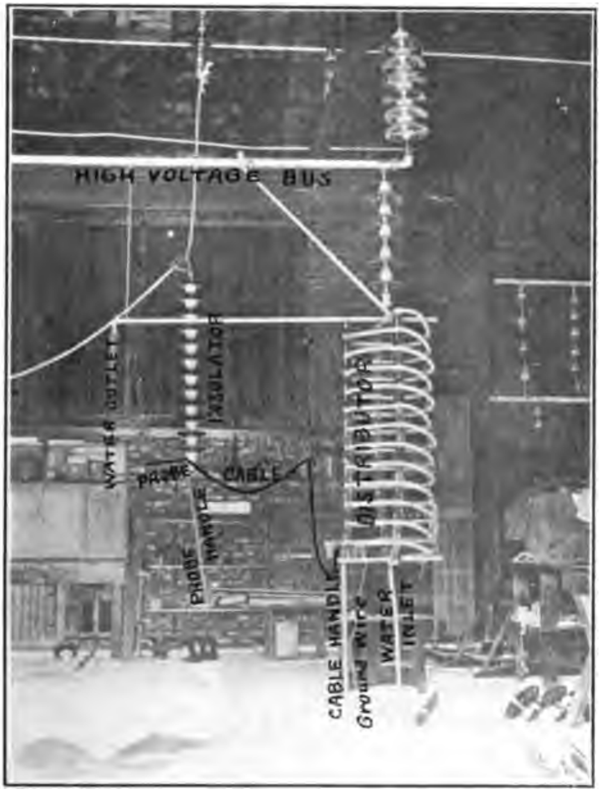


FIG. 1—HIGH VOLTAGE POTENTIOMETER [RYAN]

located at the metal connectors. The hose starts at the bottom from one branch of a supporting cross formed of *three-quarter*-in. (1.9 cm.) galvanized iron pipe and a five-way fence-pipe fitting. It ends at the top in a branch of a duplicate pipe structure. The bottom end is attached to the water supply and grounded if this water connection is made through rubber or other non-conducting hose. The branch of the top cross is connected to one of the high-voltage source terminals and extended horizontally to a convenient distance, five ft. (1.5 m.), and terminated downward in a common sprinkler nozzle. The openings in the nozzle are large and numerous enough to permit ample exit of water without pressure. The water then falls away in drops, thus breaking the circuit that would otherwise be formed in parallel with the distributor circuit.

One of the four columns formed by the strain insulators is selected for mounting the tapping-in terminals of the conductors that lead through the interior of the helix to their corresponding metal hose connectors. These tap conductors are made of No. 10, B. & S. gage galvanized steel wire. To make probe connecting terminals at the outer ends of these tapping wires, such ends are formed into nearly complete rings finished with eyes and clamped with small bolts in proper order around the strain insulators. In an over-all sense this construction is strategic against corona formation.

Ordinarily 75 kilovolts will set up 50 milliamperes through this distributor. The amount of the current naturally depends upon the temperature of and the impurities in the water. Obviously variation in the value of the current through the distributor does not affect the integrity of the potentiometer results. It is only necessary in connection herewith that the current shall always be large compared with the charging current that passes from the probe cable to surrounding objects. The length of the cable used with this distributor is *ten* ft. (three m.) Its capacitance to earth does not exceed 0.000025 microfarads and the charging current liberated from it at 75 kilovolts to earth is, therefore, not more than *seven-tenths* of a milliampere.

The development and study of these various forms of high-voltage potentiometer was begun in March, 1912. Many integrity trials of them have been made. Some of the results thus obtained have been published.* The water resistance

*High-Voltage Potentiometers *Jour. Electricity, Power, and Gas*, Vol. 34, April 10, 1915.

distributor was developed during the present year and after the author was told by Mr. Faccioli that a resistance distributor had been found to give excellent results. Experience with the transformer and condenser types of distributor showed that the water resistance distributor must yield reliable results, consequently only one integrity trial of it has been made, and that with no particular care. In this trial the potentials of a light chain were determined when suspended in the electric field formed between two parallel lengths of pipe by 140 kilovolts. The chain was mounted at various distances from one of the conductors and its corresponding potentials were determined by the potentiometer and calculated from the known dimensions. The results are charted in Fig. 2. No great accuracy is claimed

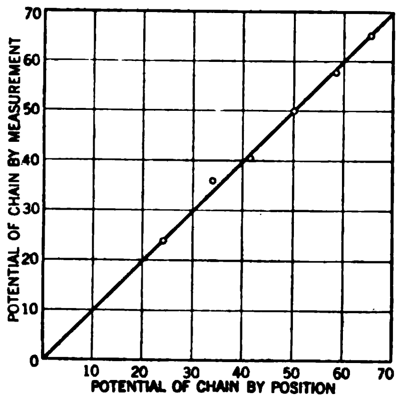


FIG. 2.

for the outfit. It is intended only for those studies in which the results are not required to be known within two or three per cent of their actual values.*

The potentiometer may be used to determine the potential of any outline or surface of an insulation system whereat or where-on a metal wire or sheet may be mounted and to which the potential probe can be applied. Such wire or sheet is called the insulator *potential electrode*. In general the capacitance of the insulator potential electrode is relatively small. The effect of the presence of the probe will, therefore, be such

*It should be noted that the results of the integrity trial charted in Fig. 2 embrace two classes of errors, only one of which is chargeable to the potentiometer, while structural deformities and defects in chain location measurements are responsible for the other.

as to alter the potential of the electrode somewhat. The only result thereof is to widen the zone of potential through which the detector indicates an equally good balance. This effect occurs alike above and below the true potential of the insulator electrode and is eliminated by reading at the middle of the potential balance zone. The true balance must often fall between the potential taps as actually provided in the distributor. This is an additional cause that generally prevents a tap being found at which absolutely no probing spark is discernable in full darkness. For example in securing the results charted in Fig. 2 when the center of the chain was located seven in. (2.1 m.) from the surface of one of the high-voltage conductors a faint but definite spark occurred between the probe point and chain at the 22 per cent tap and again at the 25 per cent tap; 23.5 per cent of the line voltage was, therefore, given as the reading for the potential of the chain in this position. When the probe point was applied to the chain carrying potential tapped at 23 and 24 per cent of the line voltage, barely discernable sparks passed; they did not differ in recognizable degree showing that the true balance occurred midway between them.

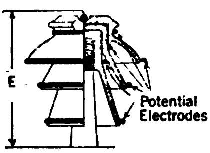


FIG. 3.

It is not thought necessary to discuss matters of this sort further. It is believed that anyone whose general training and experience have prepared them to take up work of the present character will have no difficulty in learning quickly from their own perceptions and efforts the correct procedure for this sort of potentiometer. Obviously two persons must work together to apply it. One handles the probe and the other handles the probe cable from tap to tap in the distributor until a potential balance is found. The probe and tap ends of the probe cable are each handled at the end of a suitable stick of clear quality wood, such as redwood, white pine or poplar, impregnated with paraffin as a precaution against the absorption of water. In work upon such insulation systems as a suspension type insulator the person or the operator should be as distant as possible and permit of the proper handling of the probe in order that the electric field about the insulator and therefore the voltage duties of its parts will not be disturbed. It is thought unnecessary to point out the many expedients that may be employed in locating and mounting insulator potential electrodes so as to explore the intensity of the electric fields in the air, oil or within the solid dielectrics of any system of insulation. These will promptly suggest themselves to anyone likely to have work of this sort on his hands to do.

In Fig. 3 the cross section of a pin-type insulator is given showing the location of wire hoops to constitute insulator potential electrodes for the purpose of determining the voltage duty of the air about the insulator, over its surfaces and through its solid sections. It is obvious that these wire hoops must be located in equipotential surfaces. Their presence does not disturb the electric field nor the voltage duties of the insulator parts and of the surrounding air.

Presented at the Pacific Coast Convention of the American Institute of Electrical Engineers, Seattle, Wash., September 6, 1916.

AN ARTIFICIAL TRANSMISSION LINE WITH ADJUSTABLE LINE CONSTANTS

BY C. EDWARD MAGNUSSON AND S. R. BURBANK

ABSTRACT OF PAPER

A description is given of an artificial transmission line which can be readily adjusted to represent 200 miles (321.86 km.) of commercial transmission lines of any spacing up to a maximum of 120 in. (3 m.) and any size wire up to 4/0 copper. It can also be made to correspond to aerial or cable telephone lines and to power cables. The use of this type of line in laboratory courses on transmission line phenomena is illustrated by a number of typical experiments. It is shown that quantitative data, sufficiently accurate for instructional purposes, may be obtained by using portable voltmeters and ammeters and by the oscillograph.

THAT artificial transmission lines can be used to advantage in investigations on transmission line phenomena is well known. It has been proved by extended research* that actual transmission line phenomena can be accurately reproduced in laboratory structures and that the theoretical equations correctly express the quantitative relations between the line constants, voltages, currents, time and space phase angles and other factors that enter in the general transmission line problem. Artificial transmission lines have, however, been used only to a very limited extent either as laboratory apparatus for experimental work by students in power transmission courses, or by engineers when investigating industrial transmission systems. Very few engineering colleges have any facilities for laboratory work on transmission lines. The instruction is given by lectures, text-book recitations and class-room problems, without the aid of quantitative laboratory experiments. As a consequence comparatively few students gain a clear insight into transmission line phenomena, and although they may be able to develop the standard equations they fail to comprehend the physical phenomena involved or to understand what actually takes place in the transmission system. That quantitative laboratory experi-

*See Bibliography on page 1257.

ments would be as desirable in the study of transmission lines as the customary experimental work in courses on alternators, motors or telephones, is admitted. The difference in practise has been due chiefly to a lack of suitable apparatus for giving laboratory instruction on transmission lines.

The purpose of this paper is to describe the design and construction of an artificial transmission line adapted to the requirements of laboratory apparatus for undergraduate instructional experiments as well as for research, and to report a few typical experiments. The line has been in successful operation for the past three years in the Electrical Engineering Laboratories of the University of Washington. It consists of twenty units connected in series as shown in Fig. 1. Each unit, Fig. 2, is complete in itself and represents approximately ten miles of a power transmission line. The line can readily be adjusted, within wide limits, to any spacing or size of wire, or converted into a standard telephone line. The wiring diagram for the units is shown in Fig. 3 and for the complete line of twenty units in Fig. 4. The apparatus represents one line to neutral and can therefor be used in experiments on either single-phase or polyphase systems. The diagram shows that the line is of the " lumpy " type, similar to the artificial line at Harvard University,* with the condensers connected at the middle point of the inductance in each unit. While lines with uniformly distributed† inductance, condensance and resistance comply strictly with actual transmission line conditions the first cost and maintenance are much greater than for the "lumpy" type. Moreover the latter type can be made adjustable so as to represent

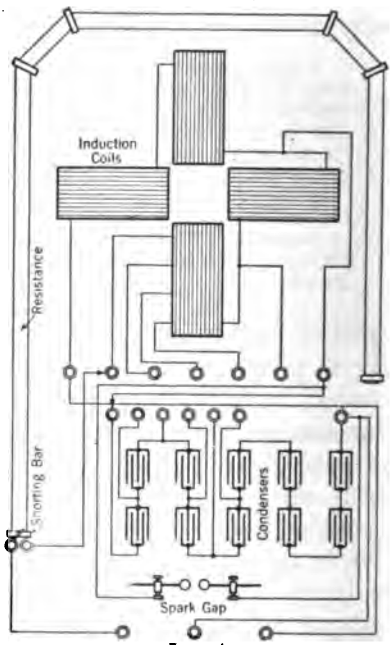


FIG. 3—WIRING DIAGRAM OF EACH UNIT

*See bibliography Numbers 5, 6, 7, and 8.
†See Bibliography Numbers 2 and 3.

[MAGNUSSON AND BURBANK]

Fig. 1—Complete Line of Twenty Units

[MAGNUSSON AND BURBANK]

Fig. 2—Assembled Unit

lines of almost any size of wire and for different spacings. The spark gap on each unit can be adjusted so as to provide protection to the condensers against excessive voltages that may develop under resonance conditions. The ten-mile unit was selected as a sufficiently close approximation to the uniformly distributed line constants of industrial transmission lines for frequencies up to 800 cycles per second.

Both for instructional and research purposes it is desirable to have an apparatus that can be adjusted so as to represent lines differing, not merely in length, but also in size and spacing of the conductors. This line is so designed that it can readily be adjusted so as to correspond to a line of any spacing up to 120 in. (305 cm.) and for any size of wire up to No. 4/0 hard-drawn copper. By the insertion of a 50-ohm non-inductive resistance between the units it is converted into a telephone line of practically standard specifications.

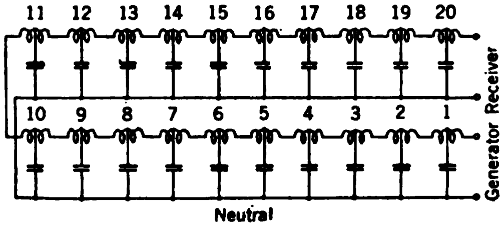


FIG. 4—WIRING DIAGRAM OF COMPLETE LINE

To comply with the above requirements the line constants must be adjustable within the following limits:

Resistance, minimum value = 2.59 ohms.

Inductance, maximum value = 0.021 henry;

Condensance,............ = from 0.1 to 1.0 microfarad

Resistance. The resistance of the inductance coils must not exceed minimum resistance in the unit, each of the four coils must be equal to or less than 2.59 ÷ 4 = 0.65 ohm. Selecting No. 14 A. W. G., d. c. c., copper, the length of wire in each coil must not exceed 257 ft. (78.3 m.). The coils as constructed* have 250 ft. each, thus allowing for the resistance of the connecting wires and for a slight adjustment when the line represents No. 4/0 copper wire. For lines with smaller sized conductors the additional resistance is obtained by moving the short-circuiting clamp on the loop of "Advance" resistance wire. Figs. 2 and 3.

*Bibliography No. 11.

Inductance. The inductance is obtained from four short air-core solenoids arranged in a square. For a given length of wire the inductance depends on the dimensions of the coil. The required dimensions were obtained by means of Brooks Formula†. The final dimensions of the coils as constructed are:

Mean radius.......................................2.20 inches (5.59 cm.)
Length of coil.....................................2.15 " (5.47 cm.)
Thickness of winding............................0.60 " (1.52 cm.)
Length of wire....................................250. feet (76.3 m.)
Number of turns (eight layers of twenty-seven turns each)..........216.

The mutual inductance is very nearly 8 per cent of the self-inductance for each unit. With the coils in position the measured value corresponds to the amount required.

The inductance in each unit can be varied by turning the right hand coil and by using the taps on the lower coil. Any inductance up to the maximum value can be obtained by making the proper adjustments. All the units have been calibrated showing the inductance for five positions of the movable coil and for four taps on the lower coil as illustrated in Table 1.

TABLE I.
Unit No. 15.

Position of movable coil	Coils in Series					
	4	3¾	3½	3¼	3	2
0°	0.0214	0.0193	0.0176	0.0161	0.0154	0.0098
45°	0.0209	0.0186	0.0167	0.0156	......	......
90°	0.0199	0.0178	0.0160	0.0149	......	......
135°	0.0188	0.0171	0.0158	0.0145	......	......
180°	0.0185	0.0168	0.0152	0.0142	......	......

The average maximum inductance for the whole line is 0.0213 henry for each unit. The measured inductance for the several units varies from 0.021 to 0.022 except for unit No. 2 which is 0.0197 henry.

Condensance. The line condensance is obtained from 200 standard telephone condensers, type No. 21-AA, guaranteed to stand 1000 volts. Each unit has ten condensers connected in series with taps brought out at the terminals of the 5th, 6th, 7th, 8th, 9th, and 10th condenser. Each unit has been calibrated and the results tabulated as illustrated by Table 2.

†University of Illinois, Bulletin No. 53.

A spark-gap was connected across the condensers as a protection against voltages in excess of the rated value of 1000 volts per condenser. Under resonance conditions this protection is necessary.

Cost. The cost per unit was approximately $24.00, or a total of $480.00 for the complete line of twenty units.

Instruments. For accurate measurements an a-c. potentio-

TABLE II.
Unit No. 15.

	Number of condensers in series.					
	5	6	7	8	9	10
Microfarads	0.182	0.151	0.131	0.114	0.102	0.092

meter is necessary and an instrument like the Drysdale-Tinsley alternating and continuous current potentiometer gives excellent results. Unfortunately the potentiometer is expensive and requires more skill in the operator than can be expected from ordinary students in power transmission courses. Quantitative values, sufficiently accurate for instructional purposes, may be obtained by means of ordinary portable voltmeters and ammeters,

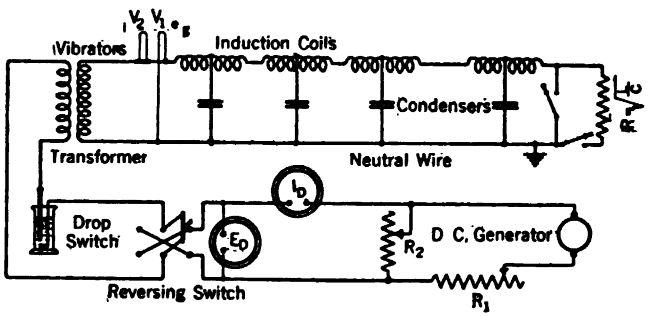


FIG. 5—WIRING DIAGRAM FOR IMPULSE OSCILLOGRAMS IN FIGS. 6, 7, 8, 9, 10, 11

for numerous experiments, as may be seen by comparing the calculated and the observed values in several of the experiments described in this paper. The instruments used were Standard voltmeters, ammeters, speed indicators, and a three-element oscillograph.

Great care must be exercised in keeping the frequency constant throughout each test. Slight changes in frequency will cause considerable changes in the voltmeter and ammeter readings.

Typical Experiments. The experimental data have been selected from student's laboratory reports, and credit is due Mr. R. Rader for Figs. 6, 7 and 8; Messrs. G. S. Palmer and D. K. Chaudhuri for Figs. 13 to 18 and 20 to 27; and Messrs. S. R. Burbank and F. T. Yamada for Figs. 9 to 11 and 28 to 37.

The circuit connections are shown in Figs. 5, 12 and 19 for each experiment. The oscillograms and the drawn curves are in a large measure self-explanatory. In all cases the size of wire was equivalent to No. 4/0 hard-drawn copper. The spacing was either 96 in. or 120 in. (2.4 or 3 m.) as noted below each figure. Experiments with other spacings and for other sizes of wire gave similar results.

The experiments selected may be grouped into three divisions:

1. Sudden impulses impressed on the line.
2. Voltage and current readings along the line. Constant voltage at the generator end and constant frequency.
3. Resonance.

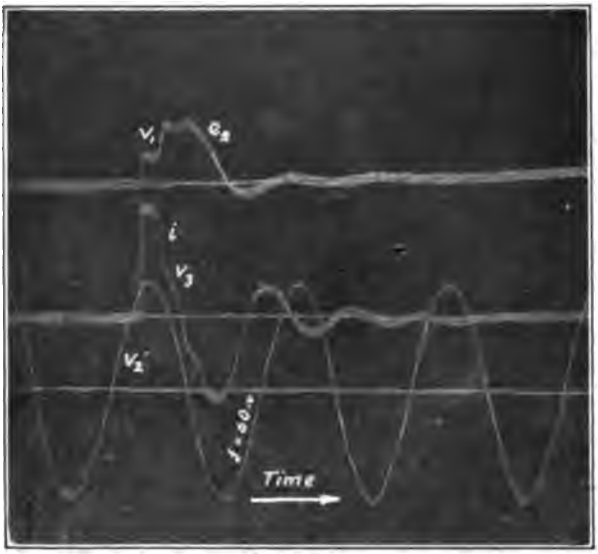
GROUP 1

A direct-current generator was connected to the primary of a transformer and the line to the secondary. Between the generator and the transformer was a drop switch, Fig. 5. Upon closing the switch a sudden impulse was impressed on the line from the secondary winding of the transformer.

For Figs. 6, 7 and 8 the line constants were $R = 51.7$ ohms, $L = 0.427$ henry, $C = 2.92$ microfarads. The original voltage and current impulses with the reflections are shown for receiver end open in Fig. 6 and short-circuited in Fig. 7. No reflections appear in Fig. 8 when the receiver has a resistance equal to

$$\sqrt{\frac{L}{C}} \text{ ohms.}$$

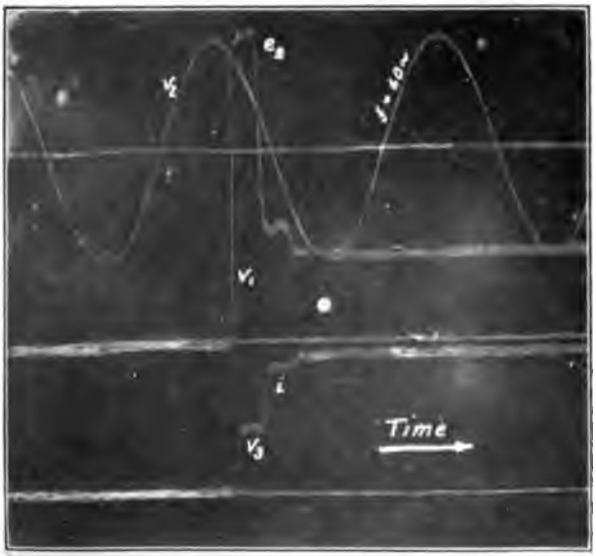
Calculating the length of the line from the line constants it should be equivalent to 208 miles (334.7 km.). Measuring the time taken for the impulse to be reflected from the receiver end as in Fig. 7, and assuming a velocity of 3×10^{10} cm. per second, the equivalent length of line was 214 miles (334.4 km.). A number of trials gave a similar discrepancy of approximately 3 per cent. In the fall of 1916 the condensers, a cheap grade, were replaced by Type 21-AA condensers, Measurements on



[MAGNUSSON AND BURBANK]

FIG. 6—RECEIVER END OPEN

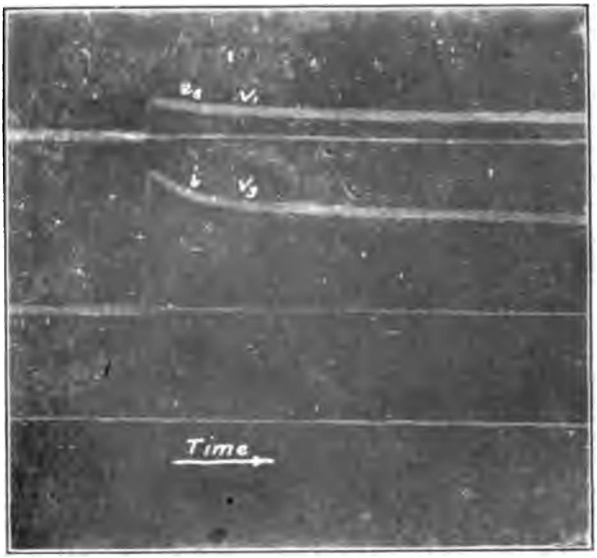
Spacing 120 in. — E_D = 98 v. — I_D = 6.00 amp.



[MAGNUSSON AND BURBANK]

FIG. 7—RECEIVER END SHORT CIRCUITED

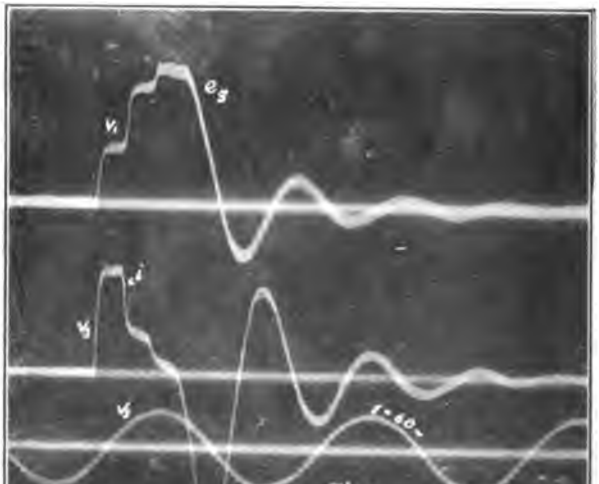
Spacing 120 in. — E_D = 100 v. — I_D = 2.5 amp.



[MAGNUSSON AND BURBANK]

FIG. 8—RECEIVER END CLOSED THROUGH $\sqrt{\frac{L}{C}}$ OHMS

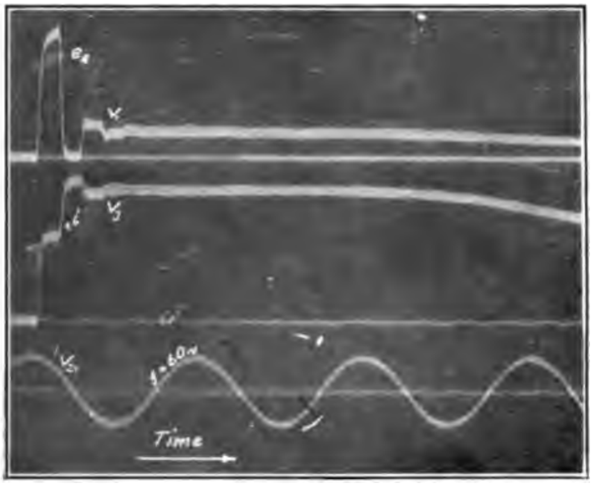
Spacing = 120 in. – E_D = 104 v. – I_D = 2.3 amp.



[MAGNUSSON AND BURBANK]

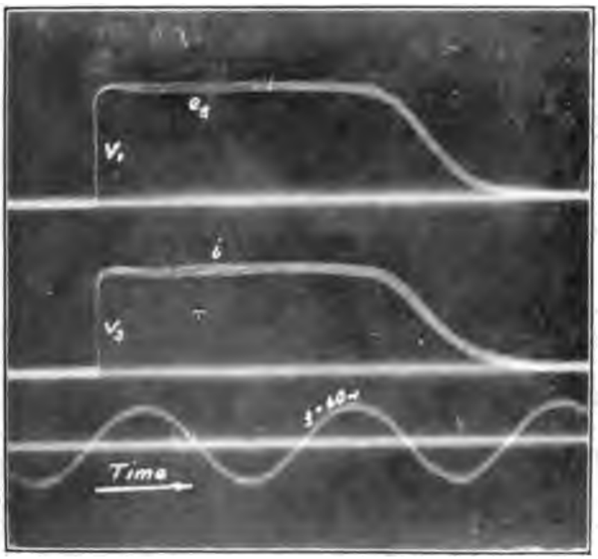
FIG. 9—RECEIVER END OPEN

Spacing = 96 in. – E_D = 110 v. – I_D = 19.8 amp.



[MAGNUSSON AND BURBANK]

FIG. 10—RECEIVER END SHORT CIRCUITED
Spacing = 96 in. – E_D = 101 v. – I_D = 20.0 amp.



[MAGNUSSON AND BURBANK]

FIG. 11—RECEIVER END CLOSED THROUGH $\sqrt{\frac{L}{C}}$ OHMS
Spacing = 96 in. – E_D = 110 v. – I_D = 19.7 amp.

oscillograms taken after the new type of condensers were on the line, as in Figs. 9 and 10, checked more closely with the length calculated from the line constants. Thus for Figs. 9, 10 and 11 the line was adjusted for a spacing of 96 in. (2.4 m.) The line constants were R = 52.9 ohms; L = 0.412 henry; C = 3.03

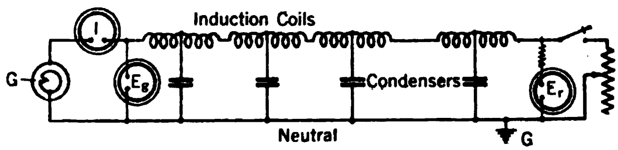


FIG. 12—WIRING DIAGRAM FOR LINE CHARACTERISTICS, FIGS. 13, 14, 15, 16, 17, 18—AND RESONANCE CURVES FIGS. 28 AND 33

microfarads. From the line constants the equivalent length of line was 208.5 miles (335.5 km.) From measurements on the oscillogram in Fig. 9 the equivalent length was 206.5 miles (332.3 km.) and from the oscillogram in Fig. 10, 208 miles (334.7 km.) A slight leakage in the first set of condensers probably caused the retardation of the electromagnetic wave. After

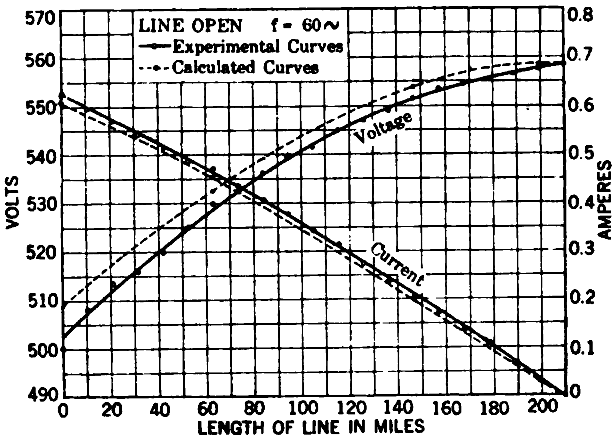


FIG. 13—VOLTAGE AND CURRENT CHARACTERISTICS

three reflections in the open line, (Figs. 6 and 9) the transformer and the line oscillate together causing an oscillatory transient of lower frequency.

GROUP 2

The change in the magnitude of the voltage and current along the line is shown in Figs. 13 to 18, inclusive, for the line open and for frequencies of 60, 100 and 120 cycles, respectively, in Figs. 13, 15 and 17, and similarly for the line loaded so as to have generator and receiver voltages each equal to 500 volts, in Figs. 14, 16 and 18.

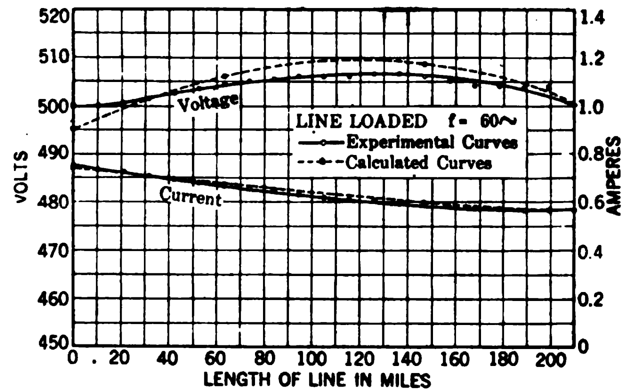


FIG. 14—VOLTAGE AND CURRENT CHARACTERISTICS

Necessarily the shunting of the voltmeter across the line changed the conditions in each case and caused discrepancies in the curves as indicated by the difference between the drawn and broken lines. Extreme care had to be exercised in keeping

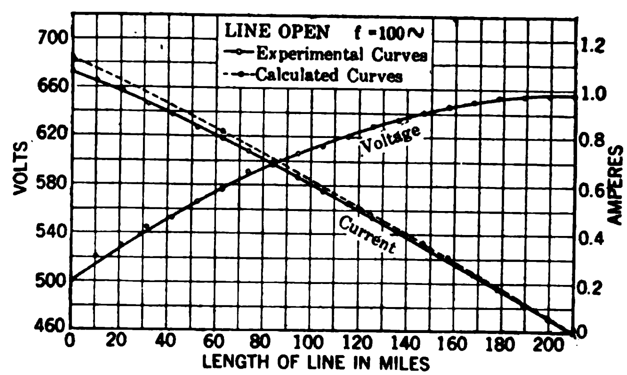


FIG. 15—VOLTAGE AND CURRENT CHARACTERISTICS

the frequency constant for each set of readings. A slight change in frequency will cause a considerable change in the receiver voltage with the line open. This is readily seen by comparing the receiver voltages for 60, 100 and 120 cycles in Figs. 13, 15 and 17.

Group 3

In obtaining the data on resonance, two single-phase alternators were used. Alternator *A* gave a voltage wave which appeared to be simple harmonic but on analysis was found to

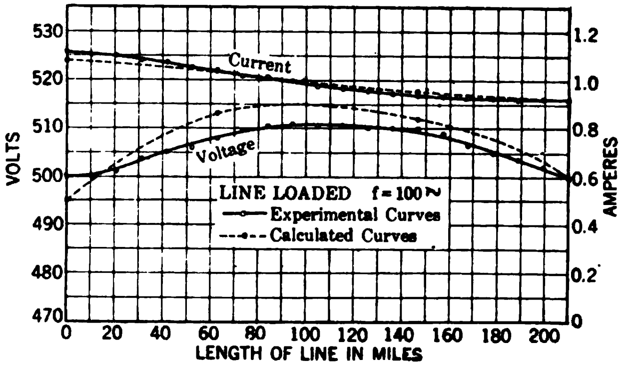


Fig. 16—Voltage and Current Characteristics

have a small third harmonic, about one per cent, of the fundamental. The shape of the voltage wave of alternator *B* is shown in Fig. 32, consisting of a fundamental combined with a 28.2 per cent third harmonic and a 5.4 per cent fifth harmonic. The

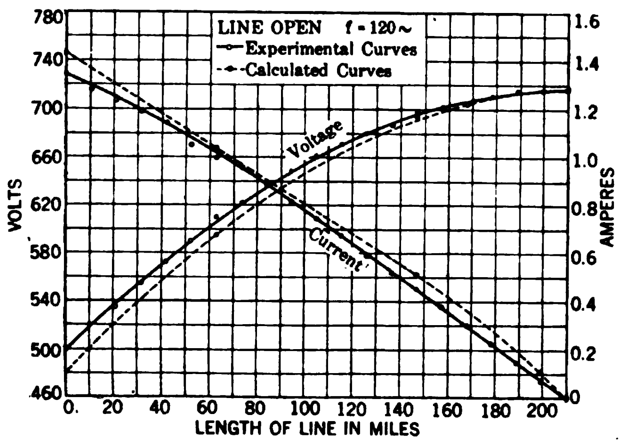


Fig. 17—Voltage and Current Characteristics

frequency of alternator *A* was normally 137 cycles and for *B*, 60 cycles.

At first it was assumed that alternator *A* gave a simple sine wave. The first indications that the assumption was not true were difficulties in securing consistent readings at all frequencies, particularly between 70 and 75 cycles. With the generator voltage of 1000 volts and the frequency about 72 cycles, the condensers in unit No. 20, at the receiver end, were punctured. Upon investigation it was found that the third harmonic caused resonance in the line and that the receiver voltage was greatly

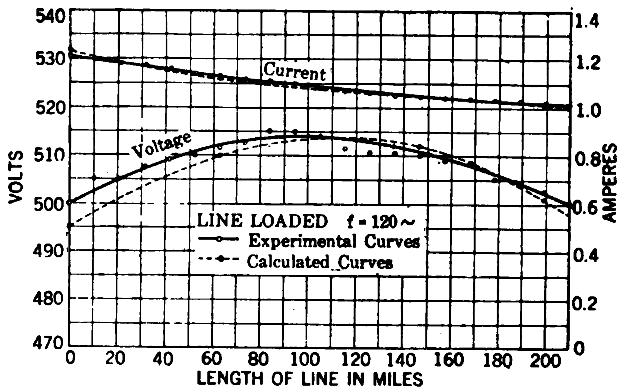


Fig. 18—Voltage and Current Characteristics

in excess of what would be produced by the fundamental. To prevent a similar accident spark-gaps were placed in each unit as shown in Figs. 2 and 3.

To secure accurate readings on resonance values, an a-c. potentiometer is necessary, but the effect may be observed on ordinary oscillograms and to some extent measured by portable voltmeters.

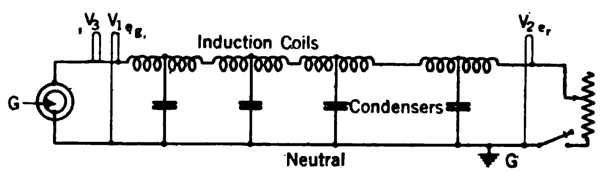
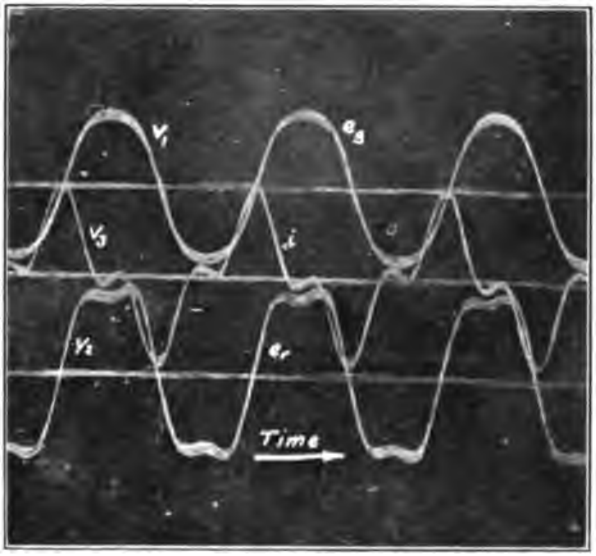


Fig. 19—Wiring Diagram for Oscillograms in Figs. 21, 22, 23, 24, 25, 26, 27, 29, 30, 31, 34, 35, 36, 37

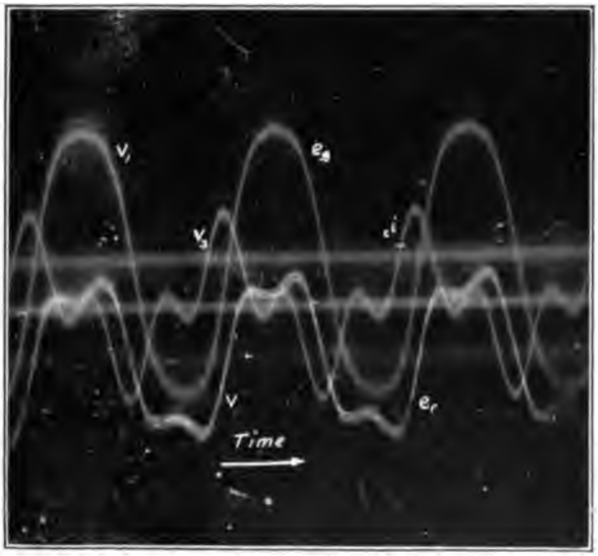
In Figs. 20 to 24, inclusive, are shown the oscillograms of the generator and receiver voltages and the charging current for 60, 66, 72, 100 and 120 cycles using alternator *A*. The generator voltage is nearly a sine wave in all cases. The receiver voltage and the charging current show a third harmonic in Fig. 20; an increased distortion in Fig. 21 and a maximum third harmonic



[MAGNUSSON AND BURBANK]

FIG. 20—RECEIVER END OPEN

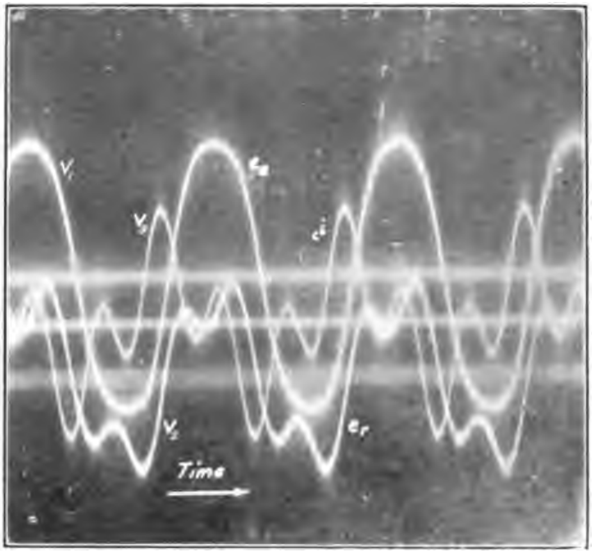
Spacing = 120 in. – f = 60 ~ – L = 0.427 h. — C = 2.96 mf. – E_g = 500 v. – E_r ≐ 558 v – I = 0.63 amp.



[MAGNUSSON AND BURBANK]

FIG. 21—RECEIVER END OPEN

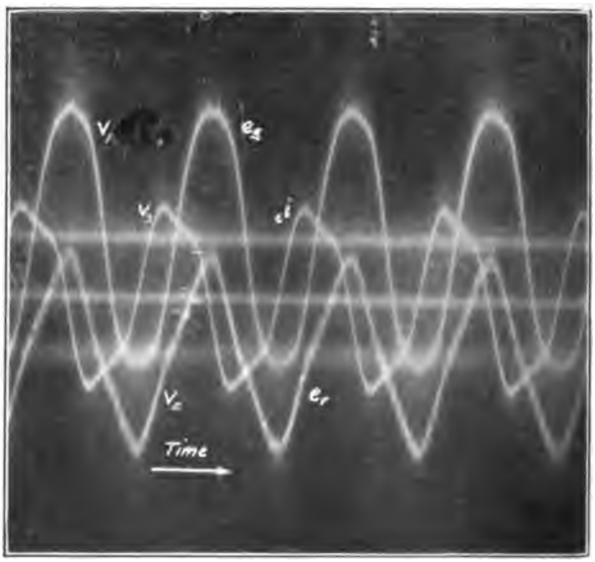
Spacing = 120 in. – f = 66 ~ – L = 0.427h. – C = 2.96 mf. – E_g = 500 v.



[MAGNUSSON AND BURBANK]

FIG. 22—RECEIVER END OPEN

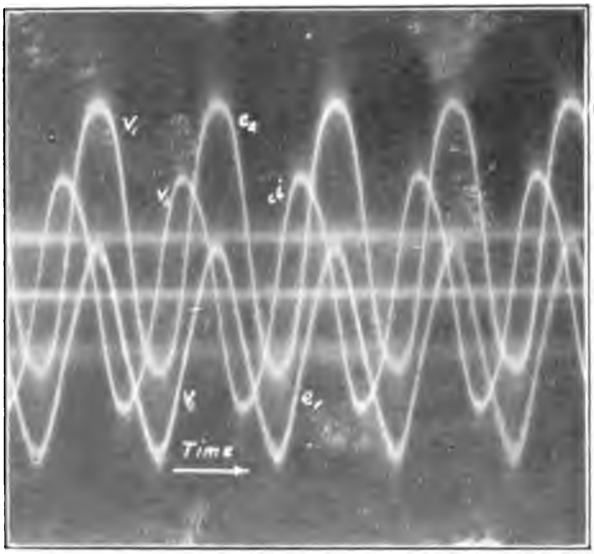
Spacing = 120 in. – f = 72 ~ – L = 0.427h. – C = 2.96 mf. – E_g = 500 v.



[MAGNUSSON AND BURBANK]

FIG. 23—RECEIVER END OPEN

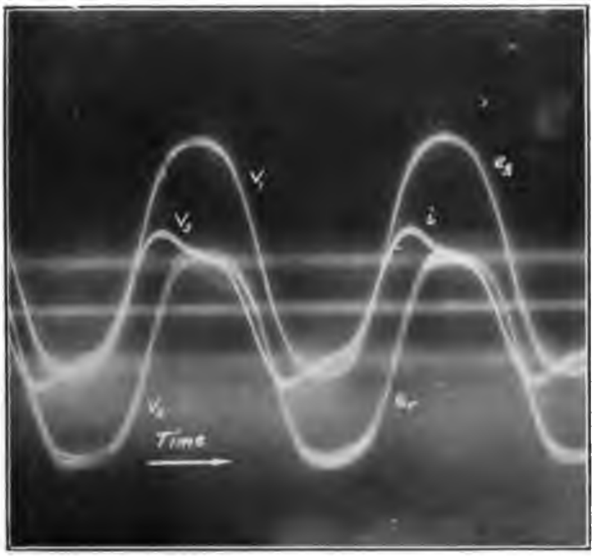
Spacing 120 in. – f = 100 ~ – L = 0.427 h. – C = 2.96 mf. – E_g = 500 v. – E_r = 655 v. – I = 1.06 amp.



[MAGNUSSON AND BURBANK]

FIG. 24—RECEIVER END OPEN

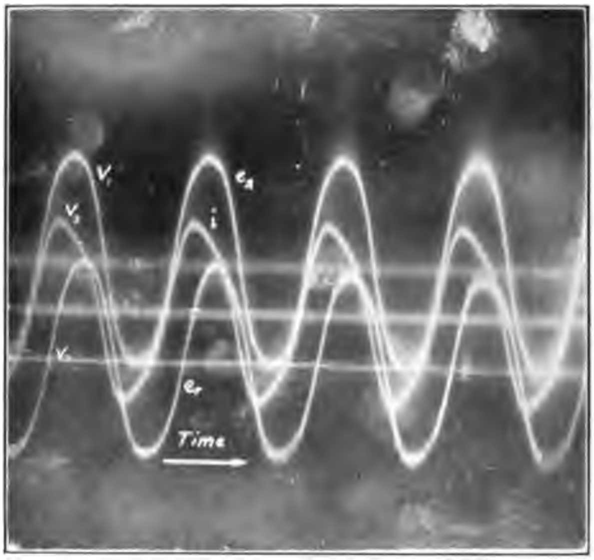
Spacing 120 in. – f = 120 ~ – C = 2.96 mf. – L = 0.427 h. – E_g = 500 v. – E_r = 716 v. – I = 1.34 amp.



[MAGNUSSON AND BURBANK]

FIG. 25—RECEIVER END LOADED

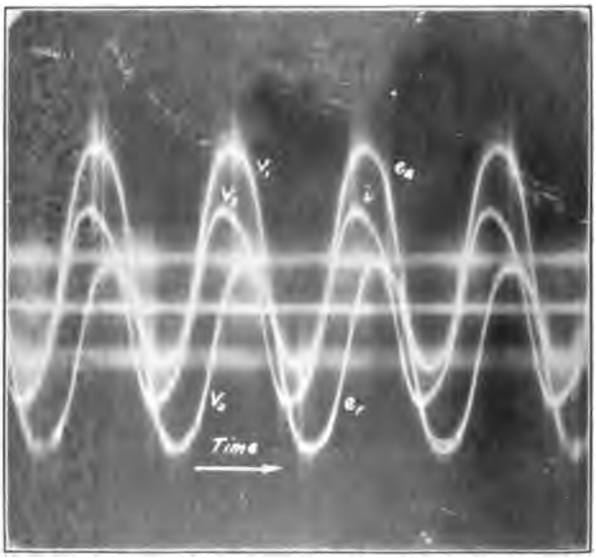
I_r – 0.56 amp. – Spacing 120 in. – f = 60 ~ – C = 2.96 mf. – L = 0.427 h.–E_g – 500 v. – E_r = 500 v.— I = 0.75 amp.



[MAGNUSSON AND BURBANK]

FIG. 26—RECEIVER END LOADED

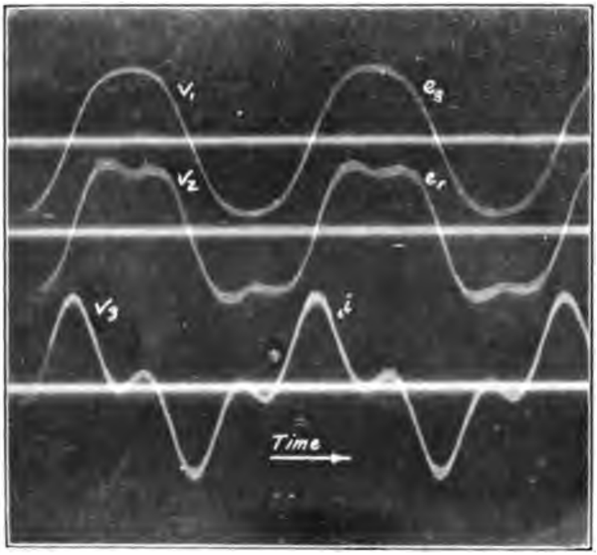
I_r = 0.92 amp. – Spacing 120 in. – f = 100 ~ – C = 2.96 mf. – L = 0.427 h. – E_g = 500 v. — E_r = 500 v. – I = 1.12 amp.



[MAGNUSSON AND BURBANK]

FIG. 27—RECEIVER END LOADED

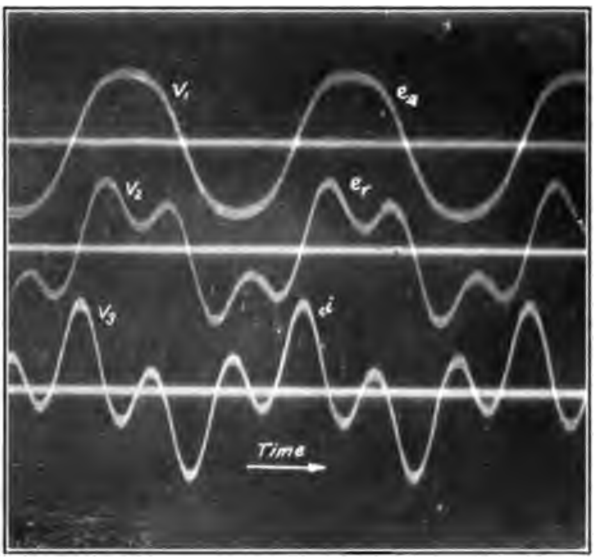
Spacing 120 in. – f = 120 ~ – I_r = 1.01 amp. – L = 0.427 h. – C = 2.96 mf. – Eq = 500 v. – E_r = 500 v. – I = 1.21 amp.



[MAGNUSSON AND BURBANK]

FIG. 29—RECEIVER END OPEN

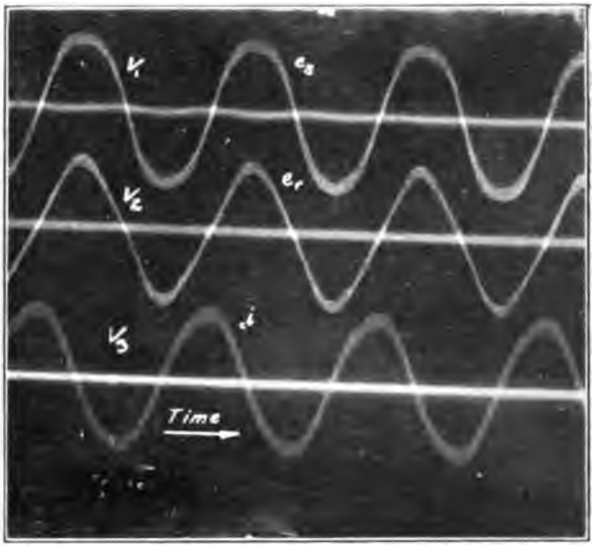
Spacing = 96 in. – f = 60 ~ – C = 303 mf. – L = 0.412 h. – E_g = 500 v. – E_r = 570 v. – I = 0.70 amp.



[MAGNUSSON AND BURBANK]

FIG. 30—RECEIVER END OPEN

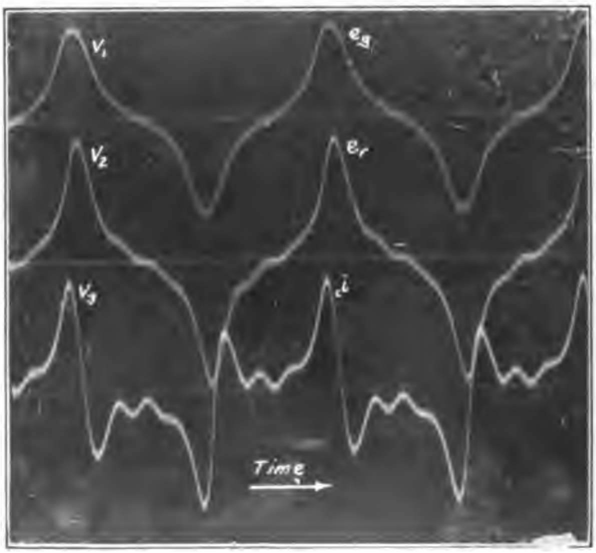
Spacing = 96 in. – f = 74 ~ – C = 3.03 mf. – L = 04.12 h. – E_g = 500 v. – E_r =690 v. – I = 1.35 amp.



[MAGNUSSON AND BURBANK]

FIG. 31—RECEIVER END OPEN

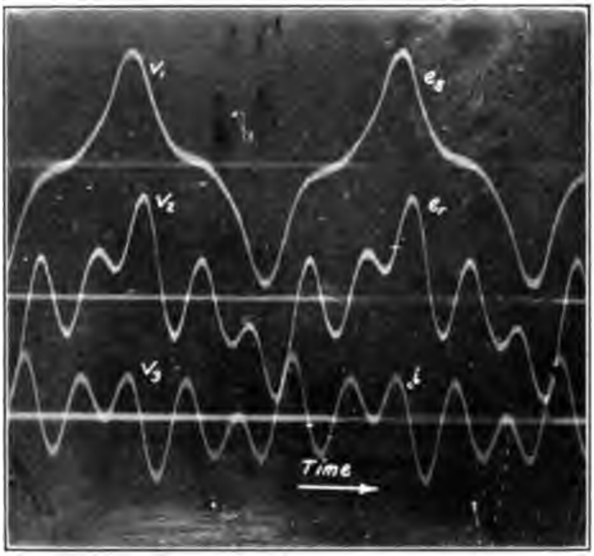
Spacing 96 in. – f = 120 ~ – C = 3.03 mf. – L = 0.412 h. – E_g = 500 v. – E_r = 750 v. – I = 1.49 amp.



[MAGNUSSON AND BURBANK]

FIG. 34—RECEIVER END OPEN

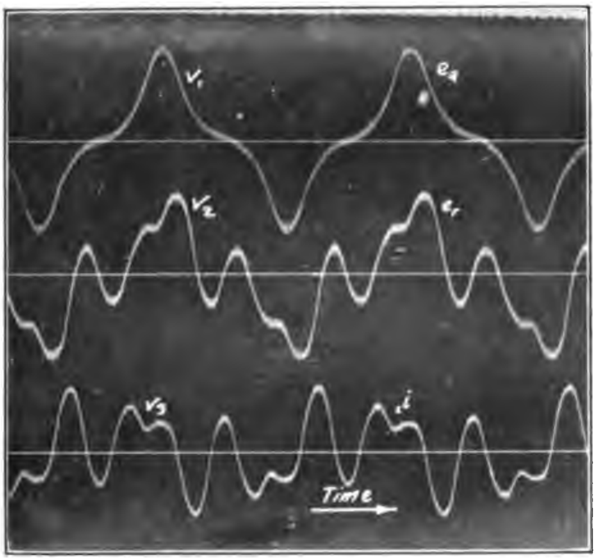
Spacing = 96 in. – f = 25 ~ – L = 0.412 h. – C = 3.03 mf. – E_g = 2.50 v. – E_r = 260 v. – I = 0.20 amp.



[MAGNUSSON AND BURBANK]

FIG. 35—RECEIVER END OPEN

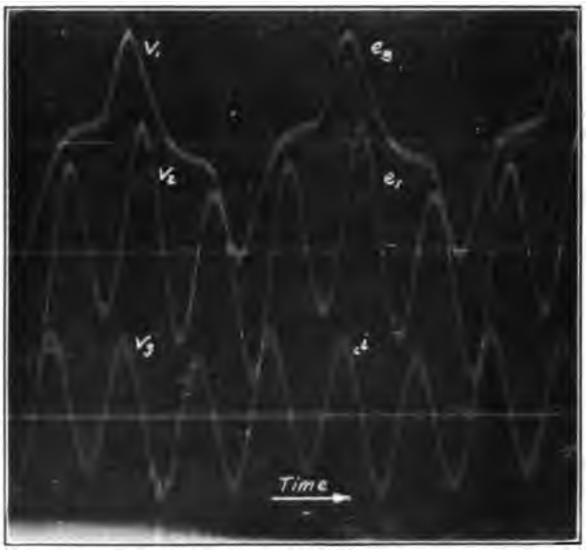
Spacing 96 in. – f = 43.5 ~ – C = 3.03 mf. – L = 0.412 h. – E_g = 250 v. – E_r = 420 v. – I = 1.00 amp.



[MAGNUSSON AND BURBANK]

FIG. 36—RECEIVER END OPEN

Spacing 96 in. – f = 50 ~ – C = 3.03 mf. – L = 0.412 h. – E_e = 250 v. – E_r = 325 v. – I = 0.55 amp.



[MAGNUSSON AND BURBANK]

FIG. 37—RECEIVER END OPEN

Spacing 96 in. – f = 72.5 ~ – L = 0.412 h. – C = 3.03 mf. – E_g = 250 v. – E_r = 860 v. – I = 2.5 amp.

in Fig. 22, or at 72 cycles. The distortion is smaller at 100 cycles, Fig. 23, and practically disappears at 120 cycles, Fig. 24. The line constants give a resonance frequency of 222.2 cycles and hence for the third harmonic in resonance the fundamental frequency would be $\frac{222.2}{3} = 74$ cycles.

Similar oscillograms for a spacing of 96 in. (2.4 m.) and for frequencies of 60, 74 and 120 cycles are shown in Figs. 29, 30 and 31. The third harmonic is at a maximum for 74 cycles.

The dampening influence of the load on the receiver end is shown by comparing the voltage and current waves in Figs. 25, 26 and 27 with the wave shapes for the corresponding frequencies in Figs. 20, 23 and 24.

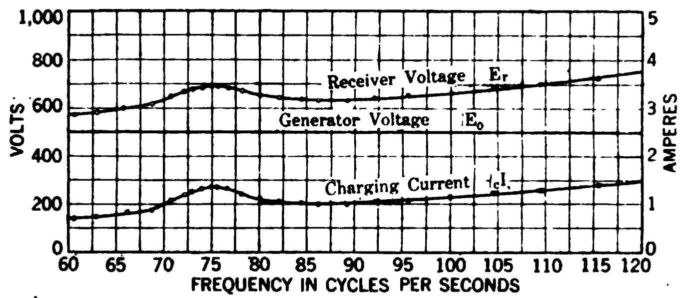


FIG. 28—RESONANCE CURVES WITH MACHINE GIVING NEARLY SINE WAVE AS SOURCE (ABOUT 1 PER CENT THIRD HARMONIC)

A much greater distortion is produced when using alternator *B*. The influence of the frequency for resonance conditions of both the third and fifth harmonics are shown in Figs, 34,35, 36 and 37.

For 25 cycles, Fig. 34, the receiver voltage is practically of the same shape as the impressed voltage wave at the generator end. For 43.5 cycles the fifth harmonic produces resonance and causes a marked distortion of the receiver voltage. At 72.5 cycles, Fig. 37, the third harmonic is near resonance and the receiver voltage consists chiefly of the third harmonic. At 50 cycles, Fig. 36, the distortion of the receiver voltage is less than for either 43.5 or 72. 5 cycles.

Not only the wave shape but also the magnitude of the rereiver voltage is affected by the resonance of the harmonics in the impressed voltage wave. In Fig. 28 is shown the receiver voltage and charging current plotted as ordinates with the frequency of the impressed voltage from alternator *A* as abscissas. The voltage at the generator end of the line was held constant at 500 volts. The hump in the curve between 70 and 80 cycles is due to resonance produced by the third harmonic.

In Fig. 33, similar voltage and charging current curves are drawn for alternator *B*. The humps in the curves are produced by resonance in the line by the fifth and third harmonic.

The maximum point for the fifth harmonic comes at 43.5 cycles and for the third harmonic at 72.5 cycles. The great increase of the receiver voltage for resonance in the third harmonic should be noted; while at 85 cycles the measured receiver voltage drops

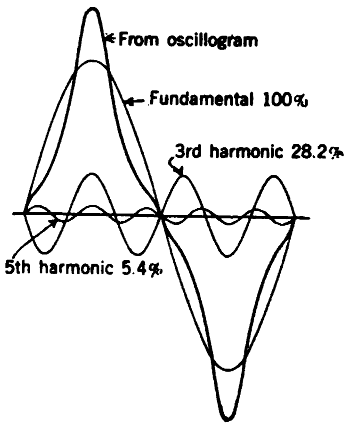


FIG. 32—ANALYZED WAVE OF PEAKED WAVE ALTERNATOR

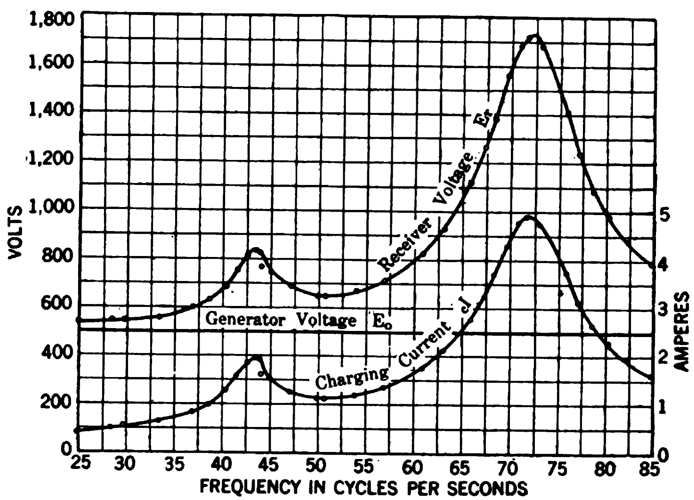


FIG. 33—RESONANCE CURVES WITH MACHINE GIVING PEAK WAVE, AS SOURCE—(5.4 PER CENT FIFTH AND 28.2 PER CENT THIRD HARMONIC)

to a comparatively low value, although considerably in excess of what would be produced by a simple sine wave.

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DISCUSSION ON "AN ARTIFICIAL TRANSMISSION LINE WITH ADJUSTABLE LINE CONSTANTS" (MAGNUSSON AND BURBANK), SEATTLE, WASH., SEPTEMBER 6, 1916.

L. J. Corbett: In connection with these artificial transmission lines, I presume that those of you who are familiar with the subject, recognize the two forms which have been in use for the last few years, the "distributed" type and the "lumpy" type. The more expensive is the distributed type, which is actually designed to correspond to a certain line. One of these, the first I believe, is the one at Schenectady. The wire is wound on glass cylinders with tinfoil on the inside surface. The cylinders are 4½ feet long (1.36 m.) and 6 inches (15 cm.) in diameter, and the length of line that each represents, is about one half mile. It would take a large room to hold a representation of a transmission line of even moderate size compared to some of our western lines. Another of this type was recently brought out at the University of California. You may be familiar with it. The cylinder was made of wood and the tinfoil was laid upon it; then followed a layer of insulation, then a layer of wire. The capacity was greater than in the Schenectady pattern, so smaller wire could be used, and the units were made to correspond to about ten miles of line. At the University of Idaho, we attempted approximately the same thing, using built up paper instead of wood cylinders. We modeled our line after one of the lines of the Washington Water Power Company, and constructed a unit which was to represent ten miles of line, but during that investigation, we found it rather unsatisfactory, because it was difficult to get the constants to correspond to the calculations. The variations in the wire might make our resistance vary a little, but we could adjust that by moving our contacts farther along the wire to get the proper value. The inductance also would vary slightly, but the greatest difficulty we had was in the capacity. With such a unit it was necessary to cut the tinfoil a great deal to avoid induced currents and have it with its sections not continuous around the cylinder. Even then the effect of eddy currents was so noticeable that the line would have a different capacity at one frequency from what it would have at another. So, it was practically impossible to get a really clear-cut set of constants on such a line. Another disadvantage of the distributed type is that after you once build your line, your constants are fixed. There is a great advantage possessed by this lumpy line described in the paper. While some do not approve of this type in general, because of the fact that it does not actually and accurately represent the transmission line, this one is adjustable so that it can be made to represent lines of various spacing, and by taking measurements between the units, a very true picture is obtained of conditions on the line at points ten miles apart. I would like to ask Prof. Magnusson how he maintains the frequency constant, or what instruments he uses to show the frequency if he does not use the vibrating reed.

W. D. Peaslee: I would like to ask Prof. Magnusson about this: Is it possible to pass enough current through the line—that is, load the line sufficiently—to use an ordinary laboratory synchronous generator as a synchronous condenser, and illustrate to the class the use of the synchronous condenser in maintaining the voltage drop constant under varying conditions of load. If it could be made of sufficient capacity to do that, without undue heating, that would be a very valuable addition to its use. The greatest value of a line of this kind is the ability with which you can reproduce a given line.

J. D. Ross: Dr. Magnusson's paper suggests an idea that is applicable to the larger central stations. The university faculties have been reaching out in the last few years to become more and more practical. All of us have observed that they have had considerable success in doing so, and I often wonder if the large central stations are reaching out on the technical end to the same extent. I do not believe they are. I think our testing work is often poorly arranged and under too many departments. We have, for instance, the testing of our distribution transformers under one man, our testing of inside construction under another. Hydraulic testing done by one man, and electrolysis by another, and the testing of meters, of course by a meter man. Probably the testing of meters properly belongs in the meter department. A properly constructed laboratory, constructed along the lines of all general testing as well as for special work, like this paper brings out, would be the proper way for a large central station to arrange this work. We have been promising ourselves an oscillograph for some time, and I think there will be a demand in our concern for an artificial transmission line such as Dr. Magnusson describes, especially at the small cost, comparatively, that he estimates. The way the most of us do now, instead of going at the cause of the trouble, and removing that, is to try to find a partial cure. When a surge comes, on our lines or we repeatedly have trouble, we attempt to put on some apparatus that may cure them rather than find their cause and take them away altogether. The method we have been following, for instance, with the trouble we have had with surges in our high-tension work is really a cut and try method.

I believe that a well equipped testing laboratory with the testing of a large concern all put under it, would yield better economy in the end than our present system. Of course, it would all come back to the question how technical and practical the man in charge would be. He would have to be a very good man to get good results, but there are such men, and I think most large concerns have three or four of them that they can pick from for that particular work. Apparatus of the sort mentioned here would be of considerable value in connection with our troubles if it was in the hands of a competent man. An example, which, is of course, on a larger scale than any of us can reach, is the laboratory of the General Electric Company. Those of you who have read the papers from the *General Electric Review* lately can see the remarkable work they have done. The work should not all be left to the universities. While they are reaching out to be practical, every large plant should reach out to be technical at the same time.

S. R. Burbank: I want to speak strictly from the student's standpoint. This work was exceedingly interesting to me, and I know that it was to other students. The way in which the work checked with the theory was of great interest. One point of particular interest was the shape of the curve, in Fig. 33, referred to by Dr. Magnusson. When the frequency at which the first hump occurred is multiplied by five, and that of the second hump by three, the same frequency is obtained, and checks the theoretical surge frequency calculated from the line constants. We would like to have obtained the hump for the fundamental, but the machine would not stand the necessary speed.

C. A. Whipple: I believe there is a use for these artificial power lines outside of the universities. I believe that in practise, we can find them of great usefulness. On several occasions I have found it somewhat difficult to persuade a board of directors or a city council that certain things were necessary for the proper operation of their system. By having such equipment as described here available, they could, possibly, by their own observations, have been convinced that such was the fact. I have an instance in mind, where a certain body of men had called me in to report to them upon the feasibility of purchasing a certain piece of equipment to correct and economize their existing power system. I told them they were wasting their money absolutely, but the salesman from the manufacturing company gave a very brilliant talk, and they finally purchased that machine. I visited the place three months after it was installed, and it was standing there idle, absolutely useless. They could have bought a dozen of the models described here for the money they wasted in that one mistake. I believe that frequently, capitalists and those handling the financial end of the transactions, who will not look to the engineer for advice, can be persuaded by such a means as this.

C. E. Magnusson: Answering the question asked by Mr. Corbett, I will state that we used a standard electric frequency meter, which consists of a magneto or constant magnet generator connected to a millivolt-meter. The vibrating reed has altogether too large a variation between the successive indicating reeds.

In reply to Mr. Peaslee, you may note from the curves in the paper that the current was about one ampere or 1.5 amperes in some cases. I do not recall that the coils showed any appreciable rise in temperature. The coils are made of No. 14 wire, and are not very thick. I think they cool at least as readily as the fields of an ordinary motor, and a higher voltage could readily be used. In fact, the only reason for using only 500 volts was that this was sufficient for the purpose of this test. The condensers were rated at 1000 volts each and a much higher voltage could be used. As you will notice, we have a spark gap on each unit. This was found necessary in order to protect the condensers during resonance conditions.

Presented at the Pacific Coast Convention of
The American Institute of Electrical Engineers,
Seattle, Wash., September 8, 1916

CHARACTERISTICS OF ADMITTANCE TYPE OF WAVE-FORM STANDARD

BY FREDERICK BEDELL

ABSTRACT OF PAPER

It is generally agreed that a sine wave of electromotive force at generator terminals and on transmission lines is best. A sine wave is now specified as standard by the Standardization Rules of the Institute, but the present methods for prescribing allowable limits and for determining how near an actual wave is to a true sine wave are very unsatisfactory. The Standards Committee, through a sub-committee, is studying the subject in order to ascertain whether a standard can be specified that will be more suitable in its characteristics and more practical in its application. As a contribution to this study, the characteristics of a certain type of standard are here set forth.

It is hoped that various points of view and much information may be brought out in discussion, which may be on the general subject and not limited to the particular phase discussed in the paper.

INTRODUCTION

ALTHOUGH in certain respects a departure from a sine wave of electromotive force at generator terminals or on a transmission line may not be objectionable, it has been found that in most respects such a departure is objectionable to a very high degree; the sine wave is, therefore, the generally recognized standard or ideal that all desire to see approached more and more closely as the art of electrical engineering progresses. The troubles that are caused by a departure from a sine wave depend to a considerable extent upon the frequency of the harmonic or harmonics which are present in the wave in addition to the pure sine wave of fundamental frequency. For example, harmonics of a certain more-or-less low range of frequencies cause trouble in the parallel operation of machinery, while harmonics of a somewhat higher range cause trouble by inductive interference with neighboring telephone circuits. In penalizing therefore, a departure from a sine wave, it becomes necessary either to penalize all harmonics equally, or to endeavor to make the penalty fit the crime and to prescribe different penalties to the various harmonics, which are present in addition to the fundamental, according to their frequencies.

The present Standardization Rules of the Institute, after stating that the sine wave shall be considered standard, specify the manner (Rule 406) by which the so called "deviation" from a sine wave shall be measured. This measure of deviation has been found generally unsatisfactory, not only because it involves expensive special apparatus (commonly an oscillograph) and the services of a man expert in such work, but also because even in the hands of an expert the numerical results are not directly obtainable, being found only, after a kind of cut-and-try or juggling process.

On account of these objections to "deviation" as a practical measure of wave distortion, there was introduced Rule 17*, which defines distortion factor without specifying the numerical value that will be allowed. It was doubtless felt that experience was needed before specifying such a numerical value; but experience has shown objections to a distortion factor as defined in Rule 17, as will be pointed out later. Meanwhile the objecttionable "deviation" rule, which all hope may soon be superseded, still persists.

The question of a standard for wave shape has been discussed† before the Institute on several occasions, and during the past year has been the subject of study of a sub-committee‡ of the Standards Committee. This paper describes certain work done in connection with the work of this sub-committee. It is not intended to be complete, nor to present conclusions, nor to commit the members of the committee in any way. Its object is to bring the matter to the attention of those interested, with a view to obtaining, through discussion or correspondence, different points of view and, so far as possible, to ascertain all the facts bearing on the matter. It is felt that to attempt to

*Rule 17. The Distortion Factor of a Wave. The ratio of the r.m.s. value of the first derivative of the wave with respect to time, to the r.m.s. value of the first derivative of the equivalent sine wave.

†A *Proposed Wave Shape Standard*, by C. M. Davis, TRANS. A. I. E. E., p. 775, Vol. XXXII, 1913; discussion, pp. 831-845. Three papers on *Irregular Wave Forms*, by F. Bedell and others, presented at Deer Park, 1915, TRANS, A. I. E. E.. Vol. XXXIV, p. 1135.

‡ Messrs. L. W. Chubb, F. M. Farmer, H. S. Osborne, L. T. Robinson and F. Bedell, Chairman. Aid in the preparation of this paper, and in experiments not here reported, has been obtained from Messrs. A. Bailey, R. Bown, G. E. Grantham, W. G. Mallory and P. T. Weeks.

standardize wave form with our present knowledge would be premature. There are so many sides to the question, and the interests involved are so diverse, that it is only through wide spread interest and discussion that all the facts and all the aspects of the case can be brought out. The scope of this paper is limited to the characteristics of a certain type of standard but the discussion may be more general.

Admittance Standards

Of the various factors that have been discussed before the Institute for defining the distortion of an alternating wave, the differential distortion factor, (which is the distortion factor of Rule 17, as given above) meets the requirements of a commercial standard perhaps better than any other.

For practical purposes this factor can be defined in terms of the admittance of a condenser as follows:

(*Condenser Admittance Standard.*) The distortion factor of an e.m.f. wave is the ratio of the admittance of a condenser supplied with that wave at its terminals to the admittance of the same condenser when supplied at its terminals with a sine e.m.f. of the fundamental frequency.

The objections to the condenser standard are three-fold: *First*, the wave form of the alternator under test may in some cases become distorted by the condenser used in making the test on account of resonance between the condenser and the inductance of the armature. (This resonance would be for some particular harmonic component of the alternator wave and this component would be unduly magnified so as to distort the e.m.f. form.) *Second*, the penalizing of lower harmonics is too little and of higher harmonics is too great. *Third*, for accuracy the condenser circuit must contain capacity only; hence any resistance or inductance of the ammeter used to measure condenser current introduces error.

These objections, however, can all be eliminated, if certain modifications are made in the definition of the standard and in the method of test; in this way a more practical and a more desirable working standard can be obtained. There are several ways in which these modifications can be made, leading to several possible wave form standards that will now be discussed.

As is well known the admittance of *any* circuit, or combination of circuits, containing inductance or capacity varies with the wave form of impressed voltage and with the fundamental frequency, so that, for a given fundamental frequency, the admittance of a specified circuit is an indication of the wave form of voltage impressed at its terminals and may be taken as a measure of wave distortion.

A general definition of distortion factor, in terms of the admittance of some standard circuit, is, accordingly, as follows:

(*General Admittance Standard.*) The distortion factor of an e.m.f. wave is the ratio of the admittance of a specified standard circuit supplied with that wave at its terminals to the admittance of the same circuit when supplied at its terminals with a sine e.m.f. of the fundamental frequency.

Special cases arise according to the standard circuit specified. A condenser standard (giving the differential distortion factor, δ) and an inductance standard (giving the integral* distortion factor, σ) are seen to be special cases.

Any one of a limitless number of possible circuits might be specified as a standard, and each would give a distortion factor with certain characteristics of its own, as in the particular cases of δ and σ.

Circuits that might be taken as standard can be classified under two heads:

I. *Simple Standard Circuit*, in which resistance, inductance and capacity (or any one or two of them) are arranged in series and are given specified relations or values.

II. *Composite Standard Circuit*, in which the component parts are arranged in other than simple series arrangement.

A simple standard has the obvious advantages of simplicity; it is possible for the testing engineer to check up the standard or to duplicate it with apparatus commonly available. The significance of the standard and the results obtained can be readily grasped and the standard has, to a certain extent at least, a rational rather than an arbitrary basis. A composite standard, on the other hand, has the advantage that it offers a greater range of possibilities in the weighting of harmonics of different frequencies.

A simple standard itself offers great range in the weighting of harmonics, as will be brought out later, but, if no one of these possible weightings comes sufficiently near to the requirements of the case, it may be preferable to abandon the advantages of simplicity and to adopt a composite standard, provided that one is found that is so distinctly superior in its weighting as to make its adoption worth while.

*See Deer Park papers, *loc. cit.*

A standard circuit consisting of resistance only would be impossible, for the admittance of such a circuit does not vary with wave form. A standard consisting of an inductance only would be impracticable (even were it desirable), for the admittance on any commercial wave would differ so little* from the admittance on a sine wave that the difference could scarcely be determined. For the same reason, a circuit consisting of R and L, combined, would be impracticable. Furthermore, a circuit consisting of L and C with no resistance (were this possible) would be unsuitable as a standard, for it would prohibit absolutely the existence in an alternator of an harmonic of a particular frequency; for acceptance of an alternator, the allowable value for the harmonic of the frequency at which L and C were in resonance would be zero, as seen later in connection with the curve marked "$R = 0$" in Fig. 2.

This leaves as possible the condenser standard, the $R\ C$ standard (which is the condenser standard with some resistance added in series) and the $R\ L\ C$ standard (which is the condenser standard with some resistance and inductance added in series). In all these cases the condenser is the predominant element, that is there would be but a small difference between condenser voltage and line voltage.

The condenser standard, without resistance, gives a chance for error in measurement (due to resonance between the condenser and armature inductance) as already pointed out. This error, however, may be reduced and practically eliminated by the introduction of resistance. We have, then, to choose between the $R\ C$ standard and the $R\ L\ C$ standard, and the choice between these two should be made after comparing the characteristics of each. It is to be noted that the presence of R and of C is essential; whereas the inductance† is not necessary, being added or not according to the characteristics that may be found desirable.

The accompanying curves show the characteristics for various standard circuits. The ordinates for each curve show the relative amplitudes that are allowed by the various standards for

*This difference is only a fraction of one per cent; thus, if the admittance of an inductive circuit on a sine wave is unity, it is 0.9952 on a wave having a fifth harmonic of ten per cent in addition to the fundamental.

†Inasmuch as the RC standard should be free from inductance, a small error is introduced by inductance in the ammeter; with the RLC standard this error may be avoided by including the inductance of the ammeter as part of the inductance of the standard circuit.

harmonics of different frequencies, it being assumed in all cases that no more than one harmonic is present. The mathematical relations on which these curves are based are given in Appendix I.

As a basis for comparison, a curve for the condenser standard is shown by the dotted curve in each figure. The scale of ordinates is relative, the absolute values depending upon the specified value for the distortion factor. Thus, for the dotted curves, a distortion factor 1.12 allows a fifth harmonic equal to 10 per cent, of the fundamental, a seventh harmonic equal to about 7½ per cent., etc., the allowable amplitude decreasing* with the order of the harmonic. The fifth harmonic is marked for con-

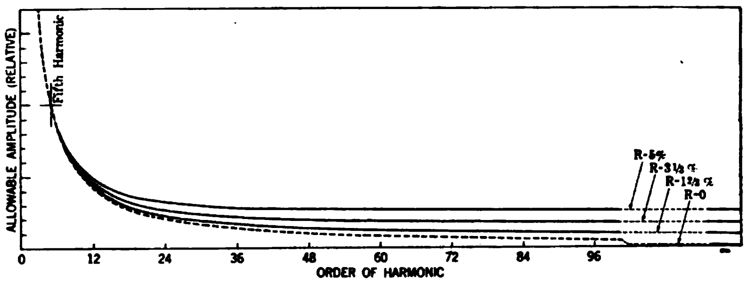

FIG. 1. *RC* standard, resistance being 1 2/3 per cent, 3 1/3 per cent and 5 per cent of reactance of condenser at fundamental frequency. The curves approach, $E_{\infty} = 5\, E_5 \dfrac{R}{X_1}$ (approx.) at infinite frequency. Dotted curve is condenser standard.

venient reference. The value of the fifth harmonic, E_5, for different values of distortion factor, δ, are as follows:

E_5	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12
δ	1.02	1.03	1.045	1.06	1.08	1.10	1.12	1.145	1.17

The scale for the curves is thus determined in terms of distortion factor.

In Fig. 1, the solid curves show the characteristics of the *R C* standard for three different values of *R*, namely, 1⅔, 3⅓

*The amplitude varies (approximately) inversely as the order of the harmonic. If k is the order of the harmonic,

$\delta = (1 + k^2 E_k^2)^{\frac{1}{2}} \div (1 + E_k^2)^{\frac{1}{2}}$, as derived in Appendix I. The denominator $(1+E_k^2)^{\frac{1}{2}}$ differs from unity by less than half of one per cent, if E_k is not over 0.10. Substituting unity for the denominator, we have then, with an error of less than half of one per cent,

$\delta = (1 + k^2 E_k^2)^{\frac{1}{2}}$, or $E_k = (\delta^2 - 1)^{\frac{1}{2}} \div k$. For constant δ, E_k accordingly varies inversely as k, the dotted curve being an hyperbola.

and 5 per cent of condenser reactance at fundamental frequency. These curves approach the limiting minimum value,

$$E_\infty = 5\ E_5\ \frac{R}{X_1}, \text{ approximately.}$$

The RC standard is practically free from the objections given for the condenser standard and it is readily assembled from apparatus commonly at hand. In this respect it is superior to the $R\ L\ C$ standard and, from the standpoint of practicability,* is the most satisfactory working admittance standard. Whether its characteristics are more or less desirable than those of the $R\ L\ C$ standard is a question to be determined; these latter characteristics will now be discussed.

The current flowing through an $R\ L\ C$ circuit at constant voltage increases with frequency until resonant frequency is reached and then decreases, as is discussed in various text books.† In the case of a distorted wave, the current produced by a particular harmonic varies in a like manner, a fact that has been made use‡ of in the determination of the amplitudes of the harmonics to which distortion is due. In the use of such an $R\ L\ C$ circuit as a standard, it is not necessary, however, to go so far as to determine the numerical values of the harmonics that may be present, but merely to make sure that the harmonics do not exceed certain specified values.

The curves in Fig. 2 show the characteristics for an $R\ L\ C$ standard and correspond to the curves shown in Fig. 1 with the addition of a certain inductance, so that L and C are resonant at a particular frequency, in this case 1500 cycles. Except for the inductance, the circuits for the curves in Figs. 1 and 2 are identical. It is seen that, in Fig. 2, the curves come to a definite minimum $\left(\text{approximately } 5\ E_5 \frac{R}{X_1}\right)$ at the resonant frequency instead of at infinite frequency, as in Fig. 1; this min-

*With the possible exception of the effect produced by ammeter inductance.

†See, for example, Fig. 32, "Alternating Currents" by Bedell and Crehore, 1892.

‡See "Analysis of E.M.F. Waves," by P. G. Agnew, *Bul. Bureau of Standards*, p. 95, Vol. VI., 1909, where the use of a series RLC circuit is described; for another arrangement, see articles by M. I. Pupin, *Am. Journ. Sc.*, pp. 379, 473, 1894. Resonant circuits have also been used to determine harmonic currents that are present in addition to direct current in trolley circuits.

imum value is determined by and is directly proportional* to the resistance.

It will be seen that by selecting the values to be specified for distortion factor, and for R and L in the standard circuit, the characteristics of the $R\ L\ C$ standard can be adjusted to a wide range of conditions. The minimum of the curve, which is the point of maximum penalty, has its position (*i.e.*, the fre-

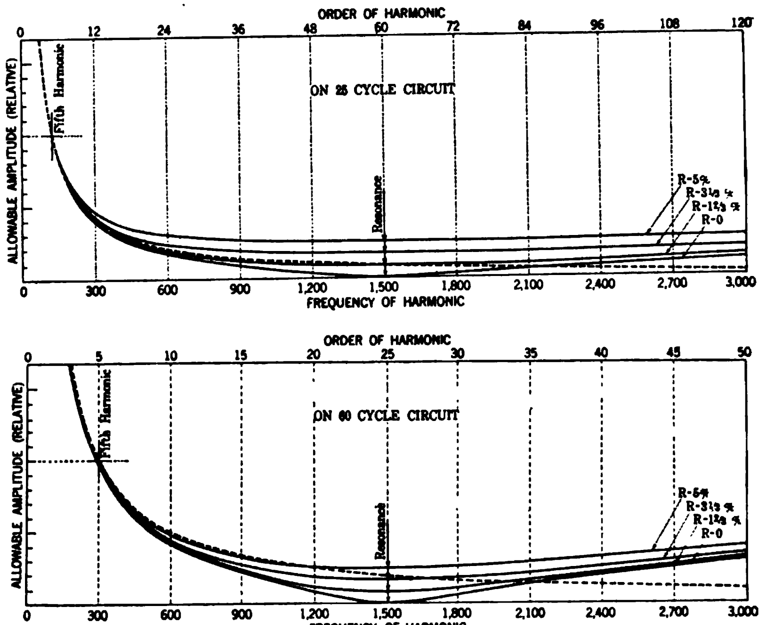

FIG. 2. *RLC* standard; resonance at 1500 cycles. Resistance is 0, 1 2/3 per cent, 3 1/3 per cent and 5 per cent of reactance of condenser at fundamental frequency. E at resonance $= 5\,E_s\,\frac{R}{X_1}$ approx. (On 25-cycle circuit, R is 1, 2 and 3 times reactance of condenser at resonant frequency. On 60-cycle circuit, R is 0.41, 0.83 and 1.25 times reactance of condenser at resonant frequency.) Dotted curve is condenser standard.

quency at which it occurs) determined by L; its relative value determined by R. The absolute value of the scale, for the whole, curve, is determined by the specified distortion factor.

It will be noted that no changes in the values of $R\ L$ or C affect materially any of the curves for the lower harmonics,

*This is very close to a true proportionality for all practical cases; the departure from proportionality only occurs when the amplitude of the harmonic is much more than is generally found in practise.

the allowable values for the lower harmonics being determined solely by the specified value for distortion factor. For the lower harmonics, the dotted curve for the condenser standard is seen to coincide practically with the solid curves of the *R C* and the *R C L* standards. It is thus seen that the constants of the circuit have a material effect only on the values of harmonics of the middle and higher ranges.

Fig. 2 shows the effect of varying *R* when *L* is constant.

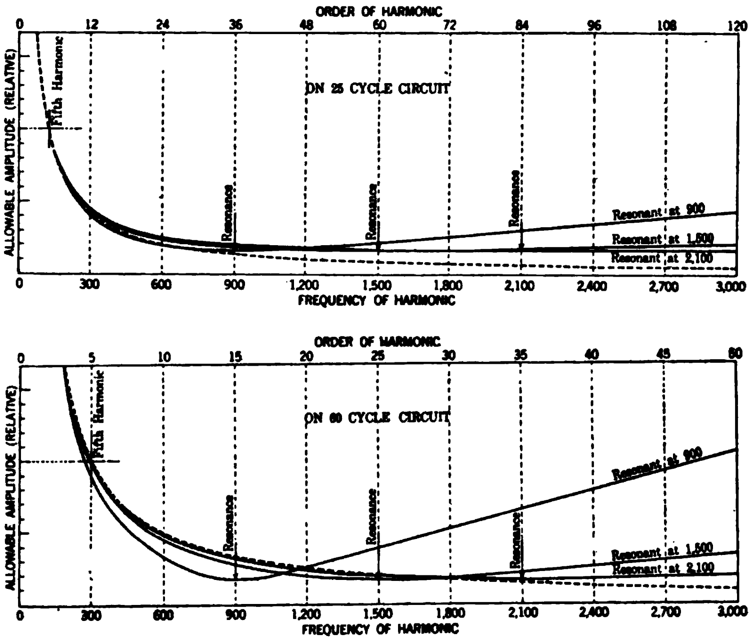

FIG. 3. *RLC* standard; resonance at 900, 1500 and 2100 cycles. Resistance is 3 1/3 per cent of the reactance of condenser at fundamental frequency. Dotted curve is condenser standard.

(It is understood that these values are not absolute but are relative to the value of *C*.) The intersection of the dotted curve with one of the solid curves at resonance is due to the fact that in this case the resistance had a value equal to the reactance of the condenser at resonance, a relation discussed further in connection with Fig. 4.

Fig. 3 shows the effect of varying *L* when *R* is constant. Three values are taken for *L* giving resonance at frequencies of 900, 1500 and 2100. A rapid rise in the curve after the minimum is reached is objectionable in a standard, and this is seen to be the more marked the lower the resonant frequency.

In Figs. 2 and 3, the value of R is specified in terms of the reactance of the condenser at fundamental frequency, and accordingly is different for 25- and 60-cycles circuit. As a result, the ordinates of the 25-cycle and 60-cycle curves are equal at resonant frequency; the amplitude of harmonic allowed is thus constant at this absolute frequency, irrespective of the order of the harmonic with respect to fundamental frequency.

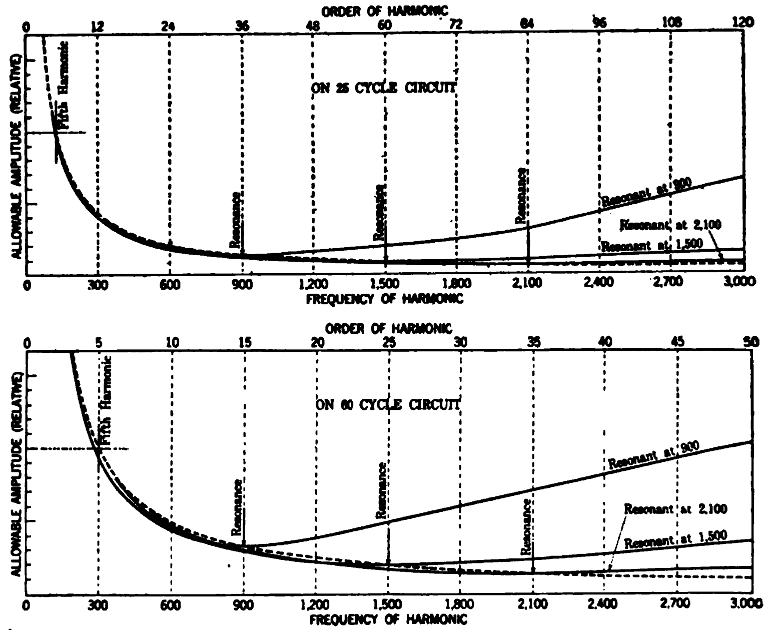

FIG. 4. *RLC* standard; resonance at 900, 1500 and 2100 cycles. Resistance is equal to reactance of condenser at resonant frequency, irrespective of fundamental frequency. Dotted curve is condenser standard.

Fig. 4 shows the characteristics of the *RLC* standard when R is constant, irrespective of the frequency of the circuit, R being equal to the reactance of the condenser at resonant frequency. Curves are drawn for three resonant frequencies. It is seen that in each case, in Fig. 4, the curves closely follow the dotted curve of the condenser standard up to the resonant point. Up to this point, each curve lies just below the curve for the condenser standard, thus imposing a slightly greater penalty on harmonics through this range.

Although it is more logical for the value of R to depend upon fundamental frequency, there would be an obvious practical advantage in having R constant, irrespective of fundamental frequency, for all circuits. If R were made equal to the condenser reactance at resonant frequency, there would be a further advantage that the resonant distortion factors thus defined differ little in numerical value from the present (differential) distortion factor, the solid and dotted characteristic curves, in Fig. 4, following each other closely up to the point of resonance, where they intersect; resonant distortion factor is then a modification of the distortion factor of the condenser standard. But such a factor would be open to the objection already raised to the condenser standard, namely, that the lower harmonics are not penalized enough or the higher harmonics are penalized too

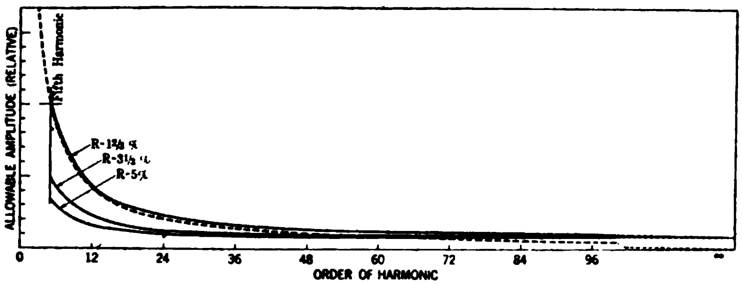

FIG. 5. *RC* standard; the same as Fig. 1 with scale changed so that curves coincide at infinity. Resistance is 1 2/3 per cent, 3 1/3 per cent and 5 per cent of reactance of condenser at fundamental frequency.

much. By increasing the value of R, the solid curves in Fig. 4 would be raised in the region of resonance in the same manner as in Fig. 2.

It is to be kept in mind that any change in R affects only *relative* values of the allowable harmonics at different frequencies, provided the appropriate numerical value is assigned to the distortion factor.

A comparison of Figs 5 and 6 with Figs 1 and 2 may make this clearer. Each curve in Fig. 1 is drawn for the same value of distortion factor, this causes the curves to practically coincide at low frequencies (irrespective of the value of R) and to diverge at high frequencies. The curves of Fig. 1 are redrawn in Fig. 5, each for a different value of distortion factor, so that they coincide at infinite frequency and diverge at low frequencies. In a like manner, the curves of Fig. 2 are redrawn in Fig. 6, with different values of distortion factor, so as to coincide at resonant frequency.

From the foregoing study it will be seen that an increase in R decreases the penalizing of the high harmonics *relative* to the low (or increases the penalizing of the low harmonics relative to the high), the absolute value of either high or low being not necessarily affected.

It should be noted that an increase in resistance tends to decrease the sensitiveness of measurement; thus, in Fig. 5 or 6, the distortion factor might be changed from, say, 1.17, with the smaller resistances, to about 1.05 and 1.02, respectively with the larger resistances.

If a standard of the admittance type is deemed desirable, there are many points to be decided before the exact specification

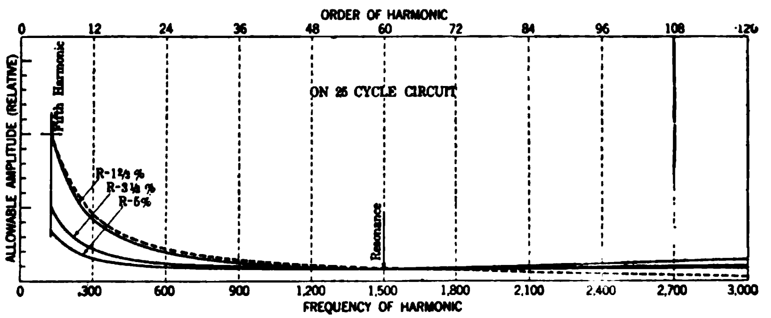

FIG. 6. *RLC* standard; the same as Fig. 2 with scale changed so that curves coincide at resonant frequency. Resistance is 1 2/3 per cent, 3 1/3 per cent and 5 per cent of reactance of condenser at fundamental frequency, or 100 per cent, 200 per cent and 300 per cent of reactance of condenser at resonant frequency.

of the standard can be determined. Some of these points are as follows:—

1. Shall the standard circuit be a simple circuit, as described in this paper, or a composite circuit?

2. If a simple circuit is to be adopted, shall this circuit contain an inductance and, if so, how much; or, in other words, what shall be the resonant frequency?

3. How much resistance shall the standard contain; should this resistance be different for circuits of different frequencies, or should it be the same for all frequencies?

4. What numercial value of the factor thus specified should be allowed in acceptance of alternators?

5. What details and what load conditions conducting tests should be specified?

APPENDIX I

FORMULAS FOR DISTORTION FACTORS

An irregular voltage wave, composed of a fundamental E_1 and harmonics E_3, E_5, E_7, etc., has a r.m.s. value

$$E = (E_1^2 + E_3^2 + E_5^2 + \ldots)^{1/2}$$

If Y_1, Y_3, Y_5, etc., are the admittances of the standard circuit for the fundamental and for the several harmonics, respectively, the current taken by the standard circuit when subjected to the irregular voltage E, is

$$I = (E_1^2\,Y_1^2 + E_3^2\,Y_3^2 + E_5^2\,Y_5^2 + \ldots)^{1/2}.$$

The admittance of the standard circuit on the irregular wave is I/E; its admittance on a sine wave is Y_1. The former divided by the latter gives

$$\text{Distortion factor (general)} = \frac{\frac{I}{E}}{Y_1} = \frac{\sqrt{1 + \left(\frac{Y_3\,E_3}{Y_1\,E_1}\right)^2 + \left(\frac{Y_5\,E_5}{Y_1\,E_1}\right)^2 + \ldots}}{\sqrt{1 + \left(\frac{E_3}{E_1}\right)^2 + \left(\frac{E_5}{E_1}\right)^2 + \ldots}}$$

$$= \frac{\sqrt{1 + \left(\frac{Y_3}{Y_1}E_3\right)^2 + \left(\frac{Y_4}{Y_5}E_5\right)^2 \ldots}}{\sqrt{1 + E_3^2 + E_5^2 + \ldots}}$$

In this last equation, E_1 has been taken as unity.

When only one harmonic of order k is present

$$\text{Distortion factor} = \frac{\sqrt{1 + \left(\frac{Y_k}{Y_1}E_k\right)^2}}{\sqrt{1 + E_k^2}}$$

All the curves in this paper are determined by this equation, by giving a constant value to distortion factor and determining E_k for different values of k.

The preceding equations are general and apply to any standard circuit. For the particular case of the condenser standard, $Y_3/Y_1 = 3$, $Y_5/Y_1 = 5$, etc.; hence

$$\delta = \frac{\sqrt{1 + (3\,E_3)^2 + (5\,E_5^2) + \ldots}}{\sqrt{1 + E_3^2 + E_5^2 + \ldots}}$$

When only one harmonic is present,

$$\delta = \frac{\sqrt{1 + (k\,E_k)^2}}{\sqrt{1 + E_k^2}}$$

This equation may be used in determining the dotted curves in Fig. 1 to 4.

APPENDIX II

Measurements

It has not been the object of this paper to discuss at length experimental details, nor to bring up various questions relating thereto. A brief statement concerning test methods will, however, not be out of place.

The admittance of a standard circuit, when supplied at its terminals with the voltage under test, is readily determined by ammeter and voltmeter readings. Unless an electrostatic voltmeter is used, the ammeter should be included as part of the standard circuit, the resistance and inductance of the instrument (unless negligible) being included in the specified values of R and L for the standard.

The admittance of the standard circuit on sine-wave voltage may be determined either by calculation or by voltmeter and ammeter readings when sine voltage is impressed at the terminals of the standard.

In the former case, it is necessary to know accurately the absolute values of $R\,L\,C$ and frequency, and also the absolute values of the current and voltage in the determination of admittance on the irregular wave. Great care is therefore necessary to insure dependable results.

In the latter case the value of I/E on the irregular wave, divided by I/E on the sine wave gives the distortion factor. It is seen that in this case only relative values are necessary, as the result is a ratio; fairly accurate results can be obtained even with rather crude instruments, provided, of course, that the readings on the irregular wave and the sine wave are both taken with the same ammeter and voltmeter.

A sine wave sufficiently pure for the purpose can be derived from the irregular voltage wave by augmenting the fundamental and choking out the harmonics. One way* for accomplishing this that has been found satisfactory is to place in parallel with the standard circuit a condenser C' having a capacity preferably much larger than the capacity of the condenser in the standard (say five times as large) and to place a non-ferric inductance L' in series with the combination of C' and the standard circuit in parallel. The inductive reactance of L' at fundamental frequency should be greater (say at least 25 per cent greater†) than the capacity reactance of C' at fundamental frequency. With suitable switches, the ammeter and voltmeter readings giving the admittance first on the irregular wave and then on the sine wave are readily taken; the ratio gives the distortion factor.

The numerical values of distortion factor with the $R\,C$ or $R\,L\,C$ standard will differ but little from the value of differential distortion factor δ, particularly when R and L are specified with a view to making this difference small. To do this may be worth while, in view of the fact that δ is a constant of definite theoretical significance and of use in certain calculations.‡

It may be pointed out that the measurement of $\delta\,\sigma$ by the split dynamometer method, referred to in one of the Deer Park papers, is also practically a measurement of δ, inasmuch as the value of σ is so nearly unity,—more than 0.995 in most cases. (For this reason certain objections to the condenser or δ standard hold as well for the $\delta\,\sigma$ standard.) The dynamometer reading varies as the product of the current in the two windings. The current in one winding is derived through a condenser reactance and is proportional to $\delta / C\omega$; the current in the other winding is derived through an inductive reactance and is proportional to $L\omega$. The product is proportional to $\delta\,\sigma$ and is independent of frequency. The reading of the instrument is, however, dependant upon voltage. By substituting suitable resistances for the reactances, the reading of the instrument with reactances in circuit divided by the reading with resistances in circuit gives the value of $\delta\,\sigma$ irrespective of voltage or fre-

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*This is essentially the method by which a sine wave has been obtained for the Ryan Cathode Ray Oscillograph; see TRANSACTIONS, A. I. E. E., p. 539, Vol. XXII, 1903.

The Davis method (*loc. cit.*) is a particular case in which $C = 0$. The presence of C' reduces the size of L' and gives a resultant sine wave with greater accuracy when the standard contains R and L as well as C.

†Strictly speaking, it must be greater than the joint reactance of C' and C in parallel. It should be enough greater to make *sure* that it is greater and to avoid instability of readings that may occur when inductive reactance and capacity reactance are nearly equal.

‡See Mizushi paper, Deer Park, *Loc. cit.*

quency. Variations of voltage and frequency even as much as 100 per cent have been found tolerable.

The dynamometer wave-form meter has been made more sensitive by a differential arrangement, two dynamometers being mounted on one moving system, the two coils of one dynamometer deriving current through inductive and condenser reactances, respectively; the two coils of the other, through resistances. The simpler single split-dynamometer has, however, been found by the writer to be sufficiently sensitive.

Theoretically the split dynamometer gives true values of $\delta\,\sigma$ only when the two reactances have zero resistance, a condition that can be approached but not exactly obtained. By putting resistance or resistance and inductance in series with the condenser, it might be possible to make the readings of the instrument approximate the distortion factor of the $R\,C$ or $R\,L\,C$ standard, but these possibilities have not been investigated.

DISCUSSION ON "CHARACTERISTICS OF ADMITTANCE TYPE OF WAVE-FORM STANDARD" (BEDELL), SEATTLE, WASH., SEPTEMBER 8, 1916.

Joint Committee on Inductive Interference: The importance of wave-form as a factor in determining the extent of inductive interference with telephone service resulting from cases of parallelism of power and telephone circuits, has been pointed out on several occasions by this Committee and by others. Its supreme importance from our point of view renders particularly desirable the adoption of a suitable method of measurement and the enforcement of the lowest practicable limiting value of distortion of wave forms of rotating machinery measured by such standard. We have had occasion to take this matter up with the Standards Committee of the Institute and are glad to note the interest manifested by the Standards Committee in undertaking a study of the subject through the appointment of a subcommittee, whose Chairman is the author of the paper under discussion.

In principle, an admittance standard for determining the distortion factor of an e.m.f. wave appears to be eminently suitable from our point of view and has a great advantage over methods which require a tedious analytical or cut-and-try process. As to the specific type and constants of an admittance standard and the numerical value of the distortion factor which should be taken as a limit, our present information does not warrant us in making a recommendation.

The first and most difficult problem to be solved before settling upon a particular circuit to be employed in measuring the distortion of wave form is to determine the law expressing the relative detrimental effects of different harmonics in a machine wave-form under representative conditions of operation. This involves, besides a knowledge of the variation with frequency of the damage due to induced current in a telephone receiver (physiological effect), a consideration of the distortion of wave form of voltages and currents which takes place between the telephone receiver and the rotating machinery of the power system. Doubtless somewhat arbitrary assumptions will have to be made in evaluating many of the facts, lines in the chain between telephone receiver and generator. However, every effort should be made to determine this law, in order that the relative interference-producing powers of various machine wave forms may be known. Only through this knowledge can improvement over present conditions be most economically made. Given the law expressing the relative importance of the different harmonics in a machine wave form, if the matter of inductive interference is to govern (and we believe it to be the most important consideration usually involved and the one requiring the most rigid limitation of harmonics) the variation with frequency of the admittance of the standard selected should follow this law as closely as practicable. Though our present information on this subject is not complete, it indicates that a standard penalizing the higher harmonics to a greater degree (relative to low harmonics) than the condenser standard is desirable. This apparently requires a composite circuit, rather than one of the simple circuits described in Dr. Bedell's paper. It seems to us that the disadvantages of a complex circuit are to be regarded as of minor importance. If it is impracticable at this time to determine the relative weights which should be assigned to the different harmonics and to prescribe a composite circuit which would weight the harmonics exactly as desired, we recom-

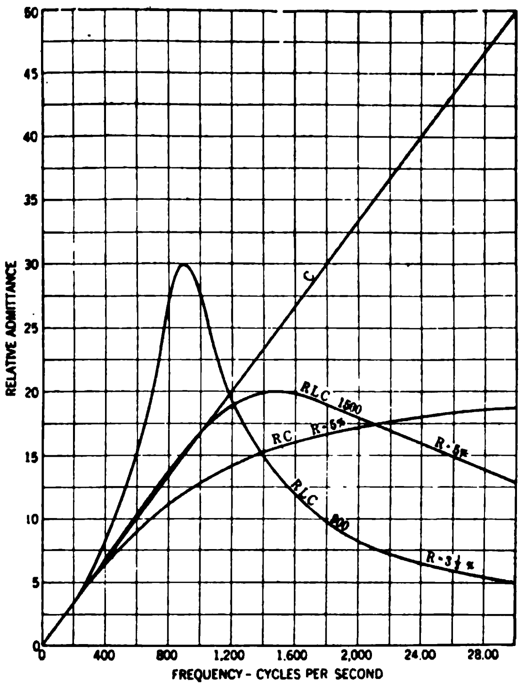


FIG. 1

mend the condenser standard as being far superior to the present or "deviation" standard.

It is well to note the fact that the curves and discussion given in the paper are based on the assumption of a single harmonic, whereas several are usually present. Possible misinterpretation of the plots on this account could be avoided by plotting "relative penalty" curves, which would apply regardless of the number or amplitude of the harmonics present. In keeping with the designation of the type of standard, the ordinates would be directly proportional to the admittance of the circuit and the curves for the condenser standard become straight lines. Fig. 1

shows several curves plotted on this basis. They are approximately reciprocal to the curves given in the paper for circuits with the same constants.

With respect to the five questions at the close of Dr. Bedell's paper:

1. As discussed above, a composite circuit is probably desirable.

2. If a simple circuit is to be adopted, the inductance should be such that the circuit does not resonate below 1500 cycles.

3. The resistance in the simple circuit should be as small as possible.

4. The numerical value of the factor would have to be determined after careful consideration of present practise and opportunities for improvement in design. It is possible that alternators of different types and ratings should be classified in different groups and different factors specified for each group. For example, small, slow-speed, high-voltage synchronous motors might be allowed a greater factor than large turbine-driven generators, for the reasons that the wave-form of an extensive network is generally less affected by a small motor than by a large generator, and the suppression of harmonics is more difficult in the former than in the latter class of machines.

5. As it is the wave form under load conditions in which one is primarily interested, and as this is different from the no-load wave form, tests should be conducted, as far as practicable, under conditions simulating those under which the machines will operate. We realize the difficulty of so doing in many instances.

Apart from the consideration of an admittance standard for determining the distortion of machine wave form, there may be a field for an admittance type of standard in determining the equivalent "noise-volts" in telephone conductors subject to inductive interference.

H. S. Osborne: Prof. Bedell has pointed out that the selection of a wave-shape standard involves two general problems:

1. What shall be the relative amounts permitted of components of different frequencies.

2. What numerical values shall be set under different conditions to the standard thus defined.

From the standpoint of inductive interference in telephone circuits, the relative weighting of harmonics of different frequencies is of importance both in connection with the consideration of wave-shape standards and for practical use in the investigation of induced noise in telephone circuits, particularly in considering the relative effect of different generators or other electrical machinery in producing interference in a given parallel.

In considering inductive interference it is evidently the frequency, rather than the order of a harmonic which is important, and a component of a given frequency and magnitude is of equal importance in a 60-cycle, in a 25-cycle alternator and in a direct-current machine.

At the Deer Park convention of the Institute there were presented the results* of some preliminary work, done for the Joint Committee on Inductive Interference of California, in determining approximately the relative amount of interfering effect of given amounts of currents of different frequencies in a telephone receiver. These results are reproduced in curve *C* of Fig. 2. The amount of current produced in the telephone circuit by one volt or one ampere in the power circuit is approximately proportional to the frequency, and is represented by curve *A* in Fig. 2. Assuming the telephone terminal apparatus to be such that the same proportion of currents of all frequencies pass from the line into the telephone receiver, the relative interfering effect of one volt or one ampere of different frequencies in power circuit can be

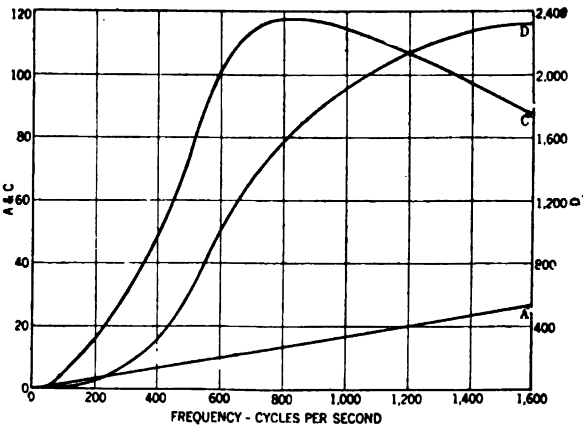


FIG. 2

represented by curve *D* in Fig. 2, in which each ordinate is the product of the corresponding ordinates of curve *A* and curve *C*.

The work which has been done to date indicates that the interfering effect of a compound wave shape can be represented as the square root of the sum of the squares of the effects of the sine components of the wave. An interference coefficient of an alternating current-wave can be defined as proportional to

$$K = \sqrt{\Sigma(V_f D_f)^2}$$

where V_f is the voltage component of the wave of frequency f, and D_f is the ordinate of curve *D* corresponding to that frequency.

By arranging a measuring instrument in a network so that the readings of the instrument will be proportional to *K* a very simple method is made available for determining approximately the interference coefficient of a wave, thus avoiding a complicated

*See TRANS. 1915, Vol. XXXIV, page 1180.

oscillographic analysis. The arrangement, beside having a transfer admittance at different frequencies proportional to the ordinates of curve *D* must have a high impedance at commercial frequencies if it is to be used with ordinary potential transformers, must give a measurable current through the branch containing the measuring instrument, and must make allowance for the impedance of the instrument, which must measure the effective value of the current flowing through it, independent of frequency.

An experimental arrangement, worked out by Mr. H. W. Hitchcock, which approximately meets these requirements

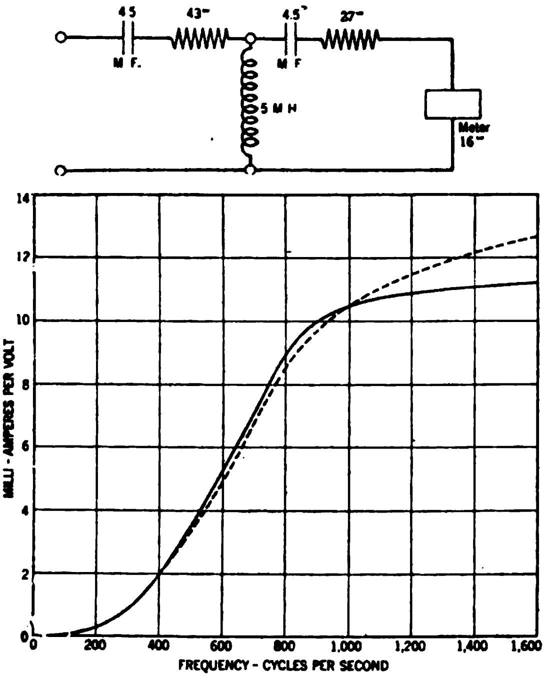


FIG. 3—CALIBRATION OF VOLTAGE WAVE-SHAPE METER
Dotted line: Curve D of Fig. 1   Full line: Curve obtained with apparatus

is shown diagrammatically in Fig. 3, which also shows the degree of approximation obtained. The particular form of network here shown makes use of a suggestion made by Mr. Chubb for a possible wave-shape standard. The measuring instrument comprises a thermocouple connected to a d-c. milliammeter. The instrument is provided with a universal shunt for the protection of the thermocouple against excessive currents. The apparatus is provided with a switch by means of which the meter can be connected across the line through a 10,000-ohm resistance so as to measure the effective voltage at the terminals. In most practical cases this is near enough to the value of the fundamental voltage so that it can be used as the fundmental without excessive error.

The few results which have so far been obtained with this apparatus are very encouraging. In the following table are given two comparisons between the noise induced in the telephone circuits in a given parallel when the paralleling power circuit was supplied from different generators and the readings of the wave-shape meter on the generators.

	Reading of wave-shape meter, milli-amps. per volt	Noise units in telephone circuits
Southhampton, Gen. No. 1	0.31	170
" Gen. No. 3	0.58	350
Iowa Gen. No. 7	0.086	1700
" Gen. No. 8	0.043	800

The proportionality is seen to be very good.

The noise was in each case measured by the means regularly employed by the Bell telephone companies, in which the noise in the telephone circuits is compared with noise of fixed quality and variable intensity from a standard source of tone.

The large variations in the interference coefficients of the voltage waves of different generators and in some cases the very considerable variation with load are indicated in the following table. The last eight cases of this table, and the second comparison of the table given above, are taken from the results obtained by the Iowa Inductive Interference Committee. I wish to acknowledge the courtesy of the Executive Committee in charge of this work, Mr. W. G. Raymond, Mr. John Drabelle, Mr. R. H. Fair, in permitting the use of these results.

Number of phases	Kv-a. capacity rating	Load kw.	Reading of wave-shape meter, milli-amps. per volt	Remarks
3	200	150	0.30	
3	300	145	0.59	
3	300	350	0.24	Same machine as above
Quarter	250	50	0.070	
Quarter	250	100	0.12	Same machine as above
2	100	50	0.70	
3	150	45	0.037	
2	50	0	0.058	
3	50	0	0.52	
3	300	100	0.086	
3	200	120	0.043	

These few results warrant the expectation that an arrangement similar to this will in the future give very valuable results in the study of inductive interference.

In establishing a standard of wave shape the inductive effects in telephone circuits are, of course, only one of several factors which must be taken into consideration. Such factors as the effect of harmonics on the operation of power circuits, and the difficulty in attaining a desired degree of reduction in the magnitude of voltages of any given frequency should be included. Weighting the harmonics proportional to their frequency has the advantage of simplicity, and excessive weighting of very high frequencies could be avoided by having a constant weighting for all frequencies above two or three thousand cycles. The *R*, *L*, *C* standard described by Prof. Bedell, with the condenser predominant at fundamental frequencies with resistance equal to the condenser reactance at resonance and with a high resonant point can be made to very closely approximate a standard of this sort for the frequencies commonly generated in electrical machinery.

To completely cover the field, it would, of course, be necessary to establish standards not only for alternators, but for motors, also, for d-c. as well as for a-c. machinery, and also for converters, rectifiers, transformers, and other electrical machinery. It is to be hoped that it will be found practicable in time to cover the whole of this rather extensive field.

L. F. Curtis: I would like to ask Prof. Bedell if, in order to determine the order of the harmonic, as well as its amplitude, in testing an e.m.f. wave, it would not be practical and desirable to make use of as a standard, a resistance, inductance and capacity, with, possibly, a variable inductance, calibrating the unit to give a certain amplitude or allowable amplitude of wave with varying positions of the inductance. It seems to me that this standard, or, rather, piece of apparatus could be calibrated with a sine wave to show the amplitude produced for different positions of the inductance, and then showing with the wave in question the additional humps or peaks induced by the higher harmonics.

C. E. Magnusson: The manufacturers of electrical machinery, and the operators of large systems, especially large central stations should state their views. No doubt, the manufacturer could give us accurate data as to the increase in cost of the generators for a reduction in the harmonics and an estimate of the relation between these factors, would be highly desirable. The operators do not, so far as I have been able to determine, appreciate quite as fully as the telephone people how much would be gained if the harmonics could be largely eliminated. I think it would be an interesting study to determine, for example, how much energy is lost in induction motors by the presence of harmonics, as only the wave of fundamental frequency produces torque. All the harmonics produce heat, but no torque. With the tremendous increase in the size of power systems and especially where a large number of central stations are combined together, it is of increasing importance that the wave forms from the several machines and throughout the system, should be as nearly of the sine-wave shape as possible.

L. W. Chubb: At the meeting last year at Deer Park, the discussion by the Committee on Inductive Interference and by

Mr. Osborne, showed that the low and very high-frequency components of voltage wave shapes are of no consequence in telephone interference, and that the great restrictions should be in the range from 700 to 1500 cycles. The operator and designer must watch the lower distortional frequencies, and others in the electrical industry are interested in the high harmonic components. The restrictions which the telephone interests wish to impose are the most severe, because the range of objectional frequencies falls within the range of the tooth harmonics in the usual commercial machines.

The setting of limits on wave distortion of generators affects the operating interests, the manufacturer of electrical apparatus and the telegraph and telephone interests. To the operator, the elimination of the low-frequency distortions is of direct importance because of the influence on losses and the paralleling characteristics. The elimination of tooth frequencies may influence the cost of right-of-way for lines in the neighborhood of telephone lines and the elimination of the very high harmonics (which seldom, if ever, come from the generators) will preclude or reduce the possibilities of oscillation and resonant breakdown trouble in the connected apparatus. The purity of the wave, which he will require, will depend upon the extra cost of machines, and the gain in cost by using the same right-of-way, etc.

To the manufacturer, the lowering of distortional harmonics is of little consequence. He must now guarantee the satisfactory paralleling of machines, and can lower the higher frequency distortions if the additional cost, which must be borne by the customer, will be justified by the savings of the latter.

The telephone interests have everything to gain and nothing to lose by close limits in wave shape, and it seems that they should bear some of the burden of the problem, by installing metallic balanced systems, which will greatly reduce the effects of inductive interference. The many discussions and schemes of measuring wave-shape distortion, and setting a standard, and the continuance of the deviation standard indicates that a just specification for wave-shape variation and its measurement is not a simple matter.

In the present paper Prof. Bedell lays greatest stress on the simple series full resonant circuit, which, after considerable discussion by the committee, seemed to be the most practical. Composite circuits have been considered, some of which give better curves than the simple circuit, but the additional complication has made it seem inadvisable to use the composite if the simple circuit will do. The simple series circuit can be made to limit any given range of frequency, but to prevent the admittance of high frequencies from falling off, and at the same time to approximate δ in the low-frequency range, it is necessary to have the resonant point at a frequency higher than that which should be penalized the most. This fault can be overcome theoretically, by the composite circuit, which will follow δ at the low frequencies, have resonance at any point in the worse range, and limit the high frequencies almost as much as the resonant frequency. The circuit shown in Fig. 4 illustrates this. It resonates at 1000 cycles per second, and limits the very high harmonics almost as much as it does the resonant frequency. This and other similar schemes are impractical, because the ordinary electromagnetic ammeters have inductance and the thermal meters are not accurate enough for the purpose. Besides, when deciding whether an admittance standard is desirable, we must decide whether the composite circuit, with more difficult testing requirements and better penalties, or the simple circuit with better testing and poorer penalty curves is the more desirable.

Generators do not have the very high harmonic frequencies, and for this reason, (since the standard is primarily for the acceptance of machines), it will not matter whether the curve turns up at high frequency, as shown in Figs. 3 and 4 of the paper. If the curve is allowed to turn up, the simple circuit with resonance at about 1000 cycles seems to me to be the best, if suitable limits can be agreed upon.

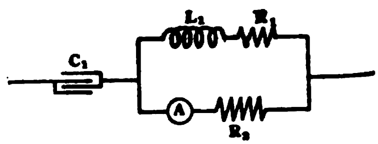


FIG. 4

A = Ammeter $C_1 = 5 \times 10^{-6}$ farad $L_1 = 0.02$ henry
$R_1 = 50$ ohms $R_2 = 83$ ohms

L. T. Merwin: The power man must recognize the fact that the subject matter of the paper is to become of exceeding importance to him, not only on account of the increasing importance of inductive interference problems that are constantly arising, but from the fact that our power systems are constantly becoming more complex, and he will be face to face with some of the problems involved in this paper.

In operating his system, however, he will not be so much interested in the form factor, as outlined in the paper, as he will in its effects on some composite circuit or branch circuit with reference to some particular harmonic that may be present in his system. This will come from the fact that as the distributing or transmission system becomes more and more complex, the presence of harmonics will constantly be thrusting themselves before him. No doubt but that the power man in the past would have avoided many of the difficulties that have come up if he had harmonics arising from his generators. I have a particular instance in mind from past experience in a system in which I had operating concern and at the time, while I realized in a vague way what was happening, I was unable to diagnose my trouble in a satisfactory fashion. This system was a portion of the Nevada, California Powef Co., in the mining region of Goldfield, Nevada. It so happened that whenever there was a disturbance due to a short circuit on any part of the 6600-volt distribution system involving quite an extensive network, there was one particular span in that system that always failed. I simply mention this as a matter of operating experience. It came to such a pass that whenever there was a big disturbance on this system I immediately sent one gang of linemen to the Gold Wedge claim, where this particular span was located, and usually it would be found on the ground. Probably some of the power men here have experienced the same thing. I simply diagnosed it in a general way, as owing to a resonant condition on that particular branch. The effect of some harmonic was greatly magnified.

The subject matter of Prof. Bedell's paper, however, while it covers a case of this sort, does not put it in the concrete form that would be desirable from the operator's standpoint. He is not interested so much in the numerical value of the wave form, expressing the admittance of a great range of frequencies, as in the numerical value of the admittance of a simple composite circuit with reference to a particular frequency that might produce resonance in some branch of his network.

We power men will be forced to learn more and more of the importance of the presence of these higher frequencies in our system. The paper, however, I fancy, is more designed to take care of a broader aspect of the question than that. That aspect bears upon the problems of inductive interference which are becoming more and more important as the investigations, mutual and individual, of power and telephone companies progress.

As to the penalizing of a generator on account of its wave-form. As brought out by Prof. Magnusson, that penalizing will have to take into account not merely the designs of the telephone and power interests to avoid inductive interference, but must take into account also the commercial aspect of the question. The moment we begin to penalize generators the price will begin to rise. Further, it has been hinted that the harmonics that produce troubles in inductive interference, have a fairly limited range. If the third harmonic of a 60-cycle system does not particularly interfere with communication, it would scarcely be right or wise to put a penalty on its presence. If the 5th harmonic and the 7th harmonic do not particularly interfere with the transmission of speech and if by chance they are not of much weight from the power man's standpoint, then why penalize a generator on account of their presence. The power man can avoid difficulties in his distribution system arising from the presence of any of these harmonics, by a simple change of circuits. The introduction of inductance for instance, in any particular branch that is resonant to some particular frequency, will immediately avoid difficulties that might arise. So it would seem to me that a simple or composite circuit that would by one measurement give a form standard or a form value, should be of such a nature, if possible, that it will not involve the frequencies that are of no concern. Ultimately it will be up, probably, to the telephone companies to definitely state what numerical value should be assigned to the various harmonics in order that the manufacturer may know what to avoid. My own, very superficial, investigation in the matter seems to indicate that in a 60-cycle system the 3rd, 5th, 7th and 9th harmonics are the distressing ones in general. Now it might be that in some systems the higher harmonics up as high as the 21st say, are the ones that give the most trouble. I will admit that the means of investigation at my command are very crude but in the system with which I am connected I do not find the upper harmonics within the range of speech, present in any disagreeable degree. I do find, however, that the third is decidedly present; the 5th, 7th and 9th can be readily heard and do interfere unless quenched out in some way. As I have already said, it will be definitely up to the telephone interests to state or put a numerical value upon that range of frequencies that bothers them most. Then it will be up to the investigator and the manufacturer to try to confine his attention to this particular range.

L. J. Corbett: I want to call attention to the possible effect of a long transmission line upon the wave form which may start at the power house very true to a sine wave. At the University of Idaho we are located on the end of a transmission line about 90 miles in length. During the past year we have taken the wave form as it comes to us in our laboratory. I will not guarantee the results because the wave form was taken by an oscillograph by tracing on the screen, and was analyzed by the twelve ordinate method. We found unobjectionable the 3rd harmonic, the 5th and 7th were very slight, almost negligible, but the 9th harmonic, was of far greater amplitude than the 3rd. Now the inductance and capacity of that line, it would seem to me would alter the wave form in the various parts of the circuit, and I would like to hear from some of the men who are interested in the operation of our long transmission lines as to whether they have analyzed the curves at the various points of their lines—at the power house and also at the various terminals or service points. Mr. Merwin has touched upon one matter which I have had in mind—that it may be possible in a great many cases to correct for some of these higher harmonics by quenching them out by means of inductance, just as we do in connection with lightning arresters. We can probably put in inductances which will not materially alter the regulation of our line but which will limit the harmonics to values which are not objectionable.

And in regard to the high-frequency harmonics—I think that the present means at our disposal, that of taking the curve form of an alternator and analyzing it, is about the only method that we can use at the present time. Of course, the relative harmonic of a 25-cycle generator which will cause trouble in a telephone circuit will differ from the relative harmonic of the 60-cycle generator which has the same frequency, and as has been pointed out, those frequencies within the speaking range are the only ones which will cause trouble with voice currents. Those are the ones which should be eliminated. With the apparatus which is already at hand in the various power stations it seems to me that the only possible method of correction is by some such method as indicated, that of quenching out the objectionable harmonics.

J. B. Fisken: Mr. Corbett has expressed a desire to hear from the operating men as to what investigations they have made on this question. As one operating man, I would tell Mr. Corbett that I have made none. We operating men, I think, all agree that we have harmonics. I think we all agree that, like the poor, the harmonics will always be with us. If we could get rid of them, we would be very glad to do so. The question of the elimination of harmonics, to my mind, is purely a commercial one. If the public will submit to paying such rates for service that we can buy more expensive machines, then, undoubtedly, the manufacturer can give us those machines. But, in the last analysis, it is purely a commercial proposition. I thoroughly believe that, for any reasonable expense we should endeavor to eliminate the harmonics, but beyond that we can not go, and the burden will be placed upon the telephone engineers of finding some means of carrying on their business with those higher harmonics running around loose. There is another feature of the case that occurs to me. We might have an alternator designed that would be entirely free from harmonics. We might have a line designed that would be entirely free from harmonics, but when the time comes that we have to change, possibly, our scheme connections (and in an interconnected network that is always possible), then is it not a fact that our former computations are practically of no value? In other words, instead of operating a particular generator on a particular line, we may have to operate that generator on a different line.

W. D. Peaslee: Unquestionably, if we can get a dollar per kilowatt for energy for lighting purposes, we can generate electricity that has a sine-wave voltage with practically no harmonics, and we can give the telephone people lines with which they can talk from one end of the continent to the other, and go their way in peace. But it can not be done at the present rates, under the existing conditions. It is very pleasing to see the difference in the whole situation in the inductive interference problem a year ago and today. The situation today shows that cooperation is starting. At the present time, the telephone people, I think largely because of the eternal dollar, have "passed the buck" entirely to the power people. They make the sweeping statement that all harmonics are very bad, and that they should be penalized in proportion to their frequency, and, therefore, a million-cycle wave should be reduced to absolute zero, putting the proposition flatly up to the power people in a way that is impossible of commercial solution. I personally know that it is possible to take a telephone line suffering from inductive interference, and by proper tuning methods, damp out one at a time the 3rd, 5th, 7th and 9th harmonics. I know that you can take a telephone line and damp out these harmonics for a distance of 70 miles, and do it successfully. The telephone people assure us that these methods are not efficient, and that it can not be done successfully. That is not true. I know it is possible to take a weak telephone current, and, by means of the audion amplifier, step it up to considerable proportions. I am firmly convinced that one of the solutions of this problem will be wiping out these harmonics below the frequency of the voice currents, and if in doing so, the attenuation of the voice currents is very great; I see no reason why the audion amplifier will not step up the pure wave, attenuated as it is, and pass it on again. That is a point on which the telephone interests are not giving us as much information as they should. There is no question that their laboratories are working on this matter, and that they have a great deal of valuable information, but it is like pulling teeth from a cross cut saw to get any information from them.

The only possible solution of this problem is for the power companies and the manufacturers, and the telephone people to get together, and, to use a common expression, lay their cards on the table. In that way we can get the best solution possible, and I look forward to the day when this will occur, because of the immense improvement in the situation at present over a year ago.

Harris J. Ryan: There must be a standard of wave-form. We have long since found such to be the case. In the standardization rules of our Institute, it seems to me, as I recollect now, from the beginning virtually, there has been a standard of wave-form but, as pointed out in the paper it is not satisfactory for the easons there given.

It seems to me well to take into account a few of the very broad elements in the matter. The telephone interest is endeavoring in a very strong effort to transmit fundamentals and harmonics and to transmit them faithfully. On the other hand, the power interest would gladly supply electric energy in fundamental form only, and discard the harmonics. Any extension or amendment of our present definition of wave-form should be undertaken with great care because of the important, deeply rooted, widely ramifying factors.

R. W. Mastick: In regard to Mr. Peaslee's remarks conce ning the use of drainage devices applied to telephone circuits for the purpose of filtering off the disturbing frequencies and the use therewith of amplifying devices to again restore the magnitude of the voice currents; Dr. Bedell has correctly said that it is vitally important in a telephone circuit to transmit various frequencies in their relative proportions, which are within the range of the disturbing frequencies, in order that undistorted speech may result. This statement in itself answers Mr. Peaslee's suggestion, for if drainage devices are used, certain currents of voice frequency which are identical with the disturbing frequencies will also be drained off. Therefore, even though an amplifying device be used, it is obvious that the relative proportion of frequencies in the voice current will not be the same, hence distorted speech will result. Again, consideration must be given, even though such a scheme were feasible, to the number and complexity of telephone circuits in use, to which it would be necessary to apply such a device.

L. T. Merwin: Mr. Mastick's reference was to some very crude experiments that I had been carrying on with our own telephone line, which is on the same supports as our 66,000-volt conductors for a distance of approximately 70 miles. These experiments consisted of the shunting out of the lower harmonics that were particularly distressing; so much so, in fact, that it made the use of our own telephone system for dispatching, extremely inadequate. As a matter of fact it was almost non-usable until we had devised, after much stumbling, composite forms of shunts that would effectively shunt out the 3rd, 5th and 7th harmonics, and the 9th if it were so desired. It was remarked that I did not find any harmonics above the 9th that interfered in any way with satisfactory communication, and that while talking with a particular operator of Swedish nationality it was observed that the intelligibility of his speech was remarkably increased. Now that is an actual fact, and it can be attested to by Mr. Peaslee and I think by Mr. Condit, the attention of both of whom I called to this peculiar phenomenon. I am not in a position to say how my own voice sounds over this line.

I would like to emphasize a point brought out by Mr. Peaslee, that it will assist in the solution of this problem very materially if the telephone company freely divulge the results of their own experiments as we discuss these problems with them.

Just a moment more on the penalizing of generators. If transposition is effective when a power system is balanced both for transverse and longitudinal induction, and if the parallelism is a simple one, and by the means of these transpositions the harmonics can be quenched out at very little cost, why should it be necessary to penalize a generator if it produces these harmonics? It reduces again to purely a commercial problem.

It may be cheaper in some instances to take the standard form of generators as we now have them and by a small expenditure entirely eliminate the troubles arising from inductive interference through transposition or other means.

Frederick Bedell: We are not in a position at present to adopt a final exact specification for a standard of wave-form, but with the material that is before us and with further study, certainly progress should be made. It seems that all are agreed that several of the admittance standards discussed today are superior to the present deviation standard. Now, whatever standard is adopted, it will probably not have its numerical values specified in the first instance so as to hold for all time. With experience we will no doubt later have to modify the specification of the standard; the best we can do at present is to make a first approximation, agreed to by all as better than the present standard, and later improve it. I believe that a simple standard can be found that will meet the need for practical purposes. The simple standard has the advantage not only of practicability but from the psychological standpoint it is more desirable than a composite one. We know then what we have got, for by experience we are all familiar with the characteristics of a simple circuit. Even for those of you who are most accustomed to calculations with involved circuits there is something in a composite circuit which makes it indeed difficult, if not impossible, to comprehend its characteristics at a glance. Even if ultimately a composite standard were to be the more desirable, I believe it would be unfortunate to adopt it in the first instance and to try to swallow it all at once. How much better it would be to put forth a simple standard which all can understand, and then later modify it by shunts or what not, should we so desire. We will have had the idea of a volt-ampere standard and a modification of that idea can then be readily accepted. But I believe that the simple standard can sufficiently meet the situation and that we should not try to get a law penalizing the harmonics, supposedly, with theoretical exactness down to the last dot. Such theoretical exactness would be difficult to attain for the reasons pointed out here today to the effect that wave form varies in different parts of a system, and futhermore to the effect that wave form at the same point of a system varies from time to time with load conditions. Now these variations due to circuit and load conditions, which vary with time and space, are not properly to be charged up to the generator. We want to get at a pretty fair approximation of the penalty to put on the generator, but we cannot charge it with all the idiosyncrasies of the line. Some of those who have been working on this subject have seemingly thought that there was some ultimate exact law which we could get at which would prescribe the precise penalty for this or that harmonic, and that we should make every effort to ascertain this with precision, and should then adopt a standard which would fit it, not approximately but exactly. I believe in accuracy so far as it is possible, but in this case if we can get the general trend of the relationship between frequency of harmonics and their deleterious effects and get a corresponding standard that is easy for us all to use and to understand and to apply, I think we will have done all we can do, at least for the present, and possibly the results will stand for a long time. As several of the speakers have pointed out, it is a matter involving the power operator, the telephone operator and the manufacturer; their several points of view should be harmonized, weighed and balanced and, if possible, a result obtained that meets the views of all of the people concerned so far as possible. It has also been pointed out by several of the speakers that it is an economic or commercial question, and that is true. By paying more and more money you can obtain better and better apparatus, and better and better service, and there again it is a question of weighing and balancing the importance of cost versus service. Mr. Curtis asked a question as to whether wave analysis could not be made by an R, L, C circuit by varying the inductance so as to show the amplitude of particular harmonics. This method of analysis has been carried out and a reference on the subject has been given in the paper. The method has been used, I believe, in recent investigations by the Joint Committee on Inductive Interference, and I believe has also been used in the laboratory of manufacturing companies in the study of this problem. Mr. Merwin suggested that the telephone people should state definitely the numerical values that would be permissible for various harmonics. This can hardly be done. If you cut a particular harmonic to, say, half its value, it will improve the service; if you cut it to say, one-fourth its value it will improve the service still more, and so on; so it seems no matter how good, within practical limits, you can get the wave form, the telephone service would still be improved by further improvement in the wave form. In other words, it would be desirable to reduce the harmonic from the telephone standpoint even beyond the practical limit. It does not seem, therefore, that we can get at that in just that way. We can get a standard which approximately gives the proper law of penalizing; we should make it not too hard at first so it wont be an undue hardship on any one; then, with the general scheme standardized, the numerical values of the standard can be adjusted little by little, so as to put on the screws gradually from year to year, so that they will not pinch too much and yet will bring the pressure where it seems desirable. It will be understood that, in the paper and in the discussion by the author and by other persons on the subcommittee that have been dealing with the subject, neither the Standardization Committee nor the Sub-committee is committed in any way. It was the purpose to have this open discussion so as to bring out the facts.

Presented at the Pacific Coast Convention of the American Institute of Electrical Engineers, Seattle, Wash., September 8, 1916

INSULATOR FAILURES UNDER TRANSIENT VOLTAGES

BY W. D. PEASLEE

ABSTRACT OF PAPER

The operation of a high-voltage transmission line involves changes in energy distribution that are very conducive to high-frequency disturbances and transients of very steep front. These are often superposed on the normal frequency voltage of the line in such a way as to impose great stresses on the insulators.

The mechanism of failure of an insulator is of great importance to those designing and operating transmission lines. This paper presents the results of recent investigations on the failure of insulators under impact and combined impact and normal-frequency voltages. Microphotographs of the resulting failures are included.

The breakdown of a dielectric involves energy which is a time function and the importance of the duration of the stress in determining the magnitude of the voltage necessary to puncture an insulator is discussed.

Due to the short duration of transients, insulators are often punctured repeatedly by them, the procelain in the puncture solidifying again on account of the small energy involved. These sealed punctures however weaken the insulator, lowering its dielectric strength materially.

The importance of the elimination of air holes and defects in the porcelain is shown.

Some essential features of a successful line insulator are stated.

INTRODUCTION

A PARTICULAR dielectric will be ruptured or broken down when the dielectric flux density exceeds a certain value and this flux concentration lasts for a finite time. It is necessary that the time of application of the stress be finite, as any breaking down of a dielectric involves energy which is a time function. This has been well shown by the experiments of Peek*, and others in the study of corona formation, and it has been shown that, under transient voltages, the shorter the time of application of the stress the greater the voltage necessary to produce break down of the dielectric.

Thus the breaking down of porcelain used in the manufacture of high-voltage insulators demands the application of the stress for a period of time great enough to permit the accumulation of sufficient energy to destroy enough of the porcelain to puncture the insulator, and the shorter the time of application of the voltage the greater will be the necessary voltage to produce break down.

In a study of insulator failures it will, then, be essential not only to consider the voltage applied to the insulator but also the duration of the voltage. If a transient voltage of very short duration measured in micro-seconds be applied to a dielectric, such as porcelain, of sufficient value to rupture it, with very little power behind it we might expect to find the porcelain punctured, but since the time of the transient is very short the energy involved is small and therefor the destructive effect very local. Thus we might expect to find the porcelain melted over a very small path and solidifying again immediately upon the removal of the transient leaving the insulator in nearly as good condition as it was before the application of the puncturing voltage. However, due to the short duration of the transient voltage and the instant solidifying of the porcelain some impurities would be carried into the porcelain and sealed there, thus weakening, to a certain extent, the dielectric strength of the insulator.

If, however, simultaneously with the application of this transient we should apply a 60-cycle voltage of sufficient value to follow the path which the transient voltage had broken through the insulator, and with sufficient power behind it to keep this path in a molten condition the power arc would be maintained through this path and the insulator destroyed.

Whenever a steady condition of a circuit containing inductance and capacitance is disturbed there is set up an oscillatory transfer of energy from the electromagnetic to the electrostatic fields, or vice versa with a concommittant change in voltage or current conditions or both. The character of the change is dependent upon the relation between the resistance, inductance and capacitance in a manner familiar to all electrical engineers. In a high-voltage transmission line we have the distributed inductance and capacitance of the line and lumped inductance (transformers), and lumped capacitance, (lightning arresters and high-tension transformer windings). These form a circuit that is highly susceptible to oscillations and responds very readily to disturbance of the steady condition. Thus an arcing ground may cause large, relatively low-frequency surges and trains of high-frequency waves, the damping of which depends on the resistance of the oscillatory circuit. The frequency of the oscillations in this case will depend on the inductance and capacitance of the oscillating circuit, so on the location of the arcing ground. Thus it will be seen that an arcing ground may produce oscillations of widely varying frequency and varying in damping from well sustained wave trains to abrupt front transient impulses. In the same way a "spill over" of an insulator or the charging of a lightning arrester may subject a line to oscillations of voltage or current or both. The operation of switches especially of the air-break type is also often productive of vicious transients.

Since then a great many of the phenomena attendant upon the operation of a modern transmission line involve the superposition upon the sixty-cycle voltage of transients or highly damped high-frequency wave trains, a knowledge of the effects of these transients on the insulators of the line is of great importance and the investigation upon which this paper is based was undertaken to discover if possible the effect of these transients, and from these effects to determine advisable precautions in the manufacture and use of high-voltage insulators.

It has been shown by Ryan*, that the effect of the superposition of a radio-frequency sustained wave train on an audio-frequency wave is to give the combination a striking distance in air equal to the sum of the sparking distances of the two separately. If then we superpose transient voltages upon a normal-frequency wave the stress imposed by the combination will vary between the limits represented by the sum of the maximum transient and maximum 60-cycle voltages and their difference, according to the part of the cycle of the normal frequency wave in which the transient occurs, being the sum if a positive transient coincides with the positive maximum of the sixty cycle wave and the difference if it coincides with the maximum of the negative half wave. At any other point of coincidence the effect would be somewhere between these two limits.

The probability that a transient of known duration will fall within a certain part of a 60-cycle wave if impressed at random on the wave can readily be shown mathematically. Using the part of the positive half of a 60-cycle wave above the effective value it is found that one out of every fifteen million random

*Sustained Radio-Frequency High-Voltage Discharges, Trans. Inst. Radio Engineers, Sept., 1915.

impulses each consisting of the positive half of a 750,000-cycle wave will be likely to fall within this interval. If, when this does occur, the summation of the two voltages is sufficient in amount and duration to puncture the insulator the power arc would be very likely to follow the transient, blowing out the melted porcelain before it could solidify, thus permanently puncturing the insulator. It will be readily appreciated however that a transmission line might be operated for several years without this coincidence occurring and further that it might occur very locally and so effect only a few or even single insulators.

Method

An insulator of the type shown in Fig. 1 was selected because of the zone of the flux concentration in the plane at section *AB* and because the dielectric flux concentration near the pin in the inner petticoat was about seven times that near the cap in the outer petticoat. For the purpose of the test the cement can be considered as a perfect conductor and the manufacturers claimed a specific inductive capacity of 4.8 for this porcelain. Knowing these constants the dielectric field can be drawn to scale and the direction of the lines of force determined as indicated roughly in the figure. This insulator, designated as No. 1, and another of somewhat similar design (No. 2) and a 66,000-volt triple-petticoat pin insulator (No. 3) were subjected to a combination of a 60-cycle 50-kv. wave with a transient highly damped and corresponding to one half of a 750,000-cycle wave with a maximum of 30 kv. this transient applied at random with respect to position of coincidence with the 60-cycle wave.

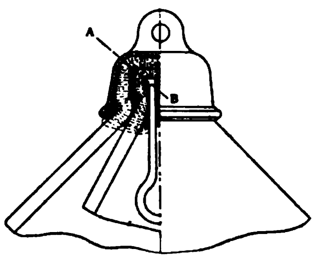


Fig. 1—Type of Insulator Used in Tests

After approximately eight million impulses insulators Nos. 1 and 3 broke down. Insulator No. 2 was then removed but punctured under the attempt to apply dry flash-over voltage, (95,000 volts).

Discussion of Data

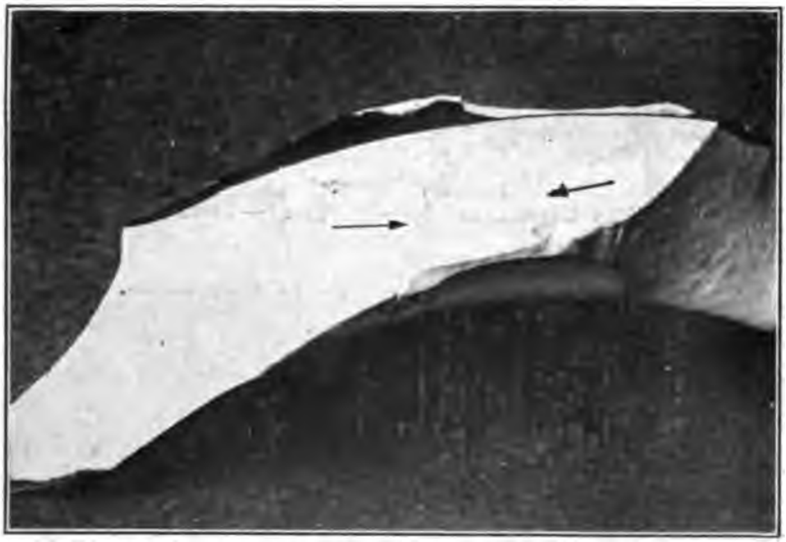
Insulator No. 1 was then carefully broken up and examined. The zone *A B* was riddled with fine hair-like lines which under the microscope proved to be tubes of slightly discolored melted porcelain. The discoloration seemed to be due to impurities

[PEASLEE]

FIG. 2—FRACTURES FROM ZONE A-B INSULATOR NO. 1. TWO AND ONE-HALF DIAMETERS — INNER PETTICOAT

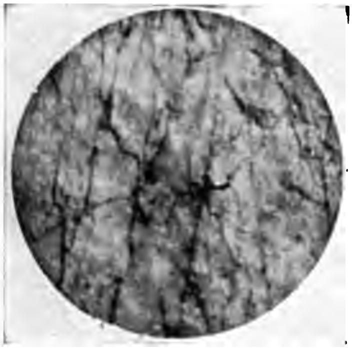
[PEASLEE]

FIG. 4—TEN DIAMETERS



[PEASLEE]

FIG. 3—POWER ARC PUNCTURES OUTER PETTICOAT INSULATOR NO. 1—TWO AND ONE-HALF DIAMETERS



[PEASLEE]

Fig. 5—Ten Diameters

[PEASLEE]

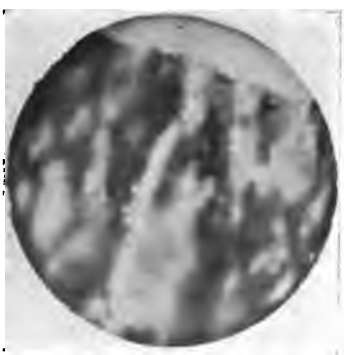
Fig. 6—Ten Diameters

[PEASLEE]

Fig. 7—Ten Diameters

[PEASLEE]

Fig. 8—Twenty Diameters



[PEASLEE]

Fig 9—Forty Diameters

[PEASLEE]

Fig. 10—Ten Diameters

carried into the porcelain by the puncturing arc and sealed into the tube of melted silica. The appearance of this puncture was very different from that caused by the power arc as shown in Fig. 3, and it is very significant that while these fine punctures were very numerous in the zone *A B* in the inner petticoat, there were practically none in the outer petticoat, and what few were found were not appreciably discolored. Also the inner petticoat fractured in what might almost be called a cleavage plane along this zone of flux and puncture concentration, showing that the porcelain had been weakened mechanically as well as electrically by these break downs even though they had sealed up in time to prevent the formation of a power arc.

Fig. 2 shows a surface fractured from zone *A B* magnified two and one-half diameters showing the fine cross lines, each a tube of melted silica, representing a puncture by a transient that has sealed up preventing the formation of a power arc. This sample is taken from the inner petticoat.

Fig. 3 is from a photograph of the outer petticoat of this insulator magnified two and one-half diameters showing the two power punctures that occurred in it when the inner petticoat, weakened by these impacts, finally ruptured. This photograph shows very clearly the marked difference between the puncture produced by a transient voltage only and one followed by a power arc.

Microscopic studies of these samples were extremely valuable and reveal many interesting features that the pictures cannot show regarding the mechanism of the break down etc.

Referring to the micro-photographs, Fig. 4 is taken from the inner petticoat in zone *A B* of insulator No. 1 showing the radiating punctures from the edge of the specimen nearest the pin. The broad white streak between the arrow points is the path of the power arc that finally, striking through this weakened zone, punctured and destroyed the insulator.

Fig. 5 shows a portion of the same specimen taken along the path of the power arc further towards the outside of the inner petticoat. The tendency of the transient voltages to jump across between defects in the dielectric is very noticeable here, and Fig. 6, taken from insulator No. 1, shows this very well, as seven distinct and separate punctures may be seen striking through this air hole. As this is magnified ten diameters the size of the defect can be appreciated and also the care necessary in the manufacture of the porcelain to produce a product free from defects that will weaken the insulator.

Figs. 7, 8, and 9 are taken from the same specimen from insulator No. 2 but magnified to different diameters as indicated.

Fig. 10 is taken from insulator No. 3, and shows very well the tendency of the transient to seek out and follow a series of defects in the porcelain. Fig. 11 is also taken from insulator No. 3.

Fig. 12 is taken from the inner petticoat of insulator No. 2 and shows very clearly the path of the power arc as well as the paths of the transients.

FURTHER INVESTIGATIONS

It would seem from a consideration of the fundamental mechanism of dielectric break down that two things must be avoided to prevent damage to an insulator; a concentration of dielectric flux above a certain value and a finite duration of this concentration. This seems well borne out by the data secured, as the failures shown in the photographs occurred in the zone indicated by this theory, and as was expected, were

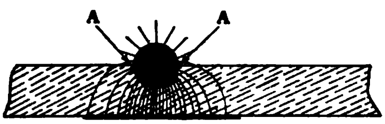


FIG. 13

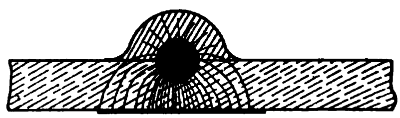


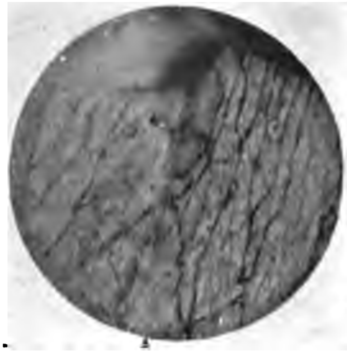
FIG. 14

almost entirely confined to the inner petticoat of each insulator. As a further investigation a piece of grooved porcelain was secured and a conductor placed in this groove with a plate against the other side of the porcelain opposite the groove. The resulting flux distribution is roughly indicated in Fig. 13. However it was feared that the corona forming on this conductor would act as a relief valve for the impact of the transient, the dielectrically weaker air absorbing the shock and so protecting the porcelain. Therefor a second sample was prepared as shown in Fig. 14 and the conductor covered with paraffin, the covering extending well up on the connection to the conductor to the point where the separation of the plate and conductor would prevent the formation of corona, thus forcing the impact onto the porcelain.

A third sample was prepared with a needle placed with its point against one side of a piece of porcelain, the whole needle being imbedded in sealing wax, while a plate was placed on the other side of the test piece.

[PEASLEE]

FIG. 11—TEN DIAMETERS



[PEASLEE]

FIG. 12—TEN DIAMETERS

[PEASLEE]

FIG. 15—FIVE DIAMETERS

[PEASLEE]

FIG. 16—FIVE DIAMETERS

[PEASLEE]

FIG. 17—FIVE DIAMETERS

These samples were subjected to the impact tests previously described, except that in this test the transients corresponded to a half of a 460,000-cycle wave, for about 70 hours with approximately 120 impacts per second. At the end of that period the samples shown in Figs. 13 and 14 were broken along the bottom of the grooves and the other under the needle point.

The sample arranged as in Fig. 13 showed no traces of puncture, while the one shown in Fig. 14 was liberally sprinkled along the bottom of the groove with the characteristic transient puncture. In none of these test pieces did the power arc follow through as the 60-cycle voltage was purposely kept low.

Fig. 15 shows the puncture found in the bottom of the groove in test piece shown in Fig. 14, and Fig. 16 shows the puncture found under the needle point. It should be noted that in this specimen the thickness of porcelain between the needle point and plate was twice that between the conductor and plate in Figs. 13 and 14.

Fig. 17 is included as of interest in showing the manner in which the transients strike into the porcelain from irregularities in the surface of the porcelain or cavities in the cement.

Conclusion

From what is now known of the action of high voltages of normal and high-frequency sustained waves and of transient duration, it is apparent that the successful insulator for continued service in high-voltage transmission lines must be designed with the following points in mind.

1. The actual puncture voltage of the insulator divided by the safety factor desired must be above the sum of the normal frequency maximum voltage that will be encountered in operation, (taking due account of relatively low-frequency surges), and the maximum transient or sustained high-frequency voltage that may be impressed on the line. If this is not done the insulator will in time be weakened by the impact of these transient voltages and ultimately must fail.

2. Points or zones of excessive flux concentration must be avoided. A careful porportioning must be undertaken to avoid the extreme dielectric field distortion and concentration commonly met with in insulators now on the market. Ratios of flux density in different parts of the field of eleven to one have been noted in certain insulators and these have almost universally given trouble in time on high-voltage lines.

3. The porcelain must be free from air bubbles and defects

and this is a problem that must be met by the ceramic engineer before it is possible to manufacture reliable insulators.

4. The insulators should have a puncture voltage as many times the dry flash-over voltage as the desired safety factor. The importance of this point is not always realized but when it is remembered that there is a large time lag in the break down of air it will be realized that severe impact stresses can be placed on an insulator by transients. With a sufficiently abrupt transient, a voltage of much more than flash-over may be impressed on an insulator in air and this is in the form of an impact delivered inside the insulator, weakening it at every application.

5. To avoid placing dielectrics of different dielectric constants in series, the surface of the insulator should follow, in so far as possible, the lines of force of the dielectric field.

6. Caps and metal parts should be smooth and of large radii of curvature to make the corona forming voltage as high as possible. It is possible to design an insulator that will flash over after the manner of sphere-gap break down without the formation of corona.

7. The design should be such mechanically as to keep the lines or zones of mechanical stress removed from the lines of electrical stress, and where this is impossible the two stresses should be as nearly as possible at right angles. This point has been brought out by recent study of the influence of the line of action of mechanical stress in porcelain upon the path of the resulting fracture.

These investigations were carried out in the high-tension laboratory of Oregon Agricultural College and the writer takes this opportunity to express his appreciation of the assistance of Mr. C. E. Oakes and Mr. Winfield Eckley who aided him in the test, and Prof. S. H. Graf of the Department of Experimental Engineering by whose courtesy the micro-photographs were made possible. Grateful acknowledgment is also made to Mr. L. T. Merwin for his very valuable suggestions in constructive criticism of the manuscript.

It is not felt that the data here presented bring out any previously unknown phenomena as this action has long been suspected by or known to many of the workers in this field, but they are presented as the preliminary results of an extensive investigation now in progress on the subject and it is hoped that a study of these photographs will increase the respect of the engineers, who are designing and using insulators, for the destructive ability of transient voltages.

Discussion on "Insulator Failures Under Transient Voltages" (Peaslee), Seattle, Wash., September 8, 1916.

J. B. Fisken: The author makes this statement: "The operation of switches, especially of the air-break type is also often productive of vicious transients." My experience has led me to believe that the substitution of the word "sometimes" for "often" would improve this paper very materially. We have never seen any occasions, in our system, where the operation of air-break switches was serious, and we have used them to quite a large extent. I want to ask Mr. Peaslee whether we are to believe from Fig. 1 that the potential gradient is constant through that insulator?

W. D. Peaslee: No. By no means. About 7 to 1.

J. B. Fisken: Then, there would be portions of that insulator where the flux density would be very much greater than it is in others?

W. D. Peaslee: There were. About seven to one.

J. B. Fisken: One of the most interesting things in the paper is the time element. There is something there that I, as an operating man, had never before realized. It seems that those high frequencies, which we all want to get rid of, keep working and it may be some considerable time before the insulator breaks down. I want to ask Mr. Peaslee if he does not think better results could be obtained if the top of the insulator was entirely covered with a metallic coating, and instead of having the tie wire which holds the high-tension wire, rest on porcelain, it should rest on some portion of the metallic covering? I ask that question for the reason that most of our punctures, or a large number of the punctures we find, take place from the tie wire and not from the conductor.

Robert Howes: We have heard a number of valuable comments upon the poor quality of insulators. About fifteen years ago I had a part in the construction of the first transmission line of the Washington Water Power Company to the Cour d' Alene District. It was early work in the 60,000-volt field and we were threatened with dire consequences, so all of us connected with the work exhausted our knowledge and wits to eliminate the threatened dangers. The construction in some features would be now considered obsolete, in others it is quite up to date, and some desirable modifications have been made. Still my record shows that in the first seven months of operation the line was out but a total of thirty-two minutes except by previous arrangement. Further, I understand from Mr. Fisken, who has had the handling of that line in his department ever since it was put up, that there have been almost no insulator failures from electrical causes on that line.

About eight years ago I had charge of the designing and construction of two parallel three-phase lines covering a distance of about sixty-five miles in British Columbia, the voltage was about

34,700 delivered with star connection and with neutral grounded at the power house. These lines were thrown on the power house suddenly upon completion and operated continuously. I have never heard of an insulator failure except by mechanical injury. However, my recent knowledge of the line is not sufficient to state whether any weakening has developed with age.

In both of these lines the precautions taken in designing were, grounded neutrals at the power house, lightning arresters, few in number, but located exactly at the terminals as opposed to location near the terminals. The insulators were tested to at least three times the voltage from wire to ground. In the British Columbia line as I remember it, each piece of the three-piece insulator was subjected to about 30,000 volts. In fact I think the top piece was subjected to 40,000 volts in actual tests. And the assembled parts to over ninety thousand, the test being made between salt water terminals. In these lines the intention was to be sure that the insulators had the same safety factor over working conditions that would be required in steel construction, for purposes of equal merit. It seems that we should not place more confidence in porcelain than we would in steel. Again as we figure steel beams on the stress in extreme fibers, so we should figure insulators on the stress in the most strained portions. It seems clear to me that the practical solution of the rotten-insulator question is first to keep insisting on proper safety factors over the working voltage, and second, use means to prevent excess voltage. Now in regard to the means of preventing excess voltage there is a little piece of ancient history in connection with the Washington Water Power Company that has influenced me whenever I have had anything to do with the installation of lines. Installed in that power house there were three monocycle generators. The connections were as follows: Generator, impedance coil, lightning arrester, bus bar, line. When the three units were in operation there were accordingly three lightning arresters at the power house. These machines were operated nominally at about 2300 volts. They had been operating for years without any serious difficulty, or at least for a considerable period. Under my direction, we installed a wattmeter which was connected by means of a two-circuit current transformer connected in the two outside wires of the bus bar. There were no changes made in the lightning arrester connections whatever. At the first slight lightning disturbances that could be noticed one of the generators punctured to ground. This was cleared up by the power house foreman and the lightning arresters gone over thoroughly and the other conditions remained as before. A very short time after that a second slight lightning disturbance caused a second puncture in the same place. I then went over the lightning arresters myself and carefully examined everything to make sure that nothing had been neglected. But the next slight amount of lightning caused a third puncture in the same place. I then thought it must be due to some change in conditions, and the only change that had been made was the installation of the wattmeter, so without changing anything else I took an ordinary air-gap arrester and connected it exactly at the outside terminals of the current transformers, after which the machine ran until it was put out of commission by disuse, without any further difficulty, whatever. Ever since that time I have positively insisted that the lightning arrester connections should be made at the first material impedance and exactly at the terminal of that impedance and not at some distance away. I have noticed several transmission lines where there have been lightning disturbances in which the lightning arrester connections were made at some distance—say at from fifty to two hundred feet from the first impedance—and those lines as far as I have noted were lines that had trouble from lightning. Now, I say lightning—I mean any high-frequency disturbance similar to lightning on the line—and it has been my experience such as I have had in both low and high-tension lines, that with insulators tested as above and the lightning arrester connection made exactly at the impedance terminal there has been no serious trouble from such disturbances.

L. T. Merwin: On this question of the impact of the higher transients on our insulators, I will confess that in years gone by, when an insulator failed from puncture or was destroyed from whatever cause, the man in charge of the repair dropped it on the ground at the foot of the pole where it was found and a new one was substituted. The line was again put in commission and that was all there was to it. Now, following experiments that are going on in the various laboratories of our institutions of higher learning, we are beginning to know why these things have been taking place. Very often it happens that the note of warning has been sent out and absolutely disregarded. I feel that probably we are disregarding every day things to which we should attend. We have had just exactly the information and the remedies already voiced if we would only listen to the notes of danger. After Mr. Peaslee had shown me the rough draft of this paper we had a failure on our transmission line, the results of which you have all seen in the fractured insulator which has been shown here today, and which absolutely corroborates his contention in the paper. Now, Mr. Peaslee has developed the theory born from the fruits of experimental investigation in his laboratory, equipped with apparatus that is beyond the range of the ordinary operating man to have, but here is a confirmation following immediately upon the heels of his announced results that is very gratifying.

Harris J. Ryan: This paper on insulator failures under transient voltages has given us an intimate and correct idea of the manner in which porcelain fails under electric stress. It properly emphasizes the almost instantaneous porcelain fusing ability of an undue amount of charging current and the powerful character of the mechanical blast that is generated by an electric spark in its own length. I heartily endorse most of the author's conclusions, drawn from the results of his experiments. I trust he will continue his work along present lines, and in so doing, that he will employ definitely porous and non-porous porcelain, the latter with and without absorbed moisture, so as to develop more evidence in regard to the basis for Mr. Osborne's claim of yesterday, that porous insulators are capable of reliable service. It is, of course, conceivable that water-logged porcelain may endure transient over-voltages pretty well. As evidence thereof, we have the failure of the oscillator to pick out defective insulators when porous and water filled. In regard to sustained 60-cycle voltage, the matter is quite different. Of that there can be no shadow of doubt. The great difference between wet and dry porcelain production processes is; in the former the porcelain can not have its pore systems closed by vitrification, while, in the latter, it can. No water-logged porcelain will endure between conductor electrodes an ample amount of sustained power voltage to render it reliable for high-voltage service.

R. W. Mastick: Mr. Fisken has called attention to the statement in Mr. Peaslee's paper and objected to it that "The operation of switches, especially of the air-break type, is also often productive of vicious transients". I wish to add some evidence in support of Mr. Peaslee's remark.

A few months ago, it was my privilege to conduct an investigation on an operating power system of transients produced by the operation of both oil and air-break switches. A number of observations were made and recorded by means of an oscillograph, of switching operations under both load and no-load conditions. These observations were made both at the point of switching, and with many miles of transmission line intervening between the switch and the point where the oscillograph was located.

In several instances, transients of a violent character were recorded and the presence of frequencies of a high order definitely indicated. The transients produced by oil switches were not so violent, nor as long sustained as those produced by air-break switches.

It is of interest to note that these observations of transients were all recorded by using the residual voltages and currents of the power system.

J. B. Fisken: I had two reasons for making the statement that I did: One is the practical reason that we are operating air switches without, apparently, having any difficulty. My other reason was that some years ago, we made a number of oscillograph tests with air switches and oil switches, and we could not see that there was any material difference. It is quite possible that our methods of connection were somewhat crude, and that we did not get as refined a test as Mr. Mastick would get, but I still am of the opinion, Mr. Mastick to the contrary notwithstanding, that this talk of the extreme high frequencies or disturbances caused by air switches, is not well taken.

R. M. Boykin: While I have heard but little of the discussion on this subject, I would like to ask Prof. Ryan what he considers water-logged porcelain, or water-logged insulators, and how much water by weight or volume can porcelain absorb before rendering the porcelain useless for insulator purposes.

Harris J. Ryan: I can only answer that question in part: The porous porcelain referred to just now is of good quality except that its porosity exceeds some low value, perhaps a tenth per cent by volume, just how much we do not know as yet. An insulator body that has its pores filled with water is liable to early failure. The resistivity-temperature relation for porcelain is negative and very high, besides it ceases altogether to be an insulator and becomes an electrolytic conductor at about 300 deg. cent. Thus in a water filled porous porcelain body subjected to power-voltage, the in-phase current will be concentrated upon a narrow route or core, producing intense local heat and puncture. Much trouble undoubtedly has come from the fact that dry porous porcelain has at all ordinary temperatures about the same high resistivity and dielectric strength as non-porous porcelain. It is here understood that non-porous porcelain is that, in which the pore systems are well limited and in which they do not in any single instance extend through appreciable depths of the porcelain bodies.

A. A. Miller: I would like to ask Prof. Ryan about his statement as to the effect of temperature upon the dielectric strength of the material of the insulator. Do I understand that he refers to a temperature of 425 deg. cent. as being the temperature of the material along the path of the puncture or does his statement cover general results of tests made upon masses of porcelain at known temperatures?

Harris J. Ryan: In speaking of the loss of all dielectric strength for porcelain at 300 deg. cent. I had reference to the results of C. E. Henderson and G. O. Weiner which may be found in their paper on, "Effect of Temperature on the Dielectric Strength of Porcelain Insulators," published in the Transactions of the American Ceramic Society, Vol. XIII, p. 469, 1911.

W. D. Peaslee: With reference to the point raised regarding the matter of the air-break switch, I will explain that I put that point in for this reason: While fundamentally, of itself, I do not believe the air-break switch or the oil-break switch is responsible for any transients of high or low frequency, whatever, it is a fact that when connected to circuits of certain characteristics, they will produce transients, and vicious transients. You can make a test on a certain circuit with an air-break switch or an oil-break switch, and show a man that there are no transients, and yet, that man, if he knows his game, will make up other circuits and show you some of the worst transients you can imagine.

Mr. Howes made a good point as to lightning arrester connections. The average man takes his lightning arresters, and connects them 150 feet from his nearest transformers, and hooks up an inductance there. The results are that every time there is an arrester discharge, a wave of approximately two million cycles highly damped goes out on the line and subjects it to wave fronts approximately a half cycle of two million cycles, and that is pretty steep. You try to plot a two million cycle wave, and you will find it is pretty nearly straight up and down when it hits. The impact goes inside the insulator and tears into the porcelain a distance depending upon the time and the steepness of the wave front and maximum value of voltage. In that way, I think a great many of the lightning arresters, as they are connected up, are a menace to the lines to which they are connected. I think they are certainly a menace to the telephone lines along side of them. Now, referring to the matter of air-break and oil-break switches, the air-break switch has, I think, more tendency to cause oscillation for this reason: The oil switches operate on a few cycles, while the air switch sweeps away out, and there is a great deal more chance in that time for one current to break before the others. If that happens, your lightning arresters may operate on double voltage, a two-million-cycle wave will rush out on the line and into the first insulator it happens to catch in a bad place. That is the reason I brought in the question of the air-break switch. It is not fundamentally a question of the switch. It is a question of the tendency to transients in certain circuits to which it is connected. It is not so much a question of the air-break or oil-break switch as it is the circuit to which it is connected, and the method by which it is connected. I think Mr. Howe's point as to the manner of connecting up the lightning arresters is very valuable, and I know a great many of the lines I have investigated present a situation such as he described. In one line I know of in the Northwest, every time they charge a lightning arrester at one end of the line, the transient impulse will jump seven turns on the inductance at the other end of the line, and the men will stand around and say "they are charging down at the other end of the line." That could be stopped completely by changing the connection of the lightning arrester, so that there would not be a circuit there oscillating at that frequency everytime the lightning arrester was discharged. Now, as to the matter of flux concentration, that particular insulator shown in Fig. 1, was chosen because the variation in flux concentration was seven to one. Take the analogy of the beam. Part of the porcelain was working at maximum stress, and that was the part on which the whole thing depended. If you could have kept your wires as far from this inner petticoat, as they were with the outer petticoat on, you could just as well have done without using the outer petticoat, because it was not doing anything.

As to the matter of metal coating, which was suggested. I have found a transient puncture on the insulator taken off the high line, wherein I imagine the end of the tie wire was struck against the insulator and probably struck the glaze. I think it would be an extremely valuable point if a complete metal cap could be put over the top of the insulator.

The question was brought up as to a great many of these insulators being out on the line a long time and failing mechanically, but not electrically. When we took one insulator off the line, we took the petticoat out intact and split it, and took hold of it, and just broke a ring right out of it at that zone of flux concentration. You could break it with your fingers. I think a great many of the difficulties we have with our insulators are due to that point of flux concentration. There are two different forms of po celain in that zone, so it is bound to weaken the insulator mechanically. The protection against high voltage is another problem that sounds easy. Mr. Howe's suggestion is a good one, but here is the trouble: You take a horn gap and put it up on the line, and if you put steep wave fronts on it, they may never pas; across it. An ordinary horn gap will not pass certain transients. A needle gap probably will not pass one of a higher frequency than half of a 100,000-cycle wave. I think the ult mate solution will be found in the equipment which will be used this winter in a couple of places—as experiments—a sphere-gap horn gap. That is, the gap will be a sphere gap, passing any transients, but you will still have the old horns. Unquestionably, there are transients, sustained waves, or damped waves that go right by our lightning arrester horn gaps, and those get into our machines. For instance, there is the case I spoke to you of, where the inductance turns are jumped by the transient. It goes by the horn gaps and jumps seven turns on the inductance, because of the sudden banking up of wave by the inductance, so it is pretty clearly proved that you can get a condition of that kind.

Prof. Ryan spoke of the fact that we should have non-porous porcelain. I may be pessimistic in that regard, but I do not believe that non-porous porcelain can be made. Consider for a moment the value: A tenth of one per cent porosity renders an insu'ator worthless after it has been soaked a while, and a tenth of one per cent porosity is a pretty small margin to work to. You may be able to make such porcelain in the laboratory, with a vacuum furnace, but when you come to manufacture insulators in car load lots, it is a pretty close limit to work to.

In the matter of the punctures in the porcelain, some go half way through the porcelain and stop. That is, their time of duration at maximum voltage was not great enough to get clear through. Under the microscope, following these out one by one, you will very often find a puncture going in, then, there will be a branch. Now, whether or not that forked branch occurred with the first impulse, or whether the next impulse caught it and followed it along, and then broke off, I don't know. Now, enough of these minute punctures finally occur so that the combination of punctures brings about disintegration which reduces the resistance of that path until the power voltage passes through. I do not believe, from my investigation, that the concommittant occurrence of the power peak and the transients, is necessary for puncture. I believe that the transients will keep coming until you get a voltage that will break through. Insulator No. 3, mentioned in the paper, was taken off the line after insulators Nos. 1 and 2 were punctured. We took it off the line and it punctured under the flash-over voltage that it had successfully withstood before. It was a good sixty-cycle wave, with a 100-kilowatt transformer behind it. A 100-kilowatt transformer does not surge on one insulator. That insulator, on a 60-cycle wave, with a 100-kilowatt transformer, punctured under the flash-over voltage, indicating that it had been weakened materially by the impact of these transients. So, a voltage lower than normal operating voltage punctured the insulator.

With reference to Mr. Merwin's remarks about co-operation. It is a little discouraging to a man in a University with a laboratory at his command to sit down and go into a thing, and then go out and tell an operating man that a condition exists in which he will get such a result, and have that man laugh at you, and then about six months later, that man comes to you, and says ' I have had such and such a thing happen on my transmission line. What is the matter"? And it does not make him feel any better to have you tell him that six months or a year before, you had told him that that very thing was going to happen. It is my experience that it is very seldom that a man from a University laboratory can go to a power man and get any co-operation in making any tests on a power line. We would appreciate a little more of Mr. Merwin's spirit of co-operation in our work in the laboratory.

E. E. F. Creighton (communicated after adjournment): Mr. Peaslee has undertaken research work in one of the most important subjects in transmission engineering today. There is great need of more investigators in this subject and to get definite results it seems necessary for the investigator to enter the field of ceramics. Personally I have come to the conclusion that electrical testing alone will give comparatively little data of value.

Mr. Peaslee's photographs are interesting and I find myself in agreement in general with his conclusions. It is desirable that all the workers in this line come to a common agreement and language and with this in view I should like to ask questions about certain features of the work.

Taking the subject in the order of the reading—I find that certain mathematical calculations give one impulse in 15,000,000 random impulses within that part of a half-cycle of the 60-cycle wave, which is above the effective value. I have been unable to arrive at the same conclusions. For example, the potential of the wave is above the effective value from 45 deg. to 135 deg. or 90 deg. of the time. Therefore, random shots should fall, one in every four, within the range designated, since the ratio of time is 90 deg. to 360 deg. total. Such random shots could be obtained only by using a separate source of a-c. potential. If the same source of a-c. potential is used the shots will not be at random but should be located at a fairly definite point of the a-c. wave.

Referring to the notes under method, I should like to inquire if the regular 60-cycle tests were made on these insulators before the high-frequency impulses were applied; also if the ohmic resistance of each skirt was taken.

In the discussion on the failure of Insulator No. 1 Mr. Peaslee touches on a subject in which many tests have been made. Back of all these tests is the question which has been raised repeatedly in the past few years—what constitutes a fair test on an insulator and when does the test damage good porcelain? If the porcelain used in Mr. Peaslee's tests was good then the very mild test was too severe. I have made numerous tests which show that this impulse test was too mild to give a satisfactory test for porcelain insulators and therefore the tests show, unmistakably, a poor grade or defective porcelain.

In tests on insulators similar to Fig. 1, giving the fan-shape discharges, as shown in Fig. 2, it has been determined that the inner skirt was cracked either before the test or by the test, and that the discharges leaving permanent traces of their paths on the broken surfaces of the inner porcelain are due to the currents which pass through the inner skirt and charge up the condenser formed by the outer skirt. If both skirts are punctured, 30 kv. of potential would surely maintain an arc through the tiniest possible puncture hole. The current flowing through the inner skirt to charge up the outer skirt as a condenser is of the order of 15 amperes effective, the calculation being made for a damped wave of 750,000-cycles frequency, a voltage of 80 kv., and a capacitance of 40 micro- microfarads. As to the cause of the fan-shape discharge—I have come to the conclusion that it is due, not to the sealing up of the path, but to the lowering of the resistance of the path. Assuming that there is a crack existing initially, the first disruptive discharge will pass through the air in the crack from one surface of the porcelain to the other and repeated discharges in this path will heat the porcelain to a temperature of partial conduction. In other words, this becomes a high resistance path. When the next discharge attempts to pass through this resistance the *IR* drop is sufficient to maintain full potential and therefore the discharge will take place through an adjacent path where it has free air to ionize. It will follow this adjacent path until it has heated it to a condition of partial conduction and then choose a new path. Each time there is a sufficient sealing up at the point of discharge and also sufficient opening up of the crack to make a new path desirable.

As a proof of this theory, two electrodes across which a disruptive discharge takes place may have a high resistance rod or pencil placed across the gap and the disruptive discharge will refuse to follow the path of the resistance material, but will jump straight from surface to surface through the air.

If porcelain punctures without a crack it is not difficult to permanently reseal it if the proper precautions are taken. If liquids can be used as electrodes it is possible to avoid carrying carbon or metal vapors into the discharge path and thereby destroying the insulation af er the spot has cooled. A porcelain cup set in water and filled about a quarter full was punctured half a dozen times with an oscillator, leaving the discharge on about 5 seconds after each puncture. The puncture hole filled up with clear-colored glass and was subsequently stronger than the rest of the porcelain.

In endeavoring in single pieces of porcelain like a suspension insulator to observe the deterioration which may take place from disruptive discharges at reasonable potentials applied over long periods of time, insurmountable difficulties seem to be encountered in determining the progress of the puncture. My experience has been that when an insulator punctures I have found unmistakable defects which caused the puncture. For example, a definite air bubble or lamination due to defective pugging of the plastic porcelain is most frequently the cause. Or it may be due to a fold in the porcelain while it is being jiggered. Or it may be due to an excess pressure of a tool which squeezed out the moisture along a sharp corner which subsequently developed into a partial fault in drying and was not fully vitrified later in the kiln. Or if the kiln is accidently under-fired, every piece may be more or less porous and therefore defective in proportion to its porosity.

Theoretically it should be possible to use the difference in potential gradient of the inner surface and outer surface of the porcelain to determine, by means of damage to the inner surface by corona, when the test becomes too severe for good porcelain. Practically satisfactory results have not been obtained due to defects in the porcelain. After an endurance test of many minutes or even several hours which has caused a puncture, the porcelain cap has been sawed off and the porcelain surfaces exposed to examination. Very rarely are other scars on the rest of the surface found even with a microscope. Such scars, indicating the possible beginning of puncture, have been found as frequently on the outer surface of the porce'ain as the inner surface. Since the potential gradient on the outer surface is only a fraction of the value at the inner surface these scars indicate defective porcelain. Once, in grinding off a scar with a carborundum wheel a bubble in the porcelain was uncovered at a greater depth than the scar. The corona was burning its way into the bubble.

Damage to good porcelain can easily be done by carrying the potential gradient above its safe value, but such a gradient could not exist on the inner surface of a porcelain insulator at 80 kv. with its diameter of 1 ½ in. or more. Therefore, I have been led to the conclusion that with most of the latest design of insulators the trouble is due, not to the design so much as to defective porcelain, which brings the problem back to the ceramic engineer. I feel we can make very little further progress on the electrical side until porcelains of reliable qualities can be reproduced.

A test was recently made in an endeavor to determine if single impulses were not more severe on the porcelain than oscillatory discharges. Several million discharges of the damped wave at 200,000 cycles were made on a suspension insulator immersed in oil. The voltage was 80 kv. for part of the test and 100 kv. for more than two hours of continual discharge at 120 per second. The porcelain was not punctured. It was subsequently broken up but no damage whatsoever could be noted on its surfaces. This porcelain happened to be perfectly made. There were no bubbles or laminations in any of the broken pieces and it was extremely strong mechanically 'n resisting the blows of the hammer.

W. D. Peaslee: Referring to Mr. Creighton's remarks, I am very glad that he has called to my attention the error in the paper regarding the number of random impulses occurring within that part of a half cycle of the 60-cycle wave which is above the effective value. This statement should read as follows, "Using the part of the 750,000-cycle positive half-wave transient above the effective value, one out of every 1,500,000 such random impulses will fall on the crest of the 60-cycle positive half-wave."

The regular 60-cycle tests were made on these insulators before the high-frequency impulses were applied but the ohmic resistance of each skirt was not taken as our megger was out of commission at that time.

I do not believe that Mr. Creighton's explanation of the fan shaped discharge lines is the correct one for all cases as I have found a decided difference in character of these lines when they are formed by the discharges through a previously existing crack and when they are formed by transients puncturing the uncracked porcelain. In the latter case an examination of these discharge paths will show a complete tube of melted silica without evidence of a previously existing crack, while a discharge through a previously existing crack is more likely to show a groove nature, although the heat of the discharge may later fuse the sides of the groove in such a way that a microscopic examination is necessary to detect the difference. Grooves of this kind have been found with partially fused fragments, microscopic in size, almost entirely filling them. Referring to Fig. 14, when the conductor was removed from this groove there was not the slightest indication of a crack, though under the microscope it was possible to detect the entrance points of the punctures. The porcelain fractured very easily along the bottom of the groove and the discharge paths shown in Fig. 15 consisted of tubes of fused quartz glass.

I believe with Mr. Creighton that the problem is essentially one for the ceramic engineer, but do feel that electrical tests must always be the criterion by which insulators are to be accepted or rejected. Their duty is electrical and their fitness for such duty must, I think, be determined by electrical tests.

Presented at the 10th Annual Convention of the Association of Iron and Steel Electrical Engineers in joint session with the American Institute of Electrical Engineers, Chicago, Ill., September 20, 1916.

UNDERGROUND DISTRIBUTION SYSTEMS

BY G. J. NEWTON

ABSTRACT OF PAPER

The object of this paper is to show the importance of properly designing an underground distribution system for the district it serves and the particular service it is to supply. Simply placing the wires underground does not constitute an efficient system.

Underground distribution is the ultimate solution of the distribution problem that confronts every Electric Light and Power company operating in progressive towns and cities. The excessive cost of this class of construction, as compared with aerial construction, and the permanent nature of the system, warrant a careful study of the conditions and justifies a reasonable expense in the development of suitable plans for the system.

The financial success of an electrical undertaking depends on supplying efficient and reliable service in an economical manner, and in order to secure this result the distribution system must be carefully designed and properly installed.

The automatic substation, when perfected and adopted, will not only permit a great reduction in the number of ducts required and a lower first cost, but will provide more reliable service and bring underground distribution within the reach of many small companies where the cost of this class of service would not be warranted under the former conditions.

The suggestions offered in this paper are based on many years experience and are made with a sincere desire to aid those interested in this class of work, particularly in the design and installation of the first system in the smaller cities.

THE FOLLOWING facts and suggestions are based on many years experience with underground distribution systems, and are stated in the following article with the intention of showing the importance of careful and intelligent design as related, not only to the first cost, but to the economical operation and ultimate value of the completed system.

An inspection of many systems has made it evident to the writer that improper design is responsible for more faults than is poor construction, and it is with a sincere desire to aid others interested in this work, to avoid such mistakes in the future, that these suggestions are offered.

No two systems are entirely alike, and the conditions are different in every place; it is, therefore, impossible to formulate any definite rules that will apply under all conditions. The engineer must be guided by good judgment, based on experience, and a thorough study of the conditions in order to secure satisfactory results.

Owing to the increasing demand for electrical energy, and the serious objection to the unsightly and dangerous overhead wires and poles, underground systems of distribution have become a necessity in many places where the expense of this class of service would not have been considered warranted under former conditions.

Underground distribution is very expensive, as compared with overhead construction, and in many cases, particularly in the smaller cities, the first cost is of vital importance; a carefully worked out design is therefore necessary in order to derive the greatest benefit from the money expended. Many of the present systems have not been designed with the care, and attention to detail, that their importance deserves and frequently the cost of the system has been entirely out of proportion to its ultimate value.

The first installation of an underground system is made necessary by an order of the city authorities compelling the removal of poles and wires from certain sections of the city or by the desire of the operating company to improve the service and secure greater facilities in a district where the demand for light and power has reached a point that this class of service is warranted.

In either of the above cases, and in fact, practically in all cases in this country, underground systems are never installed until long after the district has been supplied by an overhead system. As a general rule, all overhead systems are the result of a series of extensions and changes, rather than the development of any systematic plan of distribution, and are seldom based on efficient or economical methods.

If it were possible to design and install an underground system at the start of an electrical undertaking the problem would be much simplified, as the station and consumers equipment could be selected, and the whole system designed for the most efficient results. Unfortunately the conditions are never so favorable, and the distribution engineer is confronted with many conditions over which he has no control, but must consider in making his plans.

Distribution problems are, therefore, usually very complex and permit of several methods of being solved. It is only by a careful study of the conditions and foresight as to the future requirements of the system that a satisfactory, economical and efficient design can be developed.

The conditions under which underground cables and equipment operate are more severe than on overhead systems, and a thorough knowledge of these conditions is absolutely necessary, and must be kept in mind, in selecting cables and equipment and designing the conduit system for their installation. Overhead wires can be, and frequently are, operated far above their rated capacity, without any serious danger, but underground cables and equipment must be operated within certain definite limits in order to avoid serious damage, if not total destruction.

Economy of distribution is equally as important as economy in production, particularly at the present time, when practically all public utility companies are regulated, to a greater or less extent, by state or municipal commissions. First cost is not, therefore the only factor that should be considered, as economical operation and reliability of service are equally as important in the financial success and growth of the business.

Except in the large companies, there is probably no branch of the business that has been given less thought and study than underground work; in many cases the principal object evidently has been to get the wires out of sight at the least possible expense, with no attempt being made to improve the system of distribution and little or no regard for the future development of this class of service.

The operation of an underground system, when properly designed, installed, and maintained guarantees the most reliable and efficient service of any method of distribution ever employed; the financial benefit, directly due to this class of service is, in many cases, a proof of the wisdom of its installation.

While it is admitted that underground systems are expensive to install, still it must be remembered that a conduit system is a permanent structure, has little or no depreciation; on the contrary it will increase in value as the importance of the section it serves is developed. Considering the first cost, permanent nature of the undertaking, and importance of economical and reliable service, it is advisable to make a thorough study of the conditions and future requirements of the service on which to base a design of the proposed system.

In designing an underground distribution system there is one important fact that must always be considered—the system should be designed to serve the entire district that can reasonably be expected to ever require this class of service. Such a design permits of a systematic scheme being developed for the whole district, uniform methods of construction, and standardization of equipment.

If this method is followed it is then possible to install any section, from time to time as the service demands, and each completed section will form a part of the whole general scheme and eventually develop into a system rather than a collection of more or less useful sections of conduit.

135 Washington Street.												No.	
William Henderson & Co.												VOLTS 110-220	
LIGHTING LOAD													
SIZE			10	25	40	50	60	80	100				WATTS
LIGHTING				40		20	110		.				8600
SIGN			90						5				1400
APPLIANCES													
10 Desk Fans													660
3 Irons													300
												TOTAL LIGHTING LOAD	10960
POWER													
2-5 HP. 220 Volt 3φ Motors													10000
1-10 HP. 220 Volt 3φ Motor													10000
												TOTAL POWER LOAD	20 Kw.
L. SERVICE 105 ft. #4-3 Conductor.							TRANSFORMER 14 A						
P SERVICE 110 ft. #4-3 Conductor.							TRANSFORMER 14 A-B-C.						

FIG. 1

It is not the object of this article to show each step in the design of any particular system but rather to point out certain important features to be kept in mind and offer suggestions as to the general method to be adopted; it is only by a thorough study of each case that the best methods can be determined.

The first step in designing an underground distribution system is to secure an accurate load record for each consumer in the proposed underground district. This record should be kept on cards similar to Fig. 1; where there is a large power load in the district it is advisable to make separate records for the lighting and power loads, using different colored cards for each record. The card shown in Fig. 1 is simply a sample, and the best arrangement of the inventory on the cards will depend on the requirements of each particular system.

The reverse side of the cards can be used for showing the number and location of the transformer supplying the service lateral, consumers fuse box and other information connected with each consumers service.

These cards if properly corrected will form a permanent record of great value in making future changes and balancing the load on the distribution system.

The men securing the load record should be provided with paper pads printed the same as the cards and the permanent card record can be made in the office from these slips and the cards be kept clean and neat.

A careful inspection should be made of each building to determine the most suitable location for the new underground lateral in order to reduce the cost of changing the inside wiring as much as possible. Except in the case of very heavy loads or consumers where emergency service must be provided for, it is advisable to supply all of the consumers in a building from one lighting and one power lateral, this reduces the number of laterals, handholes, and fuse boxes and permits using the least amount of copper by taking advantage of the diversity of a group of consumers.

The lighting and power load can be plotted on one drawing as shown in Fig. 2 or the loads can be plotted on separate plans, the latter method is best as the plans for each system can then be kept separate.

The load maps for each system should show the total load, both in the underground district and outside of it, that is to be supplied by cables in the conduit system from the power house so that ample conduit space can be provided and the most suitable routes and sizes of feeders determined.

Having the lighting and power loads and a map showing the street light system, the next step is to determine the most suitable plan of distribution to be adopted, this may be called the critical point in the design of a distribution system, for on the decision depends not only the first cost of the installation but the reliable, efficient and economical operation of the distribution system.

There are two general schemes of distribution:

1. To supply the whole city from one power house.

2. Divide the city into districts and supply each from substations, or rather from the power house and substations.

In many of the older systems the first method was used and a large number of ducts were installed, in one trench from the power house, to serve the whole city, or at least that portion that was to be supplied by underground eventually. This necessitated providing a large number of spare ducts, a large percentage of which remained idle for years and not infrequently resulted in too many ducts in some places and too few in others.

Not only was the first cost of such a system excessive but the manholes were almost invariably too small to accommodate the number of cables that could have been installed in all of the ducts had there ever been use for them. The most serious objection to this plan is that the losses due to the heating of so many cables in one conduit run are excessive and materially reduce the carrying capacity of the cables, particularly in cables occupying the inner ducts.

Another serious objection to this method is that a burn-out on one cable is practically certain to damage adjacent cables and cause interruption of service over a considerable area. Faults on underground systems usually affect more consumers than on an overhead system and require more time to repair, therefore, no system should be considered that does not permit being sectionalized and have reasonable emergency facilities provided for restoring service with the least possible delay.

The objections to the first plan, as stated above, preclude its adoption except in very small cities where the area to be served by underground distribution is limited, and the total number of ducts installed in one trench will not be excessive.

The second method of distribution, when properly designed, avoids all of the objectionable features of the first method and is particularly adapted to the modern practise of installing substations supplied by high-tension feeders, as each district is practically operated separate from the others and with suitable emergency feeders and switching equipment permits each district to assist the others in case of necessity.

The old saying "That you should not put all of your eggs in one basket" is particularly true if we change the words slightly—"You should not put all of your feeders in one trench or manhole" and the distribution engineer will be wise to keep this warning in mind as far as the requirements of the case will permit.

Reliable service and economical distribution are absolutely necessary for the financial success of every light and power company. Reliability depends on the following conditions:

1. The best material, equipment and workmanship.

2. Proper selection of material and equipment for the service it is to supply.

3. Efficient protective apparatus, judiciously installed.

4. Sectionalizing apparatus properly located.

5. Continuity of supply, by feeders over different routes or an arrangement that will provide at least two sources of supply for the network.

6. Regular and systematic inspection of the distribution system by competent men.

7. Accurate plans and records of the distribution system so that changes, additions and extensions can be made to the best advantage with the least possibility of error.

Economical operation depends upon a reasonable first cost, in addition to all of the above conditions, and where a system is designed at first for a whole city (keeping in mind future substations) it is possible to reduce the number of ducts and manholes to a minimum, install sections as the business warrants and extend the ultimate cost over a considerable period.

Keeping the above facts in mind the actual design of an underground distribution system should be made on the following general plan. Assuming that the first underground installation is to supply a district similar to that shown in Fig. 2, and that later this district will be extended a block or two in each direction and supplied from the main station.

While it is admitted that it is not possible accurately to foretell where substations will be located in the future, still a study of the conditions will generally permit a reasonable assumption to be made and if separate conduit is to be installed later for high-tension feeders this part of the work does not enter into the first design except in a general way.

After making the load maps for the lighting and power systems and also a map showing the location of the street lights it is a good plan to first layout the street light circuits, for assuming that all wires in the district must be placed underground it is evident that conduit must be installed to reach every light.

The location of the street lights is determined by the city authorities and can seldom be altered enough to materially change the conduit arrangement, therefore, by designing this system first it will give a general idea of where the conduit *must* be installed and keeping this plan in mind it is frequently possible to arrange the secondary mains so as to utilize the same routes

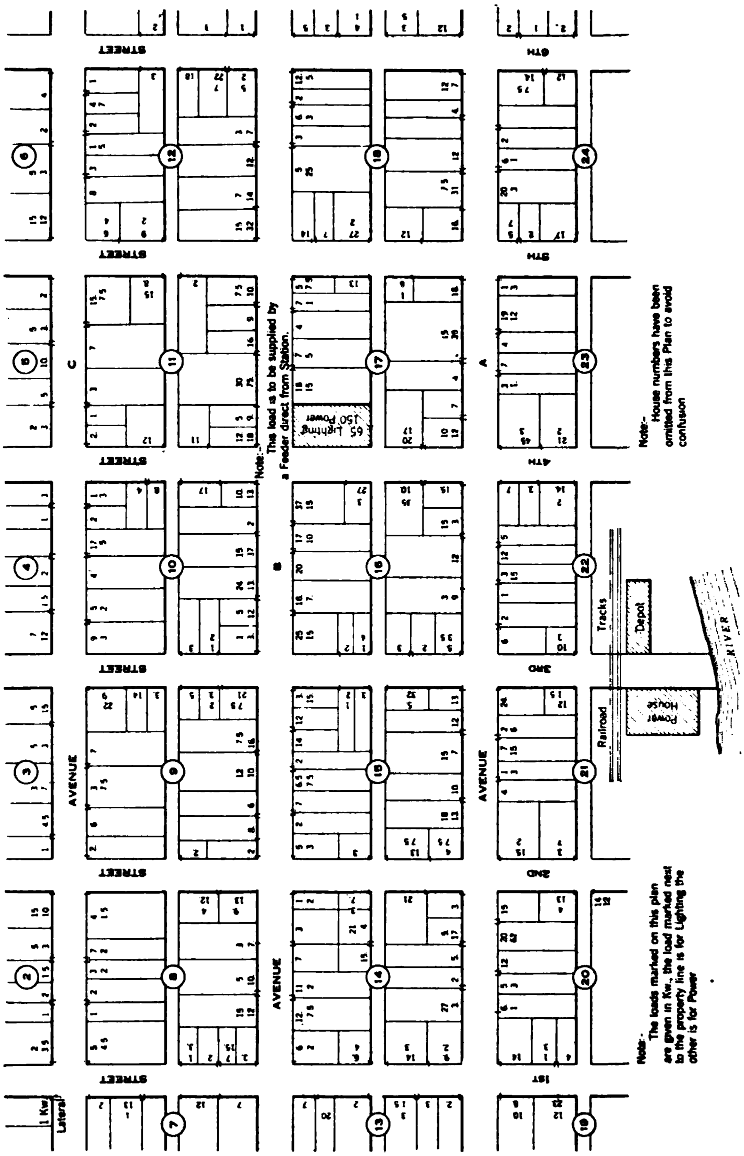


FIG. 2—LOAD MAP

(particularly in alleys and the less important streets) so as to avoid considerable conduit construction.

The proposed location of the laterals in each building should be shown on the plan for the secondary systems for light and power. A study of these locations together with the street light conduit layout will often show where slight changes in one or the other will permit considerable saving, even when changing some laterals will increase the cost of the inside wiring.

Owing to the fact that the grouping of consumers, in a district, will usually be different on an underground system than it was on the original overhead system it is practically impossible accurately to determine what the demand and diversity factors will be for the new system. A distribution system for either lighting or power usually consists of the following sub-divisions:

Primary feeders to centers of distribution.

Secondary feeders supplying the transformers.

Secondary mains supplying the service laterals.

Service laterals supplying the consumers.

In small systems the secondary feeders are not required, as the transformers are connected directly to the primary feeders.

The size of cables to use for the laterals is easily determined, the principal object is to restrict the number of sizes of cable as much as possible, using about three sizes for the whole system, and if possible, making the largest size used for laterals the same as one of the sizes used for secondary mains.

Aside from the laterals it is evident that the secondary mains receive less benefit from the diversity factor than any other part of the system. It is also evident that any increase in the load will directly affect the mains which must be large enough to maintain satisfactory voltage for all consumers connected to them.

On the one hand is the diversity factor tending to reduce the size of the mains and on the other hand the probable increase in load which must be provided for, tending to increase the size of the mains. As not only the first cost but the interest on the investment depends on the size of the copper, it is important that these two conditions be given careful consideration and it is in cases of this kind that the engineer must be guided by experience and his knowledge of the situation.

There is one point that should be remembered in determining the size of cable to install for secondary mains, particularly where they serve a number of consumers in a business district.

Owing to the fact that the service laterals are spliced directly to the mains at frequent intervals it is very expensive to replace them and the old cable, being in short lengths, is of little or no use except for its junk value; it is therefore advisable to make all secondary mains of ample size to provide for the total load that can reasonably be expected and use the best kind of cable, either varnished cambric or rubber insulated, for all secondary mains and laterals that terminate in junction or fuse boxes.

The load in the district should be divided as equally as possible into a suitable number of distribution centers so that one size and style of cable can be used for all of the feeders, as this permits standardizing the equipment and requires less cable being kept in stock for emergency purposes.

The feeders being generally small cable and having few or no taps on them can easily be replaced by larger cable and the old cable is in sufficient lengths to be used elsewhere. Instead of installing a larger cable to replace a loaded one it is generally better to install an additional feeder to another center of distribution, using the standard size of cable.

Where the requirements of the system demand the use of two-conductor cable it is advisable to have it made up in round form instead of the flat, or figure 8 style, as it is practically impossible to train this latter style without kinking it.

A careful study of the conditions under which underground distribution systems operate, particularly in medium size or smaller cities, has convinced the writer that the safest guarantee of reliable, efficient, and economical operation is to install cable and equipment, as far as the conditions will permit, under the following general rules.

Service Laterals. Use either cambric or rubber insulated cable, spliced directly to the secondary mains, and terminated in water-tight fuse boxes on the consumers property. (The number of laterals taken out at one splice will depend on the system; for single-conductor cables four laterals can be taken out, but two is about the limit where three-conductor mains and laterals are used.)

Secondary Mains. Make these cables of ample size to provide for all the growth that can reasonably be expected. Use either varnished cambric or rubber insulated cable for all secondary work where cables terminate in subway equipment.

Primary Feeders. These cables derive the most benefit from the diversity factor, are comparatively long lengths, and have few taps on them, therefore are less subject to damage than the rest of the cables and are easily replaced with small financial loss. Small reserve capacity is all that need be provided for this class of cables.

Paper insulated cable can be used to advantage frequently at considerable saving providing that the ends are properly terminated in compound-filled potheads or varnished cambric or rubber insulated tails used for connecting to the equipment.

Personally, the writer does not approve of using any paper insulated cable on distribution systems, except on cases where the emergency facilities are such that the failure of a feeder cannot cause a serious interruption to the service.

In small companies, where competent cable men are not always available, the use of paper insulated cable on the distribution system is not advisable, it is however, well suited for high-tension feeders and tie-lines.

Subway Equipment. Due to the liability of being submerged occasionally and the limited space usually available, for its installation, subway equipment is probably the most prolific cause of trouble on underground distribution systems, and the greatest care must be used in selecting and installing it.

The best insurance against trouble from this cause is to provide reliable sewer connections to all manholes and vaults in which subway equipment is located. Separate the primary and secondary equipment by placing the transformers, primary fuses and switches in a vault (preferably located under the sidewalk adjacent to the manhole in which the secondary junction boxes are located.) This arrangement reduces the length of the secondary mains, which are usually large expensive cable, and lessens the liability of a burnout on the primary equipment damaging the secondary network. See Fig. 3.

The object in placing the vaults under the sidewalk is that it is seldom possible to secure sufficient room in the street, also there is less liability of the vaults being flooded from surface water and they are more accessible in the winter when the ground is covered with ice and snow. This method of construction is more expensive than placing all of the equipment in the manholes but the added security is well worth the expense on an important installation.

Subway transformers should not be set on the floor of the vault but should be raised so that the air can circulate under and around them. Where more than 200 kw. of transformer capacity has to be installed in one vault it is advisable to provide ventilating pipes from the vault to a pole or side of a nearby building.

Subway junction and fuse boxes should not have slate or marble bases, but use ebonite or similar material that will not absorb moisture. All boxes should be subjected to an insulation test before being installed. Barriers should be provided between terminals of opposite polarity.

The iron work of all subway equipment should be permanently grounded to a reliable ground rod, plate, or if possible, to the city water pipe system. In large vaults, where there is considerable equipment, at least two ground connections should be provided.

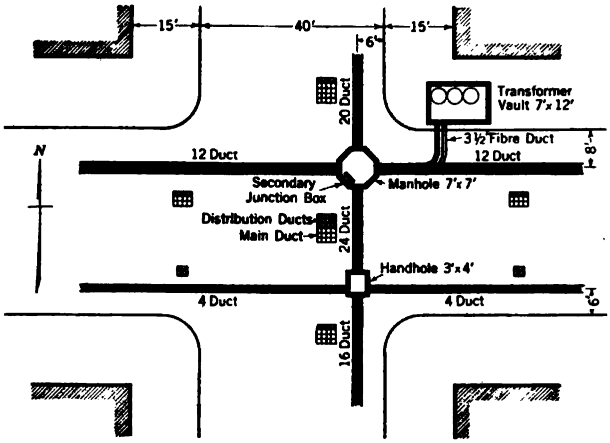


FIG. 3

Installing Cable. Assuming that all cable has passed the usual factory test, it is seldom necessary to subject it to another test before being installed unless there is some evidence that it has been damaged in transit. The conditions under which the cable is purchased and installed will, however, generally decide this point.

Use skids in loading and unloading reels, never drop them off of the truck. Place reels as near the point where they are to be used as possible. When reels must be left on the street for some time they should be securely blocked or preferably wired to a pole to prevent their being rolled about. Care should be taken not to place reels where they will interfere with hydrants, or obstruct manholes, water gates or traffic.

Never handle paper insulated cable when it is cold. In cold weather it should be kept in a warm place until it is to be installed. Paper cable should not be bent shorter than eight times its diameter and should be warmed before bending.

Always provide sufficient men and power to safely handle cable during installation, when the cable is started in the conduit try to maintain an even steady rate of pulling. For heavy cable it is advisable to use grease or powdered soapstone.

Ends of cables should be kept sealed until ready to be spliced. Cables should not be left hanging from the duct mouth, but should be supported on hangers with as little bending as possible. The final bending and training of the cables should be done by the splicer when joining the sections.

When installing a new system, all lengths of cable should be bonded together temporarily as soon as they are installed. As soon as the cable system is completely connected up tests for electrolysis should be made of the whole system and proper measures taken to protect the cables in case of necessity.

The arrangement of cables and equipment in the manholes and vaults must be carefully planned to secure neatness and ample space in which to work and operate the equipment with safety.

All cables and equipment should be plainly marked showing the operating voltage and system it is used for. Where single-conductor cables are used on three-phase circuits they should be distinguished by different colors as this will prevent mistakes in making changes as only cables of like colors should be connected together.

While it is admitted that it is impossible to install a system that will be entirely free from trouble, it is possible, by carefully designing the system to prevent many of the faults that are a constant source of trouble on many systems.

Conduit System. The conduit system should be designed to serve the electrical distribution system as previously designed. This statement may, at first, appear to be a self evident fact, but unfortunately many conduit systems are not arranged to properly and economically provide facilities for installing the proposed cable system. It is not an uncommon practise to install a conduit system based on a general assumption of the actual requirements of the electrical system.

The writer has seen conduit systems in which it was absolutely impossible to install the distribution system as it had to be operated, and which had to be partially rebuilt before the cables and equipment could be installed. These are no doubt exceptional cases but it shows the importance of a definite method of procedure in designing an underground distribution system.

It is a common practise in designing conduit systems to select streets or alleys having the cheapest pavement in which to locate the conduit, and then attempt to fit the electrical distribution to this location, and the result is invariably unsatisfactory and the saving in the cost in repaving is frequently exceeded by the additional cost of cables, and the total cost of the system thus increased.

It should be realized that a properly designed and constructed conduit system is a valuable property, and a permanent structure having little or no depreciation, and its importance in the supply of electrical energy warrants the greatest care being taken in its design and construction.

Conduit systems that are to serve high-tension or tie lines between substations can be located so as to avoid the more expensive pavements, but conduit used exclusively for distribution systems should be located so as to best serve the electrical requirements regardless of the kind of pavement on the streets or alleys.

In a conduit system used exclusively for distribution (where all wires must be placed underground) the best location is usually in the streets. In cities having an alley in each block there is a strong tendency to locate the conduit in the alley.

The desire to utilize the alleys is based on the fact that the pavement is usually less expensive, and as the majority of pole lines are in the alleys the buildings are supplied from the rear, therefore if the conduit is located in the alley there will be less expense for changing the inside wiring to meet the new distribution system At first sight these advantages appear so great as to warrant the selection of the alley; there are, however, serious disadvantages to this location.

The alleys are usually from 16 to 20 feet wide and are generally fairly well occupied by water, gas and sewer facilities, and not infrequently, by one or two telephone conduit systems (which are usually installed before the electric light wires are placed underground) and the space available is, therefore, very limited.

The rear building line is very irregular, many buildings do not extend back to the alley, and frequently there are small sheds or extensions in the rear or the main buildings. The length of rear laterals would be greater than front ones and the difficulties and cost of installation considerably more; the greatest objection is that the rear laterals would not be permanent in many places but would have to be changed whenever any new building construction or changes were made.

Where alleys are located in the business section of a city they are usually used by the merchants for receiving and shipping goods and are subjected to a heavy traffic, considering the limited space. The merchants are practically all consumers of electric power and will strongly resent any interruption to their trucking facilities.

Owing to the limited space in the alleys, and the amount of traffic, it is practically impossible to store any material in them, consequently all material used on the conduit system must be stored in the adjacent streets and usually wheeled in by hand. This work and the excavation for manholes, removal of surplus material etc., will practically close the alley to traffic and the inconvenience of doing the work will greatly increase the cost of construction.

There is another serious objection to using the alleys. An average block, in cities having alleys, is about 300 by 300 ft. (91 by 91 m.) and usually has at least twelve separate buildings in it, in the business section there are generally more. When the distribution system is located in the alleys all of the buildings in a block are supplied from one secondary main which practically doubles its size, and the number of laterals that must be connected to it require frequent handholes in order to reduce the length of the laterals. This entails more complicated and expensive splices, cuts the main into short lengths, and in case of serious trouble puts the whole block out of service.

As a general rule, with the single exception of requiring less conduit, the alley construction is less desirable than a system installed in the streets. This statement applies to the business district of a city. Where overhead laterals can be used in a residential section the alleys are preferable for the location of the conduit, and as the traffic and obstructions are usually considerably less in such sections, the construction cost will be correspondingly less, depending on the pavement.

Before making the conduit design it is necessary to plot the location of all car tracks and existing sub-surface obstructions, in order to determine the most suitable location for the new system. While it is known that the records of sub-surface conditions are seldom accurate still a study of these records and the location of water gates, sewer manholes and other surface indications will permit a fairly accurate map being prepared.

Where there is any doubt regarding space being available for the conduit and manholes it is advisable to dig test holes, and if possible they should be dug at the points where it is proposed to locate manholes.

The design of an underground distribution system is not a difficult matter if handled in a systematic manner and the result obtained from a thorough study of the conditions will fully warrant the engineering expense necessary to prepare accurate plans covering every detail of the work.

DISCUSSION ON "UNDERGROUND DISTRIBUTION SYSTEMS" (NEWTON), CHICAGO, SEPTEMBER 20, 1916.

T. E. Tynes: This most excellent paper, prepared by Mr. Newton, and so very ably presented by Mr. Gear, covers the question of underground distribution of energy in a very broad way. Mr. Newton has given a great deal of time and thought to this question of underground distribution, and while the paper applies particularly to the distribution of energy in cities and congested districts, such as we have here in Chicago and in other large cities, the principles involved are applicable to any underground system which we may have occasion to use in steel mills, such as the construction of conduits, the making of joints, the position of switches, etc.

Alfred F. Hovey: A great deal of time might well be given to the discussion of this paper as regards the detailed construction of the conduits and cables. There is one statement which involves a rather dangerous point; the author states: "Where triplex-conductor cables are used on three-phase circuits, they should be distinguished by different colors as this will prevent mistakes in making changes, as only conductors of like colors should be connected together." I have personally encountered a good deal of difficulty from just that kind of a specification. It is almost next to impossible to make joints that will be serviceable for a long term of years, such as good joints should, and at the same time secure the matching of colors. The time has come when we are using large conductors in sector form, and under those circumstances it is still more difficult to match these colors. Very often it requires one of the conductors to be drawn through and between the other two conductors in order to match the same color, and there is no safe way of identifying the conductor and be sure you are right, except by making a test one way or another, without possible damage to the insulation. Jointers find they cannot make as good a joint where they attempt to match the colors. The cable has to be manufactured in a certain way, so that the lay is all one way, and the cable has to be pulled in, in a certain direction, and sometimes it is impossible to feed the cable into one of the manholes, but it has to be pulled by means of a series of blocks and tackles, but if the cable is not drawn in exactly right, it is extremely difficult to straighten out the lay of the conductors at the joint, so to match the conductors, although it sometimes happens; but then it is a matter of chance. That is one point which I think it might be well for engineers to avoid in making up specifications to secure a perfectly satisfactory operating system.

Another point where the writer of the paper says: "Personally, the writer does not approve of using any paper-insulated cable on the distribution systems, except in cases where the emergency facilities are such that the failure of a feeder cannot cause a serious interruption to the service." Several managers of works with which I am concerned at the present time, are installing paper-insulated cables both for economy and for good operation. A paper-insulated cable requires slightly more careful installation, but if properly handled, I believe in many cases that it will make as good insulation as either the rubber or varnished cloth insulation. It has been my experience that recently the majority of engineers specify paper cable. There is no particular reason for bringing up that point, as nearly all cable manufacturers are prepared to furnish either rubber or varnished cloth or paper insulation on their cables.

Just a word of commendation to Mr. Newton, who has had considerable experience along this line for years. We have known him, particularly in conduit work, and in cable work for years, and I believe that this paper will be of great assistance to engineers in laying out either a large or small system, because it gives the basis in foundation of fact for a specification that would provide a satisfactory operating system.

Not having read this paper carefully enough to know whether any mention is made of a scheme used considerably nowadays, that is to run the trunk ducts underneath the service boxes, I would say that this is an important feature in designing space for trunk feeders and secondary mains by building a handhole over the top of the lower trunk conduits and taking in only the top ducts, using them for distributing mains and secondary feeders. That is a point on a small system that is particularly important, as it cuts down the original cost of the conduit system materially. In that way, the small conductors can be exposed through these handholes for taps and the handholes can be constructed at very small cost and at large insurance over the other scheme of opening all the ducts into all the manholes.

There is one manhole that has cost, as I was informed last week, about $10,000 because the engineers originally did not make the manhole large enough. The manhole has been rebuilt eleven times, with the consequent cutting of cables and re-racking them around this constantly enlarged manhole. One of the operating engineers told me not long ago that his company was expending over $150,000 a year rebuilding manholes. That is a point that the engineer, in laying out an underground distribution, might well keep in mind, because it is well known that the cheapest real estate is that which you enclose by a manhole wall under the street. By making a large, generous manhole, you have plenty of racking space for the cables on the sides, with sufficient room on the side-walls for proper racking and proper bending, and the original installation will take care of the operation in the future much better than having to rebuild the manhole at considerable extra cost.

F. D. Egan: My experience with underground conduit work has been entirely in the steel plant, and I could not discuss Mr. Newton's paper from the standpoint of city construction. We have installed approximately 125,000 feet of underground conduits in our steel mill, and as far as the matter of trouble goes, I find that the underground system is more reliable and more dependable than the overhead system.

Another point that Mr. Newton brought up regards the high cost of underground versus overhead. While that might apply in city construction, if compared to the type of construction to be used in a steel mill, the cost is in favor of the underground. When we distribute power at 6600 volts, or higher, for safety reasons we would construct duplicate power lines and the cost of this would be higher using bare copper pole lines than it would be with underground system and lead-covered cambric cable.

That is the experience we met with in our construction. We have been operating on this system in some of our plants for from three to four years, and so far we have experienced no trouble from an electrical standpoint. We lost two cables adjacent to the power house, which ran parallel with the old buildings, and the trouble there arose from the discharge of steam traps; this heat entered the conduit system, raised the temperature and the additional electrical load caused a breakdown. After we removed the steam trap discharge, we experienced no more trouble.

Another advantage of the underground system is the point of safety. We have there the point of totally enclosing the electrical distribution line, and the one point which would come up there, regarding safety, would be care in determining the proper line to work on in case of opening up of the cable.

S. C. Coey: Mr. Newton has given us a very interesting description of the methods used in laying out an underground cable system for a city and has pointed out many of the valuable features of such an installation. While many of the fundamental principles are the same, when we apply these data to an industrial plant system and especially a steel plant installation in which most of our members are most interested, we have a special application which calls for special treatment.

Installations in steel plants are more analogous to subway equipment than to any other type considered in the paper. The liability of having underground ducts filled with water is always present in those steel plants built on the banks of rivers having a large rise during flood periods. This applies to most of the plants in the Pittsburgh and Youngstown districts. Where plants are installed under these conditions it is usual to make the yard level only a few feet above the maximum high water. This is done from practical considerations as every increased foot that the plant is above normal water level means that many more foot pounds of energy expended in pumping the large amount of water necessary in the modern steel plant. This condition makes it necessary to lay out a duct system with the idea in mind that the cables are subject to the liability of being under water at some time. In plants of this description the use of underground transmission even with varnished-cambric lead-covered cables is subject to possibilities of trouble that are serious and makes the advisability of installing it very questionable.

In transmitting alternating current in lead-covered cables it is advisable to confine all three phases within one lead sheath. When single-conductor lead-covered wires are used for this work there is considerable loss and possibility of trouble from sheath currents. If the sheaths are bonded the I^2R loss from the sheath currents amounts to about half the normal I^2R loss in the copper conductors so that this method of operating is inherently inefficient. As it is usually impractical to insulate all the cables from one another and impossible where flood conditions are to be met the three-conductor cables should be used. In this case we have all the heating effect confined within one sheath and cable ducts must be carefully watched to see that there are not points where they get excess heating from external points.

I have also pointed out in a paper before the Association of Iron and Steel Electrical Engineers that where grouped ducts are used, the heating effect from a center duct to adjacent outside ducts with only radiation to take care of heat dissipation is cumulative, as shown by the result of tests, and for this reason ducts should not be made more than two ducts wide.

In underground ducts around steel mills as I have noted before it is often found that the ducts are heated from some external source. This is usually when the duct passes close to heating furnaces of some kind, which are impossible to get away from entirely in this class of work. This type of service calls for special study in each case. In some cases forced draught through the ducts have been used with good results. I have found for this work that varnished cambric insulation is the only type that can be relied upon as the heat affects rubber very rapidly.

While an underground system is usually spoken of as the most permanent system, and is, in the ducts proper, I would raise a question when we consider the wire insulation, as air and porcelain are more permanent than paper, rubber or varnished cambric and these are the materials depended upon in the two systems respectively to maintain the insulation of the circuit.

The principal advantage gained by the underground system is the freedom from liability of trouble from lightning, pole failure, and obstructions against wires.

In steel plants the locomotive crane problem is the most serious in the last item.

The advantages the overhead system has over the underground system are flexibility, initial cost, wire insulation and speed of location and repair of trouble.

As I see it, both systems as used today have their drawbacks and for a steel plant installation I believe that the ideal system of transmission would be to have an open concrete duct with reinforced concrete roof, well ventilated, with insulated cables strung on porcelain insulators so arranged that an inspector could walk through the duct. This could be entirely underground where the high water mark allowed, or in some plants could be above ground and used for a line fence. This system of installation would give the advantages of both the present systems without any of the disadvantages.

T. E. Tynes: We have quite an extensive duct system, originally installed about ten years ago. Our plant is built on land that was a swamp and there is a great deal of filled-in land. We have experienced some trouble due to the settling of the ducts. In locating a duct line, especially in steel plants, great care should be taken that this line is installed where it will not be interferred with by future construction, as it is a very difficult matter, after a duct line is installed, to have to rip it up to make room for a new mill going in, or some other consideration arising, which is of sufficient importance to cause the ripping up of the duct system.

The selection of a suitable foundation on which to build the duct line is very important, as I mentioned the trouble we have had due to the settling of the land. We have had some cable nearly cut off due to the settling of the ground.

The type of duct, or material out of which the duct line is constructed, is also important. In our plant we constructed every circuit of vitrified duct, and we had some difficulty with cracking joints which has allowed one thing and another from the ground to come in, and these substances have eaten off our lead coating right where the joints are. We have been troubled considerably by electrolysis, and upon taking out cable we have found pinholes, hardly visible, and they would let water into the cable.

Another important thing is making the splice. To make a good splice you should have the joint thoroughly filled with a compound, allowing no air bubbles to be formed, as in time the air bubbles will cause deterioration of the insulation and produce a breakdown. We do not know the reason for it, but we have opened up joints and found where the air bubbles destroy the insulation, and that increases until it gets to the lead sheath and then the cable breaks down.

We use paper and lead-covered cables. We have had them in operation now on 2200 volts for ten years, and have had no trouble at all with this voltage. We have had trouble on our low-voltage cable due to electrolysis and improper making of the joints.

All of our 2200-volt circuits are underground, also a great deal of our 440-volt circuits and 250-volt circuits. We are now taking the 250-volt circuits and the 440-volt circuits and putting them overhead.

We feel that where an overhead line is properly constructed, good insulators, and line put up in a permanent way, that it is much better for transmitting low voltages than the underground system. There is less trouble, and what trouble we have can be seen and taken care of before it is too far advanced. In the case of the 2200-volt circuits, the question of safety comes in, and we put those circuits underground for that reason.

C. A. Menk: I do not think I have very much to add to the paper. It is very interesting. What are you going to do with your present installation? You have an old plant, and if you are going to add to that, what will you adopt? The first question which comes up is: "You have gone along for years with your overhead construction. Is it going to pay to put it underground?"

Another thing; in designing a new plant I think it will be actually necessary to know what is going to be added in twenty years from now, if placed underground, because it is hard to tell what may develop and how soon it will develop. As Mr. Tynes said, to make extended changes would be very expensive. Take a city like Chicago and other large cities. These cities are well established, and underground work can be put in that should be good for twenty-five years, probably fifty years, especially in the residence districts, but in the case of mill work it seems as if one would have to look ahead and make very extensive provision for added improvements in the future.

In installing an underground system on three-phase work, will it be advisable to put in the triple conductor, or single it out and put it in, in triangle form?

In installing underground work, would you put in a conduit system large enough under the present day engineering, so that you could pull out the cables and put in larger ones, to avoid having to rebuild your manholes? One of the speakers said that in one case the manhole was rebuilt eighteen times. To me that looks like very poor engineering.

T. E. Tynes: In reference to Mr. Menk's question, whether to install triple conductors, or single conductors, all our underground cable is three-conductor, even the 2200 volt up to 500,000 cir. mils, and as I said before, we have had no trouble from the insulation of the cable—it has all been joint trouble and electrolytic action on the lead sheath.

S. C. Coey: I have had some experience with an installation on which single-conductor, lead-covered cables were used on three-phase work. On investigation it was found that where the lead covers of the cables came in contact, the sheath currents made pin-holes in the lead and when moisture was present paper insulation absorbed it like blotting paper. In my opinion it is a good thing to keep away from single-conductor alternating-current transmission.

H. B. Gear: You referred to low tension, I suppose?

C. A. Menk: Yes, 440-volt circuit.

H. B. Gear: I quite agree with the suggestion that the cables carrying large current should be multiple-conductor in form. A case came to my attention just recently, in an industrial plant—not a steel mill, but a condition which is very similar—where there were thirty-two No. 00 cables that had to be carried a distance of 800 to 1000 feet from the plant to the point where the power was used, and in order to keep down the inductive drop on these circuits they had made them small, but they were all overhead, and the drop was something like 33 volts on a 220-volt system in that distance. If these cables had been placed underground and made three-conductor, with a separation of only perhaps an inch between centers, the inductive component of the drop would have been very much less and the system would have been far more satisfactory. As it was, they were unable to use any additional power at the other end of the line without stringing more copper, for which room was not available on the poles.

In general, single-conductor cables are somewhat preferable for high-tension work where the lines are used for distribution purposes, that is what Mr. Newton has called secondary feeders which are really primary distributing mains.

Where joints must be made more frequently, for connecting in transformers, it is easier to do that work on single-conductor than three-conductor, from the fact that the opposite polarities can be separated. Frequently that work has to be done on either live, or very close to live wires. In general, the cost of three-conductor cables is sufficiently less than single conductors, to warrant their use, often at the expense, as is sometimes done in manholes or other places where taps are made, of fanning out into three singles. If the manhole lengths are long, say four hundred or five hundred feet, it is usually cheaper to make an extra wiped joint in the manhole, going through with singles, in order to save the cost of extra lead that would be put in the conductors in the long cable line.

In regard to paper insulated cables, Mr. Newton's statement is very well considered. He agrees they should be used and can be used where experienced men are handling them, but his statement is that they should not be used where inexperienced men are handling them. In a large system, such as that in Chicago, we use nothing but paper cable, even for laterals and secondaries.

There is no difficulty whatever with high-tension cables in taking care of ends if they are provided with potheads, as Mr. Newton suggests.

With regard to the facilities which are provided for in emergencies, the pot-head is so arranged that it is an easy matter to have one cable act as a reserve for a group of cables, doing the same class of service, and the developments in recent years are quite numerous as compared with what we used to have to get along with in the way of emergency facilities.

In connection with the ventilation of transformer rooms, I notice that Mr. Newton suggests that any transformer room for 200 kilowatts or more should be ventilated. Our experience is that is rather a high limit. We have had a number of cases of 150 or 120 kilowatts, where in the summer time the ordinary air temperatures, especially like we had last summer, were enough to make these transformer rooms run up to 130 to 140 deg. fahr., and the oil temperatures correspondingly high, so that the insulation was in danger. It takes rather a liberal ventilating system in the form of intakes and ventilating flues, etc., to take care of such an installation during warm weather conditions, especially where the transformers carry load continuously on power installations.

With regard to the size of conduits, I think that especially where secondaries are to be run, and where a three-conductor cable is advisable, the conduit should be at least four inches in diameter. We have had considerable difficulty in Chicago, because of the fact that many years ago we adopted a three and one-half inch conduit as our standard size conduit. When we get up to the point where we would use large three-conductor 20,000-volt cables, we are limited to a diameter of three and one-half inches in the ducts, and 250,000-cir. mil cable is the largest we can get into it. That leaves about one-quarter inch clearance which is the least that is practicable, and lengths between manholes are limited to 350 feet in order to allow the cable to be pulled in.

In any case where large low-tension cables are to be used and where three conductors are desirable, I would advise that a 4-in. conduit would be advisable.

B. G. Beck: We have been working with one of these underground systems for a long while. I think when we put in an underground system we should take into consideration the condition of the soil. We have one that the hotter it gets the more it leaks, and the more it leaks the hotter it gets. A great deal of the heating depends on the depth of the installation.

As pointed out, we should take into consideration the proximity of the furnace gas mains and hot water return mains, which may be installed, and another trouble we got into was in following the standard practise that ordinary city engineers used in putting in their duct system. They have really an intermittent service, a period during the day in which their heat goes into the duct systems, and during the night it can be cooled off before getting another big load in the morning, and adding more heat to it. With our system, it is a steady service, six days in the week, and we add heat all the time, and that makes our service quite different from city service.

As to using 16 or 20 ducts in a line, I do not believe I would do it, with the amount of power we have to use in these ducts.

In regard to sectionalized ducts, it is difficult to run the ducts through the steel mill in any case. In most cases you have to run it between furnaces, and when you are running from one center of distribution you cannot sectionalize your ducts.

We ought to take into account the effect of one cable transmitting trouble to another. I believe that has been taken care of by these gentlemen in a very nice way.

I have been thinking of taking out the old duct system, and making a runway through the plant, with a reinforced cover over it, and ventilators about every twenty ft., with air ducts so arranged that we can utilize a fan in case of burnout. We had a serious burnout some time ago when the cables were up to 120 deg. cent., even those cables which were not carrying current.

With all the troubles to which the underground cable system is incident, there is one thing we must take into account. We have been transmitting about 15,000 kilowatts, 2200 volts, underground, and we have not had any loss of life. The prevention of such loss of life was the primary object in installing an underground system, and we also have not had any motor losses on account of storms or lightning. On some overhead systems with which I have been connected, and on one system in particular, we had a bad lightning storm and lost fifteen motors at one time. That kept us busy for some time. A couple of those motors were big ones on which the plant depended. We have not had any trouble of that kind, but have had trouble with cables. Some of them have been minor troubles, and only one very serious trouble, and the trouble I refer to now was in the case of a cable which started to go bad, and affected the adjacent cable, and that affected the rest of them, and we had our whole duct system hot.

Regarding the running of these wires underground. As was pointed out, when you support the individual cables on porcelain insulators, the question of induction comes in, and it is a question whether with large current carrying capacity we would not run into a lot of trouble with this induction effect, it might be better to install the lead covered cables in a duct system where you could go into it and ventilate it and get your gases out, in case they did blow up.

Barney W. Gilson: I would like very much to hear something from Mr. Gear in regard to the limitations as to size of three-conductor cables. It has been my experience that three-conductor cables larger than 500,000-cm. are very difficult to handle and install, however, we now have two 500,000-cm., 3-phase cables in operation, and have some 700,000-c.m., 3-phase cables on order. These last will be laid in floor duct, and not pulled through conduit, as were the 500,000-cm. cables.

Ludwig Hommel: Mr. Coey's plan of a tunnel on the ground instead of under the ground, looks very good, where it is possible to put up such a structure. In fact, I had wondered whether a conduit system with ducts laid on the ground in a few inches of concrete with handholes where necessary might not be feasible in mills having ground water near the surface.

Where a tunnel is used, the cables should be covered for their entire length, just as is done now for the exposed part of the cables in the manholes. It would be interesting to have Mr. Hovey tell us what is the latest practise, what material is now used for that purpose. If porcelain insulators are used for supporting the cables, the lead sheaths should be grounded to avoid any possible danger to the men handling or touching the lead sheaths.

The planning of the manhole layout is important to avoid unnecessary crossing over each other of cables in the manholes. If a diagram is made of each manhole before the cables are drawn in, showing how the cables will run across ultimately when the duct system is filled, it should result in much better work and avoid trouble in the manholes.

The trouble with cables, if there is any, generally occurs in the manholes where the cable has to be bent—the bending of a cable is an operation that requires skill and experience. If a burnout occurs, it is most likely there to involve other cables.

I believe that junction boxes were mentioned in the paper. It is my experience that they are a source of trouble, while joints are practically as safe as the cable itself.

I agree with Mr Hovey on the paper insulated cable. I believe that it is fully as reliable as rubber cable and the joints are at least as easily made, and perhaps more easily and safely than on rubber cables.

George T. Street: There is one point which has been brought out in regard to manholes: the tendency in the past has been to make the manhole too small. But there is another point which has not been mentioned, and I think it is important: the tendency to make too few manholes. Each additional manhole means additional jointing, but it means much less liability of mechanical damage to the cable in installing it on account of reduction in tension while drawing in, and I think that is one point which should be carefully considered in laying out any conduit system.

Fred H. Woodhull: There is one thing that will have to be guarded against pretty carefully in using the tunnel system. The tendency, where the cables are carried on concrete carriers, where they carry heavy currents, is to have them clamped in some way. They must be held, due to the magnetic effect. I call to mind an experience I had some years ago in connection with central station work in New York City, where a short circuit occurred back of the switchboard, causing some large lead covered cables to jump off of the cable racks. It is a thing which will have to be guarded against.

A. F. Hovey: In one of the oldest and best known methods for fireproofing cables in manholes against the explosion of adjacent cables, common rope and concrete are employed. The former is wound spirally around the cable with about 1 in. separation between the turns, and the cable and rope are then plastered with a one to one mixture of sand and cement. The rope provides a rough surface to which the concrete clings readily and gives a slightly flexible back-ground, which aids somewhat in preventing cracking of the fireproofing under a chance blow.

The workmen's hands have proved to be better than any tool for applying the cement for this type of covering. As far as the fireproofing qualities alone are concerned, this covering is satisfactory, but its removal presents a formidable task. Efforts to reduce this difficulty have been made by placing the turns of rope closer together and, except for the fact that rope is now rather expensive, this method of protecting cable is fairly satisfactory.

Another method of fireproofing is that in which asbestos millboard, cut into 3-in. strips, is wound around the cable and held in place by a fire proof paste, silicate of soda. This covering proved satisfactory as long as the manholes remained dry, but if water ran in and covered the cables, the silicate was dissolved and the asbestos loosened, dropping from the cable. Recently, on account of the difficulty in obtaining deliveries of asbestos millboard, asbestos listing, a woven material with a selvage has been substituted. This material can be purchased in the form of 3-in. tape and wound spirally around the cable, and the silicate of soda covering is used to hold it in place.

When material as expensive as asbestos is used for fireproofing cables, some provision should be made for salvaging the covering when it is removed from the cable. A simple and inexpensive way of doing this is first to wrap the lead sheath of the cable with strips of cheesecloth dipped in paraffine. One layer of cheesecloth is sufficient. Then when repairs are necessary, the asbestos can be separated easily from the paraffined cloth and taken off in long strips. If these strips of asbestos are carefully rolled backward during removal, they can be preserved and reapplied.

In what is perhaps the most recent method of fireproofing underground cables, a layer of paraffined cheesecloth is wound around the sheath and over this metal lath, covered with cement and cut into strips, is spirally wound. The cloth is applied as described above, simply to aid in removing the covering. The metal lath used is a wire mesh covered with brick-clay put on under pressure and baked, the resultant product being a web of small briquettes which can be applied the same as any wire or expanded metal lath. This makes an excellent foundation for the cement mortar, as it is porous and flexible. The cement can be applied with a trowel or by hand, forming the covering into a homogeneous mass. While this type of covering is somewhat more difficult to install than the asbestos covering, it is considerably less expensive, as calculated from the prevailing prices of material. It can easily be removed by breaking the cement covering with a hammer and cutting the metal lath with tinner's snips.

Whatever covering is applied should be considered good insurance against both mechanical and electrical trouble. The added application of paraffined cheesecloth under any of these types of covering insures the lead sheath against damage at the time the covering is removed for changes in the manhole cables.

I would add one more point in regard to the fireproofing. In constructing the manholes, the scheme of putting in slate slabs to carry the cable and the joint through the manholes, particularly in the oblong or egg-shaped type, seems to be a particularly desirable addition to the conduit system itself. It gives a good support, whether the cables are wrapped or not, from one mouth of the duct to the other side. It saves putting in a lot of hangers, and can be installed by putting in T-irons along the wall and the stone or slate slab can be in three pieces, one long piece under the joint, and a section on each side of the joint, and furnishes a good protection from one cable to the other.

T. E. Tynes: One speaker brought up the question of the number of manholes to install for the duct line. Be sure to get enough. In our new lines we do not bring out all cables in the same manholes, but only bring out one-half to alternate manholes. If we lose one set of cables in a manhole, we are only incapacitated to half the capacity of our cables.

We have also used the method of wrapping asbestos tape around them to protect them in case of a ground, and that is effective except where there is gas in the manhole. We have had several bad fires due to leaky gas mains near the conduit line, and the system would fill up with gas, and that gas would destroy anything put in.

If a partial ground occurs on one of the cables, the asbestos covering in the case of dry manholes is sufficient protection, but this will not work where there is dampness.

H. B. Gear: In regard to the subject of cable protection, we have used the rope and cement wrapping in Chicago for several years now, and I think we have avoided the trouble Mr. Hovey spoke of, (of having the cement stick too tightly to the lead sheaths) by using rather more rope than he described, that is, wrapping the rope so that the spirals almost touch each other. There has been little difficulty in breaking off the rope and cement when it was desirable to get at the cable to do work on it.

There was one point raised about the maximum number of ducts referred to—twenty ducts. I might explain, further, that when anything over perhaps nine ducts or ten ducts is put into one line, it is the practise in Chicago to separate the conduit system into two halves by putting three inches of concrete between the two ducts on one side and the two ducts on the other side, never putting more than four ducts in any horizontal row, and no duct is more than one duct away from the outside earth, from radiation. This additional barrier of concrete between the two halves of the system is then carried into divided manholes where the number of cables is sufficient to fill the duct system, and not more than eight or ten cables in that way go into any one manhole. The manholes are built in a staggered form, one-half of the conduit system going into one and the other half into the other.

In the vicinity of power houses, where large numbers of cables must be brought out, this problem was solved in our most recent installation by the use of 24-duct runs. These 24-duct runs came out of three or four different busses, and fanned out into 4-duct lines, going to a series of manholes which led out from three different conduit systems. Three conduit systems went in different ways to the station, and by doubling the manholes on each of the conduit systems, and fanning out a group of 4 from each of the 24 into the manhole, all of the cross-overs were taken care of underground and a system was devised by which a cable could be brought into any conduit system or by which we have no cross-over in any manhole.

With regard to the maximum size of conductor which might be put into a 3-conductor cable, I do not know that I can answer the question specifically. I have known of cables as large as 600,000-cir. mils being used. The real limit, I think, as I stated before, is in the size of the conduit which is used. With a 4-inch conduit system, I think there will be no difficulty in using three 600,000-cir. mils or possibly three 750,000-cir. mils conductors in one three-conductor cable.

In reference to using a tunnel large enough for men to walk through, I would be inclined to think it would be preferable, even if such tunnels were used for low-tension cables, to use 3-conductor cables carried on a rack rather than to use single cables carried on separate racks which would necessarily have to be three or four inches apart. The inductive effect as well as the safety of installation, would be bettered by the use of three-conductor cables.

Presented at the 10th Annual Convention of the Association of Iron and Steel Electrical Engineers in joint session with the American Institute of Electrical Engineers, Chicago, Ill., September 20, 1916.

STEEL CONDUCTORS FOR TRANSMISSION LINES

BY H. B. DWIGHT

ABSTRACT OF PAPER

The electrical tests of some steel conductors of moderately large size have been published, and they indicate that there is an opening for the profitable use of steel cables on the branch lines of power systems of all voltages, in the same way that small steel conductors have already been used on branch lines at low voltages. Mechanical weakness or corona loss prohibits the use of small copper or aluminum conductors in many cases, and so steel becomes preferable.

Steel cables will not generally be economical on main transmission lines, except for long spans, and for high altitudes where corona is excessive. They may be advisable as bare conductors for direct-current railway feeders. They deteriorate more rapidly than copper conductors.

Steel cables for alternating current should be finely stranded and the different groups of wires should be spiraled in opposite directions. Fortunately, medium-priced grades of steel give better results with alternating current than some more expensive grades. The characteristic increase of resistance and reactance with increase of current or frequency may be valuable for limiting lightning and switching surges and short-circuit currents.

As there are large differences in electrical characteristics between different grades of steel, it is desirable that tests of medium priced steel cables manufactured in America be made and published, so that the data can be used in the designing of transmission lines.

THE RESULTS of a number of tests of the electrical properties of steel wires and cables when used as conductors of alternating current, have been published. Although these tests are incomplete, especially as regards the use of steel conductors in America, they show some attractive possibilities, from both commercial and engineering points of view, for the use of steel instead of copper in certain classes of work.

Attention is here called to the peculiar properties, the advantages and disadvantages, of steel conductors, in order to point out the advisability of making complete tests of American grades of steel, so that electric power companies may make use of this material for the cases where it proves economical and advisable for transmission-line work. Already, small sizes of steel conductors have been used with success in America, and this practise may be extended by a knowledge of the characteristics of large steel cables.

As is well known, the resistance of an iron or steel conductor is considerably greater for alternating current than for direct current. This is partly due to the skin effect, that is, the crowding of the alternating current to the outside parts of the conductor by the alternating magnetic flux in the conductor, and partly to hysteresis, or iron loss, caused by the alternating magnetic flux in the steel. In the case of copper or aluminum transmission-line conductors of usual size, the skin effect increases the effective resistance only one or two per cent and so is practically negligible. But in the case of iron or steel conductors, the flux has a magnetic path, and so attains a value from 20 to several hundred times as great as in a non-magnetic conductor. The result is that the skin effect is very pronounced and the effective resistance is increased by a large amount, in some cases by 100 or 200 per cent or more. However, the conclusion should not be assumed that steel cables are unsuitable for alternating currents. The tests so far published go to show that it is as necessary for an iron a-c. conductor to have fine strands as for an iron core to have thin laminations. The tests also indicate that if the strands are moderately fine and are properly put together, the increase of resistance at 25 or 60 cycles may be kept down to a reasonably small percentage. This is shown in Figs. 1 to 6.

The curves shown with this paper have been derived from test curves published in the *Elektrotechnische Zeitschrift* of January 28, 1915. They refer for the most part to a grade of steel or iron, called H-oo, which is a medium grade recommended in the above article for alternating-current work. That its cost is reasonably low is indicated by the fact that two other grades of steel were tested, each stated to be purer and more expensive, and also to have greater skin effect, than the grade H-oo. Although the purer material has higher conductivity for direct current, it has also greater permeability to magnetism, which is a disadvantage. Thus the cheaper grade was found to be more suitable for a-c. work. The same conclusion was also stated in a recent bulletin, No. 252 of the Bureau of Standards, Washington, D. C., by J. M. Miller, who found that of the wires tested, the grade with the highest resistance to direct current had the lowest resistance to alternating current, and was also the least expensive. The tests on American steel wire described in the above bulletin show somewhat less skin effect than that of grade H-oo steel wires.

The tests on grade H-oo steel were originally expressed in centimeter units and were made at 50 cycles. The curves have been rearranged for English units and for 60 and 25 cycles, and put on a base of amperes per cable, so as to apply to American transmission-line conditions. The Bureau of Standards' tests described in Bulletin No. 252 show that at commercial frequencies the increase of resistance is approximately proportional to

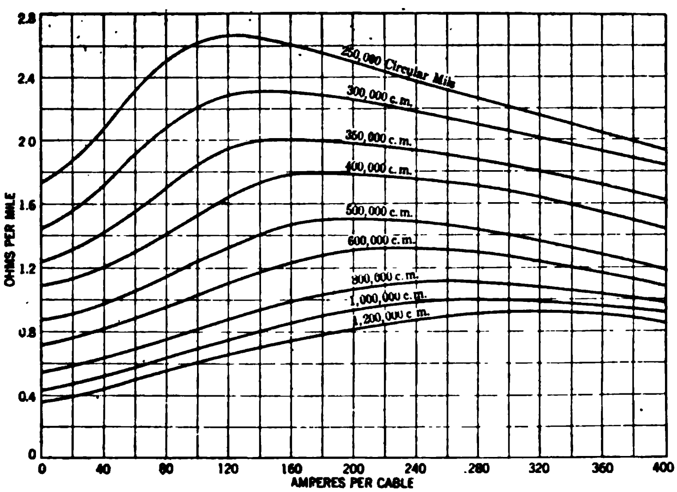


FIG. 1—RESISTANCE CURVES—60 CYCLES—49-WIRE CABLES—GRADE H-oo STEEL

the frequency, and this property was made use of in making the above transformations.

The curves of internal reactance of steel cables published in the article referred to above, are shown in Fig. 7. These curves do not refer to grade H-oo steel, but to a grade of higher permeability. This grade, as shown by resistance curves in the original article, has more increase of resistance than grade H-oo, for the same size and stranding of cable. Presumably, therefore, grade H-oo would have somewhat lower values of reactance than those of Fig. 7. The tests show that the resistance curve and the reactance curve of a given cable reach their maxima at about the same value of current. It is of interest to note that increasing the number of wires in a cable decreases the reactance, while increasing the size of the wires increases the reactance, according to the examples in Fig 7.

The d-c. resistance of each cable is given in Fig. 7, and the

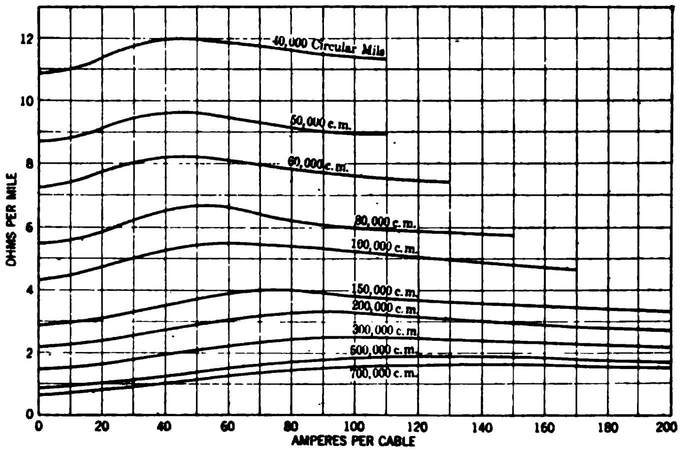


FIG. 2—RESISTANCE CURVES—60 CYCLES—19-WIRE CABLES—GRADE H-oo STEEL

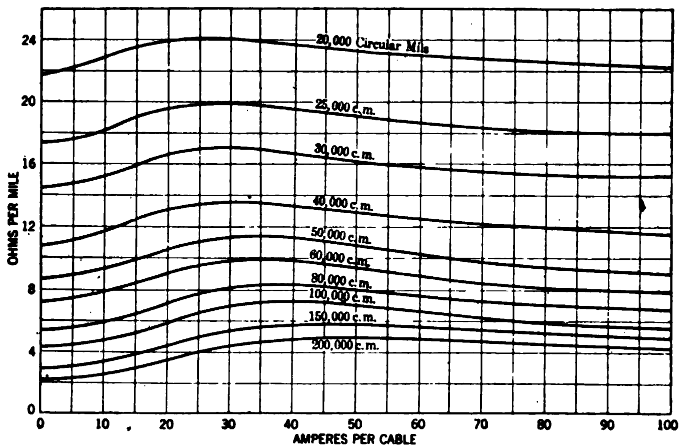


FIG. 3—RESISTANCE CURVES—60 CYCLES—7-WIRE CABLES—GRADE H-oo STEEL

maximum a-c. resistance will be about twice as great, according to Figs. 1 to 6. From the results shown in Fig. 7, the internal reactance at 60 cycles and at any current may be taken as being about 75 per cent of the a-c. resistance at the same current;

in the absence of more complete data. The external reactance should be taken from regular transmission-line tables and added to the internal reactance to give the total reactance. The above is the method by which the examples at the end of this

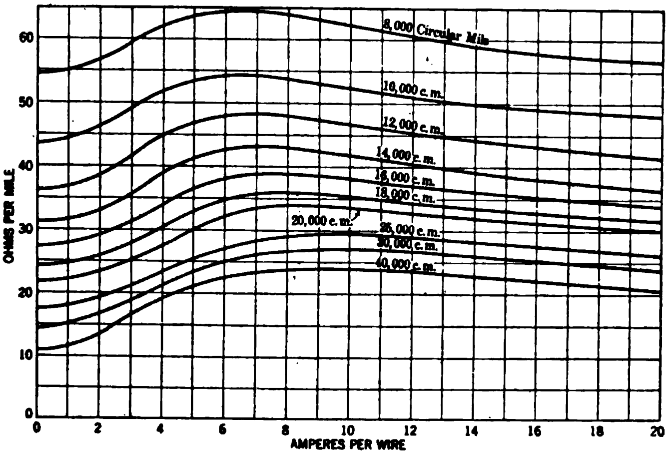


Fig. 4—Resistance Curves—Grade H-oo Steel Wires— 60 Cycles

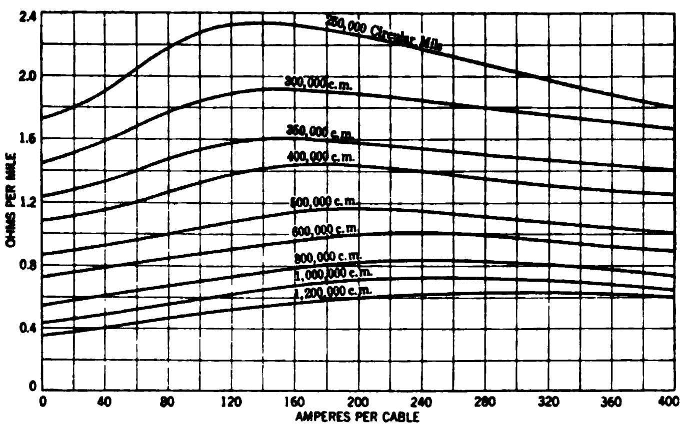


Fig. 5—Resistance Curves—25 Cycles—49-Wire Cables—Grade H-oo Steel

paper have been worked. It is merely approximate, and the caution should be given that for practical designing, test curves of the resistance and reactance of the actual type of cable to be used should be employed.

Another point brought out by the tests in the *Elektrotechnische Zeitschrift* is that a large part of the magnetization is caused by the spiraling of the wires in a cable, and if the spiraling of the different groups of wires is properly reversed, the increase in effective resistance can be reduced as much as one-half. Actual examples of this are shown in Fig. 8. Thus if the spiraling of one layer of wires is clockwise, the spiraling of the next layer should be counter-clockwise. Also, in a cable made up of several strands, the spiraling of the wires in each strand should be opposite to the spiraling of the strands in the cable. In Figs. 1 to 6, the cables are assumed to have the spiraling reversed as much as possible. Since spiraling produces so strong

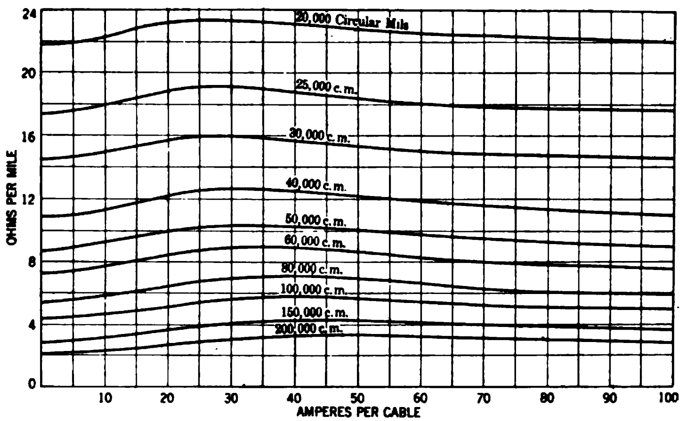


FIG. 6—RESISTANCE CURVES—25 CYCLES—7-WIRE CABLES—GRADE H-oo STEEL

an effect, the pitch of the spiral should be as long as possible without endangering the strength of the cable.

The curves accompanying this paper show that iron and steel conductors have the peculiar property that the effective resistance and reactance increase to a maximum as the current is increased, and then decrease. This is due evidently to the iron becoming saturated so that the flux and the iron loss do not increase as before in proportion to the current. In most cases, especially with the larger cables, the decrease is very slow and the resistance maintains approximately its maximum value for most large values of current. This property should prove useful in transmission-line work, for the conductor will have a low impedance to the normal load current, but will have about twice as much impedance to the current flowing in case of a short circuit. The impedance will also be large to high-frequency surges caused by switching or lightning. It may prove more economical in certain cases to protect a line against short circuits and surges by using steel conductors than by installing current-limiting reactors or by increasing the reactance of the transformers.

This property may also be of use in the case of feeders of direct-current interurban railways. If the feeder be a steel cable it will have low resistance to direct current, but high impedance to alternating currents. It will therefore tend to damp

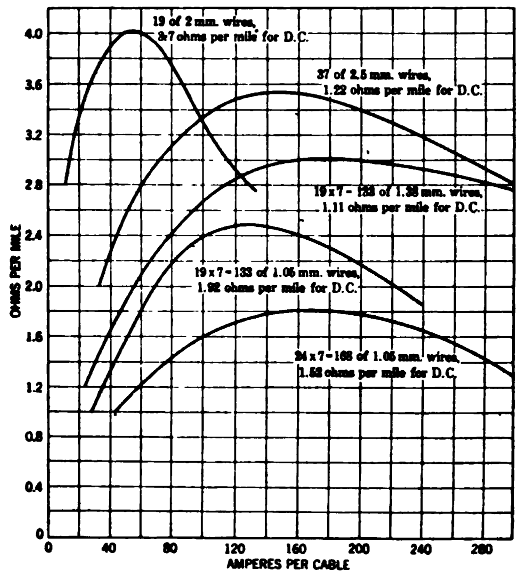


FIG. 7—INTERNAL REACTANCE CURVES—60 CYCLES—GRADE S.S.W STEEL

out the suddenness of short circuits, and lightning surges, which cause synchronous converters and generators to flash over. That there is need of taking precautions against flash-overs in this way is shown by the fact that it has already become the practise to make the nearest connection between a feeder and the trolley wire several thousand feet from a synchronous converter or generator so that the latter will be protected by the resistance of a long stretch of feeder in case of surges or short circuits.*

*The Relation of Trolley-Feeder Taps to Machine Flash-Overs, by Chas. H. Smith, *The Electric Journal*, January, 1915.

If the feeder be made of steel, and especially if the stranding be coarse, the required protection will be still more complete. Steel conductors would probably be economical only where it is allowable to use bare cables, for the large size of steel cables compared with copper ones would greatly increase the cost of the insulating covering.

The higher conductivity of steel for direct current than for alternating current makes the use of bare steel cables for d-c. feeders more economical than for a-c. lines. A steel cable has about eight times as much resistance to direct current as a copper cable of the same size, and therefore seven times as much resis-

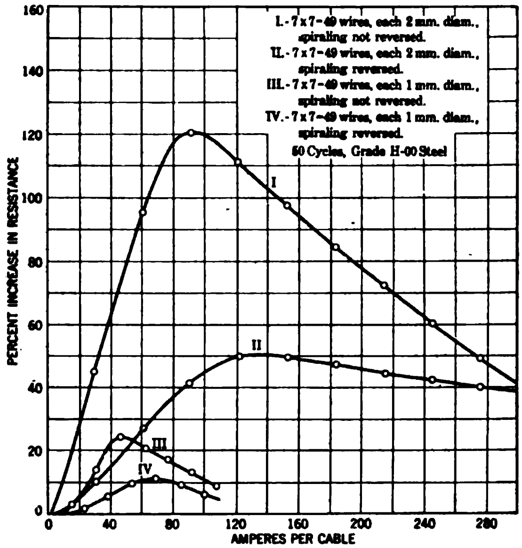


FIG. 8—EFFECT OF SPIRALING

tance as a copper cable of the same weight, since copper is more dense than steel. But galvanized steel cables usually cost less than 1/7 as much as copper cables per pound, and so should be more economical, other things being equal.

Steel cables have frequently been used on transmission lines for long spans up to 3000 feet or more. In some cases the steel cable has been the support for a copper conductor, but in many cases the steel cable itself has carried the electric current. Such applications are of such a short length compared with the entire transmission line that they have been chosen, not because of a comparison of the cost and conductivity of steel and copper, but because copper or aluminum would be too weak for such long spans, and a much stronger material, like steel, was absolutely necessary in order that the transmission line should be mechanically safe.

Another application of steel conductors which has already met with success is for small size conductors, as mentioned in the second paragraph. Here again it has not been the relative conductivity, but the greater tensile strength, which has induced the choice of steel rather than copper. It is not the practise to use a smaller copper wire than No. 6 (0.162 in. or 4 mm. diameter) for overhead lines, because any smaller copper wire would be mechanically too weak. But it is often profitable to supply a small load at a distance of several miles, which would require only a fraction of the conductivity of a No. 6 copper wire, and in such cases a No. 8 or larger steel conductor has been found to have sufficient conductivity and mechanical strength, and to cost much less than No. 6 copper.

According to a description recently published,* a large 60-cycle power system in the State of Washington makes use of a considerable quantity of No. 8 iron wire for short tap-offs and lightly loaded branch lines on 6600-volt circuits, without serious trouble resulting from voltage drop. This iron wire is of course far cheaper than No. 6 copper. One line built by the above company is an example showing that it may be profitable to supply a surprisingly small load at a distance of several miles. This line is 10 miles long and was originally built with No. 8 copper clad steel to supply a 50 h.p motor load at 6600 volts. The line afterward carried 110 h.p. for some time and was later changed to No. 6 copper in order to have a capacity for a still greater load.

An example from Minnesota shows the use of a somewhat larger steel conductor. This line operates at 40,000 volts, 60 cycles, and is 20 miles long. No. 4 galvanized steel cable, made of 3 wires, is used. The load is about 300 kv-a.

The above examples show that a power company can build up new loads by sending out to considerable distances numerous inexpensive lines, using small steel conductors. The cheapness of the lines and of the outdoor transformers makes a very small load profitable, and the chances of obtaining larger loads are increased by building lines into new territory. Most of the small steel

The Electrical World, p. 469, Aug. 28, 1915. See also similar examples described in the *Electrical World*, p. 820, April 8, 1916.

conductor lines appear to use solid wire of the kind which has been developed and sold for telegraph and telephone work, but a stranded cable would seem, according to the tests referred to in this paper, to be more suitable for a-c. transmission of power.

A line with small conductors, where steel is cheaper to employ than the minimum size of copper, is described in Example I. Here, a seven-mile steel line can be designed for 75 kv-a., but the smallest copper line that can be designed would be rated at 750 kv-a. Thus, while the poles and insulators will be the same in both cases, the steel conductors will cost only $220 against a cost of $2600 for copper. It is this large difference in cost which has been the main reason for using steel conductors on the branch lines of the power systems previously mentioned. This difference in cost of course is greatest when the price of copper is highest.

Besides being cheaper than the copper cable for small branch lines, the steel cable has the advantage of being mechanically stronger and less liable to be burned through by arcs. The steel line has therefore greater reliability at times of wind and sleet storms and at times of electrical breakdown or trouble. Steel cables are subject to the disadvantage that their useful life is shorter than that of copper cables, especially near the sea-coast, where galvanized steel is more quickly oxidized.

Example I shows also the advantage of using fine stranding. The seven-wire steel cable gives 9.6 per cent drop, while a solid steel wire of the same cross section has 12.5 per cent drop at the given load, according to the tests of grade H-oo steel.

Examples II and III show comparisons at 60 and 25 cycles between steel and copper conductors in regular transmission line work where the conditions are equal for competition between the two materials. The price of copper cable per pound may be assumed as being 10 times that of galvanized steel cable. This ratio is a usual one, being approximately true for times of low prices of metals as well as times of high prices. The lack of data on the reactance of a steel transmission line makes comparisons somewhat uncertain, but from the available data it seems probable that, considering the line complete with towers and insulators, it will cost for 60 cycles quite as much to use steel conductors as copper, for heavy transmission-line work, where the extra weight of steel cables is troublesome. For 25 cycles there may be a saving by using steel. However, there are many cases where the extra strength and size of steel cables are advantageous, and so at present the chief attention should be given to the classes of work where steel can show other advantages than merely low cost on a basis of carrying capacity for alternating-current power.

A transmission voltage of 100,000 or more is now fairly common. It is also a matter of observation that the cost of high-tension substations of the above voltage is decreasing, especially where outdoor substations are used. It is not possible to use a small copper or aluminum conductor on a 100,000-volt line on account of corona loss, as is indicated by the corona limits of voltage given in examples II and III.* Therefore the phenomenon of corona puts a limitation on the smallest allowable conductor of a 100,000-volt branch line, in exactly the same way that mechanical strength fixes the minimum size of wire for a low-voltage line, as previously described. Therefore, steel conductors have an opening for use on branch lines supplying a few thousand kv-a. on net works of 100,000 volts and higher. This is especially true in mountainous districts, where corona limits of voltage are lower, and where the other advantages of steel lines, namely mechanical strength and ability to resist burning by high-tension arcs, are especially valuable. In rugged country, also, the long spans permissible with steel cables may often save detours, and shorten the distance of transmission. There is also the probability, previously mentioned, that where steel conductors are employed, lightning and switching surges will be damped out more than where copper conductors are used.

In conclusion, it has been shown that large steel cables, if properly manufactured, can be used for carrying alternating currents. It appears that the chief opportunity for the use of steel conductors is on branch lines, where the size of copper required merely for the electrical load would be too small to use. However, in all cases, steel conductors will be nearly as cheap as copper ones, if not more so, and the use of steel will always increase the reliability of the transmission system.

EXAMPLE I

Length of line	7 miles
Voltage at receiver	11,000 volts
Frequency	60 cycles
Power factor of load	85 per cent
Phases	3

*These limits have been calculated according to the tables in "Dielectric Phenomena," by F. W. Peek, Jr., page 210, McGraw-Hill Book Co., New York, 1915.

A.	Conductor	7-wire steel cable
	Size	25,000 cir. mils
	Diameter of cable	0.18 inches
	Diameter of wires	0.06 inches
	Resistance per mile at full load	17.6 ohms
	Full load	75 kv-a.
	Voltage drop at full load	9.6 per cent
	Weight of conductors	7300 pounds
	Cost of steel cables at 3 cents per lb.	$220
B.	Conductor	Single steel wire
	Size	25,000 cir. mils
	Diameter	0.158 inches
	Resistance per mile at full load	23 ohms
	Full load	75 kv-a.
	Voltage drop at full load	12.5 per cent
	Weight of conductors	7300 pounds
	Cost of steel wires at 3 cents per lb.	$220
C.	Conductor	Single copper wire
	Size	No. 6, 26,250 cir. mils
	Diameter	0.162 inches
	Resistance per mile	2.14 ohms
	Full load	750 kv-a.
	Voltage drop at full load	9.5 per cent
	Weight of conductors	8800 pounds
	Cost of copper wires at 30 cents per lb.	$2600

EXAMPLE II

Length of line		75 miles
Voltage at receiver		60,000 volts
Frequency		60 cycles
Phases		3
Power factor of load		85 per cent
A.	Number of circuits	2
	Conductor	49-wire steel cable
	Size	400,000 cir. mils
	Diameter of cable	0.81 inches
	Diameter of wires	0.09 inches
	Full load per circuit	2500 kv-a.
	Resistance per mile at full load	1.16 ohms
	Voltage drop at full load	9.6 per cent
	Weight of conductors for two circuits	2.510,000 pounds
	Corona limit for operating voltage at 1000 ft. above sea level	164,000 volts
	Sustained short circuit kv-a. at full generator voltage, transformers with 5 per cent reactance being included at each end	4.4 times full kv-a
B.	Number of circuits	1
	Conductor	49-wire steel cable
	Size	1,000,000 cir. mils

	Diameter of cable	1.28 inches
	Diameter of wires	0.143 inches
	Full load	5,000 kv-a.
	Resistance per mile at full load	0.54 ohms
	Voltage drop at full load	10.9 per cent
	Weight of conductors	3,140,000 pounds
	Corona limit for operating voltages, at 1000 ft. above sea level	230,000 volts
	Sustained short circuit kv-a. at full generator voltage, transformers with 5 per cent reactance being included at each end	3.8 times full kv-a.
C.	Number of circuits	1
	Conductor	7-wire copper cable
	Size	No 1, 83,700 cir. mils
	Diameter of cable	0.328 inches
	Resistance per mile	0.678 ohms
	Full load	5,000 kv-a.
	Voltage drop at full load	10.7 per cent
	Weight of conductors	300,000 pounds
	Corona limit for operating voltages, at 1000 ft. above sea level	85,000 volts
	Sustained short circuit kv-a. at full generator voltage, transformers with 5 per cent reactance being included at each end	4.8 times full kv-a.

EXAMPLE III

Length of line		100 miles
Voltage at receiver		60,000 volts
Frequency		25 cycles
Phases		3
Power factor of load		85 per cent
A.	Conductor	49-wire steel cable
	Size	700,000 cir. mils
	Diameter of cable	1.08 inches
	Diameter of wires	0.12 inches
	Resistance per mile at full load	0.68 ohms
	Full load	4, 000 kv-a.
	Voltage drop at full load	10.2 per cent
	Weight of conductors	2,930,000 pounds
	Corona limit for operating voltage at 1000 ft. above sea level	215,000 volts
	Sustained short circuit kv-a. at full generator voltage, transformers with 5 per cent reactance being included at each end	4.7 times full kv-a.
B.	Conductor	7-wire copper cable
	Size	No. 2, 66,400 cir. mils
	Diameter of cable	0.292 inches

Resistance per mile	0.855 ohms
Full load	4000 kv-a.
Voltage drop at full load	10.2 per cent
Weight of conductors	316,000 pounds
Corona limit for operating voltage at 1000 ft. above sea level	76,000 volts
Sustained short circuit kv-a. at full generator voltage, transformers with 5 per cent reactance being included at each end	5.6 times full k-va.

DISCUSSION ON "STEEL CONDUCTORS FOR TRANSMISSION LINES" (DWIGHT) CHICAGO, SEPTEMBER 20, 1916.

Robt. E. Doane: Mr. Dwight has presented to us a comparatively new subject which has been little discussed by the engineering world in the past and which is of interest because of the possibility developed in certain directions. We would point out, however, as Mr. Dwight himself states, that the application is limited to certain special cases.

There are four general classes of service in which steel wire might be used to advantage.

1. Trolley wire.
2. Very lightly loaded high-voltage lines, which are not long.
3. Very high-voltage power transmission lines where the question of corona loss becomes of great importance.
4. Long spans.

In the first case the use of steel trolley wire has been quite extensively adopted in certain directions with somewhat variable conclusions as to its relative cost and general efficiency. In this field, the use of steel is restricted to certain sections of our large cities where the traffic is very dense and where the large portion of the current must of necessity be carried on auxiliary feeder lines, with very frequent taps to the steel trolley wire. In such special cases the resistance drop and consequent power loss in the steel as compared with copper is comparatively negligible, because the current has to flow along the steel but for a short distance only. Due to the greater hardness of steel, and its original first cost, together with its supposed longer life under operating conditions, it has had preference in certain cases. However, the very serious questions of corrosion and scrap value of the worn-out wire have to be taken into consideration and these are very important items which will be mentioned later.

There is another field of steel trolley wire where, as in such installations as on New York, New Haven & Hartford Railroad, it is necessary to have an exceedingly flat and smooth trolley wire for high speed work, in which cases the wire is sometimes suspended directly under a copper wire, purely for mechanical and not electrical reasons. In both of the above cases hard bronze wire is also used to advantage.

The second class of service, for which steel is applicable, is in the case of moderately high-voltage lines where very light loads are carried over distances that are not great. In such cases the smallest copper wire that would be used for mechanical reasons is, as Mr. Dwight mentions No. 6 B. & S., although in a great many cases No. 8 B. & S. has been employed for such service. This of course depends upon the climatic conditions, danger from high wind velocity, sleet and snow and distance between towers or poles, amount of allowable sag, and other considerations. There are undoubtedly cases where the smallest copper wire that could be used from the mechanical standpoint would be much heavier than would be necessary to meet the required electrical conditions of reactance drop and carrying capacity. In such cases the use of steel will be found to be economical, but here again the steel field is limited.

The third class of service, that of very high-voltage lines, where the question of corona loss becomes important is a field which has not yet been extensively covered in engineering discussion due to the fact that there are few such lines. There are probably not more than half-a-dozen such lines in the United States. Here again the field of application must necessarily be limited.

The fourth class of usefulness, that of long span work has been more extensively discussed. There are some notable examples of long steel spans, and some combination steel and copper cables such as the long span in use by the Mississippi River Power Company of Keokuk, Iowa, a discussion of which was printed in the PROCEEDINGS of the A. I. E. E. for October, 1914. It is well to point out that there are very few long spans which can not be made with a reasonable factor of safety using copper wire, provided that there is a possibility of allowing sufficient sag in order to somewhat reduce the tensile strain on the wire. The very slight increase in the percentage sag and consequent increase of the height of towers, which may be necessary in some cases, would make it mandatory for the engineer to decide on copper rather than steel. Of course in cases where additional expense in height of towers is made necessary the increase in the cost of steel towers may more than offset the advantage to be obtained from the use of copper in the span.

In making general calculations covering any particular installation, it would be logical to first assume that copper would be the natural metal to use and steel the unnatural, due to the fact that the vast majority of all transmission lines, trolley lines and long spans have in the past been constructed with copper and generally for good reasons. The percentage use of steel as compared with the copper is very slight indeed.

SCRAP VALUE AND CORROSION

There are two general conditions which make the use of copper generally mandatory, the principal one of which is the ultimate scrap value of the material used. By throwing out the consideration of fluctuations in the cost of metals, which is proper in a theoretical discussion, it may be assumed that the scrap value of copper is in the neighborhood of 85-90 per cent of the original purchase price. The scrap value of steel would probably be so low as to hardly warrant consideration, particularly if the line in question were a long distance high-voltage line extending across wooded or mountainous districts where the cost of salvage would be exceedingly high. The whole question as to the use of copper is an economic question, except for certain very special and rare cases. Lines are constantly being changed and altered and the scrap value is of great importance. It is of extreme importance in the case of trolley wire, which is frequently replaced and even if the copper trolley wire should be reduced 50 per cent in cross section, the scrap value may still be 40 per cent or more of the original cost.

The question of corrosion and life of the material is intimately connected with the scrap value. This is largely a question of climate, although the relative corrosion of copper and steel is probably about the same in most climates. It is unquestionably true that steel corrodes more rapidly than copper and its life is correspondingly shortened. In long distance transmission lines, one of the primary considerations is continuity of service, and if steel wire were used, subject to fairly rapid corrosion, it would necessarily be thrown out of consideration due to possibility of breaks occurring at unexpected times, perhaps many miles away from the nearest town, all of which would be exceedingly expensive and require a shutdown of many hours or even days before the trouble could be repaired. If copper lines are properly strung and not overstrained, this danger would be appreciably less.

Bear in mind that there are certain sections in the country where even the life of copper wire is comparatively limited and at best, lines have to be restrung quite frequently. In certain locations on the Pacific Coast the life of copper transmission line is but a very few years and in central Pennsylvania in certain localities, in the coke regions, copper is also attacked very rapidly by corrosion. Steel would probably go much faster than copper in such localities, and since the scrap value of copper is so enormously greater than the scrap value of steel, copper would almost of necessity be used under such conditions.

Mr. Dwight has mentioned the use of copper-clad steel wire which is being adopted in increasingly larger fields very rapidly. It combines the higher tensile strength of the steel, and offers 30 per cent or 40 per cent conductivity of copper as against approximately 14 per cent conductivity which the steel possesses. Its use has been very extensive indeed in the small size conductors and it has given a very satisfactory account of itself.

In discussing the commercial aspect of the case we note that Mr. Dwight has stated that the price of copper per lb. may be assumed as being ten times that of galvanized steel cable. If the present relative cost of copper and steel is a criterion, this ratio is hardly a fair comparison, for copper is in the neighborhood of 30c per lb. and we believe that base size E. B. B. galvanized steel wire is over 6.0c. per lb., so that roughly, copper would cost about five times that of steel rather than ten times. Undoubtedly some of the steel men present can comment on these figures.

Mr. Dwight has very naturally and properly chosen examples in which cases the use of steel would be more advisable and has very clearly shown in certain cases that it is worthy of careful consideration. It would, however, be unwise to consider that its use is of general application and in working out specific problems we must in all cases put both metals on an equal footing, standing strictly on their relative merits, commercial costs, and consequent applicability. In other words the question is purely an economic one, and in the vast majority of cases, copper will undoubtedly be found the least expensive, all things considered.

Mr. Dwight has made an excellent presentation of this subject and it is worthy of very careful thought.

T. H. Worcester: Mr. Dwight's paper gives valuable additional data on the subject of iron and steel electrical conductors and will be of considerable assistance to engineers in designing circuits in which such conductors may be used. The data which have previously been available are so scattered and meagre that it has been difficult to find information on a chosen size and quality iron wire or even to interpolate between known values on given sizes and qualities. With the help of Mr. Dwight's data this will be much simplified, since he has given information covering a wide range in sizes of wires, in current densities and in methods of spiraling. It is unfortunate that a greater range in quality of material is not covered and moreover that the principal quality considered is not a duplicate of American product so that direct comparisons might be made. Tests on effective resistance which we have made on ¼-in., ⅜-in. and ½-in. seven strand steel of the Siemens-Martin grade correspond very closely to the results shown in Figures 3 and 6. Our tests were not made with as high current values as those shown by Mr. Dwight, so that the drooping characteristics of the upper end of the curves has not been checked. However, this droop in the curves is what one would expect after the iron reaches saturation and the general character of the curves has been checked on other grades and sizes of wire.

As regards the internal reactance of iron cables, the value of 75 per cent of the a-c. resistance for corresponding currents seems to be high except for conductors having diameters greater than ½-inch or those made of iron having relatively high permeability. The tests mentioned above on steel wire show the reactance to be about 30 per cent of the resistance for ¼-in. and ⅜-in. cables and 50 per cent for ½-in. cable. However, this is subject to such variation with permeability and current density that it is very desirable to test samples of the conductor which it is proposed to use if accurate values are desired.

One of the interesting points about iron wire conductors is that the purer and more costly grades of wire have higher effective resistance and reactance on a-c. than the cheaper grades of steel wire, even though the latter have higher resistance on direct-current. In considering this point, however, it must not be forgotten that the high grade iron wire will not deteriorate as rapidly as steel wire after the galvanizing is once scaled off and that in some cases it may be more economical.

The advantage of using many small wires stranded together with reverse spiral in alternate ropes is worthy of careful consideration. From a theoretical electrical standpoint such cable is to be preferred. In practise, however, finely stranded cable may prove troublesome from breakage of the wires either by rusting through or by short-circuit arcs. Furthermore, finely stranded cable when each wire is galvanized as it should be, is considerably more costly than coarsely stranded wire. For the larger sized cables—½-in. and above—the 7 x 7 strand is permissible, but for the smaller sizes its use is questionable.

In view of the fact that there will be a continual demand for steel conductors in the future it is very desirable that more complete data be obtained on American grades at as early a date as possible.

David B. Rushmore: A subject of this kind is always of interest, because of changing conditions, and with the present prices of copper and aluminum, and because of the price today for steel and iron, which will probably be reduced before the others are, there will undoubtedly be, from a purely economic standpoint, a certain field for the use of steel conductors. That these have been used, and are being used, to some extent, has been mentioned in the paper—in small installations, often where the western lines run out a very small line at high voltage to a prospect—a mine may be developed later, but they are not quite sure, and the man himself just wants a little power for drilling and hoisting. Nobody knows what the future condition is going to be, so that the minimum of installation expense is usually the first consideration, and the efficiency is not of the first importance.

There are some very interesting points in regard to the deterioration of iron and steel under weather conditions. Those of you who have visited the Panama Canal will remember there is a lot of old French machinery, made in Belgium, which is still around there in heaps, or was a few years ago when I was there, and not rusted at all, with no sign of deterioration on it. Having occasion to look this matter up, to see what it was, I found that it is puddled iron, wrought-iron, and the apparent reason is that the little grains or globules of iron are covered by silicate flux which prevents the oxidation of them. As is known, a wrought-iron roof will stand practically indefinitely without rusting. Whether that is a metal which could be used as a conductor or not, I am not sure.

There is an interesting phase about the use of iron and steel conductors, in the rather able presentation of the paper and the discussion which has been had and has covered most of the points, that has not been mentioned, and that is its protective action against high-frequency disturbance. A patent has been taken out by an Italian engineer for covering copper-clad conductors with a nickel covering of high resistance so that the action of the high-frequency current in what is known as skin effect, forcing the conductor to the outside of the duct, forcing it into a cylinder of very high resistance, which absorbs the energy of surge and prevents it from passing along the line. Some such effect as that would be brought about in high-frequency disturbances which would have to stay in or on the steel, and which would be absorbed more readily than in a conductor of lower specific resistance.

It is apparent that later on this sub-division of conductors in cables, is highly desirable, and the great pressure now being put forth for the use of higher voltages—there are quite a number of active propositions at present for 200,000 volts—is forcing the conductor up to the limit of corona, so that the size of the conductor is determined much more by corona than by the current capacity, and the size of the conductor will, for small lines, be quite independent of the load transmitted. So, in many special cases, the steel conductors can be considered at the present time, and as has been said, it is a subject which is worthy of careful scientific investigation and of much more careful commercial study.

S. C. Coey: I had one question I would like to ask Mr. Dwight on the curve Fig. 1. I wonder if he has any explanation to offer as to why the curve for the smaller sized wire should have a higher peak than for the larger sizes. It apparently is while the iron or steel is becoming saturated and it would seem to me you would have about the same for different sizes.

W. T. Snyder: It occurred to me in connection with the use of steel wire there would necessarily be connections and some of the taps made with copper wire, small copper feeders branching off. I wonder what the electrolytic effect would be there, what chemical action would take place, if that would result in any undue harm. I understand that in the case of the use of copper-clad steel, if the copper envelope is scratched, and the steel is exposed, that chemical action is set up between the two elements and it rapidly destroys the wire. I wonder if the same effect would take place at the tapping of a copper wire onto a steel wire. Also, in the case of tapping of a steel wire onto another steel wire, what is the method of splicing to prevent holding water and bringing about rapid corrosion.

David B. Rushmore: It might be possible that some one here would be able to suggest a solution to a point which has not up to date been forthcoming. There have been put into use, in the past few years, a number of transmission lines of copper stranded cable with hemp centers. This, in general, has been very disastrous. In the case of one line, which was put in in South America, a cable after a period of a year or two went all to pieces. There was some action which took place between the hemp center and the copper adjacent to it which corroded the copper badly and there was evidently a chemical action which penetrated the copper for about one-quarter of the diameter.

I saw sections of the cable which were sent north, and in all our efforts we were never able to get a satisfactory explanation as to what the cause of the trouble was. The use of such copper cable, with hemp centers, has, so far as I know, been almost entirely discontinued.

The longest practical transmission line I know of, is one feeding into Los Angeles, from a point about 250 miles distant to the north, a line of the Pacific Light & Power Company, which is operating at 150,000 volts, and it is interesting to learn that they are having very little operating trouble with it. The cable there consists of a steel center, both for strength and to increase the diameter of the conductor, with stranded aluminum around and outside, and there was considerable discussion just on the point brought out, whether there might not be, as the effect of rains and moisture saturating the cable, electrolytic action which would tend to destroy it. The practical result of that would probably appear within a year or two, but there is no evidence up to date to show what it will be. Why the cable with the hemp center and copper conductors should have gone to pieces as it did, the copper becoming extremely brittle and cracking at right angles to the length of the wire, has never, so far as I know, been explained.

H. B. Dwight: In reply to the question why some of the curves in the paper have sharper peaks than others, I believe this is merely accidental, depending on the relative magnitude of the scales to which the curves were plotted.

Regarding the electrolytic action at a joint between a steel cable and a copper cable, it may be necessary to protect such joints from the weather, but the action is not to be considered as an objection to the use of steel cables. In the descriptions of practical operation referred to in the paper, it was stated that this trouble was feared, but that no trouble was experienced.

Mr. Doane's discussion was very interesting and has added considerably to the complete description of the standing of steel conductors in commercial work at the present time. The steel conductors used at present are undoubtedly a small percentage of the copper conductors used, but this ratio may be changed by the high price of copper and by an increase in the knowledge of the alternating-current properties of commercial steel cables.

Mr. Doane stated that the ratio of cost of copper to steel should not be 10 to 1 as given in the paper, but should be 5 to 1 as shown by the price of "extra best" iron wire. It is pointed out in the paper that according to the tests published in Germany and also tests made by the Bureau of Standards, pure iron is not the best for alternating-current work, and there is good hope that the grade of steel most suitable for power lines will cost only one-tenth as much as copper.

With reference to the statement that there are only a half dozen lines in America where corona loss is important, it is evident that a pressure of 150,000 volts is referred to, but it is easy to show that corona is of importance at the very common pressure of 100,000 volts. Two values of corona limit of voltage are given in the paper, namely, 85,000 volts for No. 1 copper and 76,000 volts for No. 2 copper at a usual spacing. Although such small conductors are sometimes used on 100,000-volt lines, the practise is probably not economical or advisable, owing to the heavy corona losses in bad weather. Accordingly, on branch lines of 100,000-volt systems, there is an opportunity for the use of steel cables which would have lower conductivity and cost than No. 1 copper, but would have larger diameter and would be free from corona loss.

Mr. Worcester in his discussion emphasized the value of curves similar to those in the paper, but applying to American steel cables. I believe that in view of the small cost of making the tests, it is proper to urge that test curves be prepared and published, of several grades of American commercial steel cables of medium strength and cost.

Presented at the Toronto Section Meeting of the American Institute of Electrical Engineers, September 22, 1916.

ELECTRICAL MACHINERY TESTS AND SPECIFICATIONS BASED ON MODERN STANDARDS

BY H. M. HOBART

ABSTRACT OF PAPER

Comparisons are made of the standardization rules for electrical machinery now in force in various countries. It is shown that the differences are of a very minor character and that machinery built in conformance with the American rules will usually also conform with the rules employed in other countries. The suggestion is made that 55 degrees could be employed as the ambient temperature of reference for tropical ratings and it is maintained that such a plan fits in nicely with the value of 40 degrees already adopted as the ambient temperature of reference for other than tropical ratings. Attention is called to a series of acceptance tests on some large waterwheel generators and to the temperature results obtained by making cyclic heat runs on these machines.

IN THE course of his work the author frequently has been brought face to face with the fact that the mere drafting and circulating of standardization rules constituting a radical departure from former practise, are insufficient to bring about general use of the contemplated modifications. It is necessary to have a wide and thorough discussion in order that there shall be a clear appreciation of the reasons for and the consequences of the alterations. Furthermore, in working out so comprehensive a proposition as that represented by the Standardization Rules of the American Institute of Electrical Engineers, provision has to be made for a large number of details, whose importance, if not especially emphasized, is liable to be overlooked in the practical application of the rules to concrete cases. There are a good many sections in the rules, which at first glance would seem of minor importance, but which, nevertheless, set forth requirements which cannot be disregarded advisedly on the occasions of acceptance tests and in the drafting of specifications.

The author recently has had occasion to carry out a series of very interesting acceptance tests upon some large waterwheel-driven generators. Since it was the purpose to make the tests with exceptional care, it seemed to be an admirable occasion to subject the American rules to a thorough test. Consequently especial endeavors were made to conform with the requirements set forth in the American rules. Various points arose in which this practical process of putting the rules to the test, suggested the desirability of slight modifications to increase their definiteness.

In the original drafting of a specification, the feasibility of determining by simple tests that the requirements of the specification have been fulfilled, should always be kept prominently in mind. Indeed the close association between a consideration of the terms of the specification and a consideration of the general subject of the carrying out of acceptance tests is so obvious that it is unnecessary to further justify the predominance given in this paper to the acceptance-tests aspects of the subject.

As regards electrical machinery, the British Standardization Rules issued by The Engineering Standards Committee in Report No. 72 and the October, 1916 edition of the Standardization Rules of the American Institute of Electrical Engineers are in such close agreement that machinery built and rated to conform with the one set of rules will usually also conform with the other set of rules. The slight quantitative differences between the two sets of rules practically always will be covered by the margin reserved by manufacturers. This general statement of fact is made as a matter of interest, but of course it is always important to make certain that the standardization rules according to which the machinery is specified in any particular case agree in all particulars. An appendix to this paper contains in tabular form a statement showing the slight differences in the temperature limits in the British and American standardization rules. The heating and temperature sections of the 1916 edition of the Italian rules are also in close agreement with the corresponding sections of the British and American rules.[1]

The British rules do not yet cover quite as many subjects as the American and Italian rules, which already contain sections relating to efficiency and to regulation in addition to those covered by all three sets of rules. The limitations of this paper will not permit of a discussion of these two latter subjects nor of the subject of dielectric tests, notwithstanding their interest and importance. The paper is further limited chiefly to points relat-

1. "Standards for the Ordering and Acceptance of Electrical Machines" issued by the Italian Electrotechnical Association; Central Offices: 10 Via S. Paolo, Milan.

ing to rotating machinery, the important subject of stationary transformers being excluded since its consideration would have too greatly increased the length of the paper.

Temperature Standards

So far as relates to heating and temperature, the plan underlying all modern standardization rules for electrical machinery consists in establishing approved upper limits of temperature. These limits are such as to permit of continuous subjection thereto. While as an actual fact these limiting temperatures could be exceeded safely for short intervals, this is not permitted by the rules. The approved upper limits have been determined upon with a view to providing adequate factors of safety. Having determined upon approved values for the upper temperature limits, the next step consists in adopting a reference value for the ambient temperature. The difference between the approved upper limits and the ambient temperature of reference constitutes the limiting temperature rise. The *rating* is obviously a function of the thus-deduced temperature rise.

Ambient Temperature of Reference

In the British, the American and the Italian rules the ambient temperature of reference is 40 deg.[2] This value is adopted because it is a temperature approached in all parts of the temperate zone at some time during the year.

In none of these three sets of rules is there, as yet, any provision for machinery for tropical countries. The author would suggest 55 deg. as a suitable ambient temperature of reference for tropical ratings. The suggestion is not based on any contention that electrical machinery is liable to be installed in locations where an ambient temperature of 55 deg. would be at all likely to occur, but for the three following reasons:

First, that it is desirable to employ a value which will ensure a margin of a few degrees; *second,* that the ambient temperature of reference for tropical ratings should not exceed that for temperate ratings by less than 15 deg. (a less difference would lead to ratings which would be so nearly the same for the two cases that the difference hardly would be worth taking into account); *third,* that the value of 40 deg. is, strictly speaking, rather too low for the temperate zone. While its occurrence is by no means usual, it is so often approached within a few degrees that it

2. Throughout the paper, all temperatures are given in the centigrade scale.

cannot be said to provide much margin when employed as a standard reference value. Since 40 deg. is now firmly established for the temperate zone, the consistent value for a basis for tropical ratings is 55 deg. Practical experience has demonstrated the importance of employing distinctly lower ratings for electrical machinery destined for use in tropical countries, than ratings which have proven satisfactory for the temperate zone.

The ambient temperature of reference of 40 deg. for all countries in the temperate zone was adopted only after very careful investigations. While there are many localities where an outdoor shade temperature of 40 deg. is never attained at any time in the year, nevertheless there are in the temperate zone very few localities where an outdoor shade temperature of 35 deg. is not sometimes closely approached. It was decided that 35 deg. did not afford sufficient margin. The following data bear out the correctness of this decision.

From the report of the chief of the Weather Bureau have been taken the following maximum temperatures recorded in any station in the designated states during the year 1908.

42 deg.	Kansas, Nebraska, New Mexico, Oklahoma
43 "	Montana, Idaho, Oregon, South Dakota, Utah, Wyoming
44 "	Washington
46 "	Texas
47 "	Nevada
49 "	California
52 "	Arizona

In America, meteorological observations are often made by amateur volunteers and it is possible that some of these higher values may not have been adequately verified.

From "Symons Meteorological Magazine" for 1912 has been compiled the table on the following page, of temperatures at 20 places in the British Empire. The records consulted were compiled from 30 places in the British Empire. For the remaining ten places 32.5 deg. was not reached at any time during the year 1911.

It is of importance to emphasize that it is not essential to be able to reconcile the ambient temperature of reference with the maximum temperature occurring in the locality where the machinery is to operate. The greater the amount by which the ambient temperature of reference exceeds the temperature where the machinery is operated, the greater is the factor of safety. The shade temperatures set forth in meteorological records are usually taken where there is no local source of generation of heat and where air circulates freely. Electrical machinery in operation *itself* constitutes a source of heat and increases the temperature of the surrounding air. Furthermore electrical machinery is often located in places where the circulation of air is very much restricted. Consequently the ambient temperatures near electrical machinery will generally considerably exceed the shade temperatures recorded by meteorological stations. Indeed there is no proof that the actual ambient temperatures in the neighborhood of electrical machinery are related at all closely to the official temperatures issued from meteorological stations. It is evident from the tables which have been given that, strictly speaking, even 40 deg. is too low for the reference temperature,

NUMBER OF MONTHS DURING 1911 IN WHICH THE MAXIMUM SHADE TEMPERATURE EQUALLED OR EXCEEDED:

	32.5 deg.	35 deg.	37.5 deg.	40 deg.
London	3	1	0	0
Malta	1	0	0	0
Lagos	4	0	0	0
Cape Town	3	3	1	0
Durban (Natal)	3	1	0	0
Calcutta	9	4	2	0
Bombay	9	0	0	0
Madras	8	8	6	3
Colombo (Ceylon)	4	0	0	0
Hongkong	3	0	0	0
Sidney	3	2	2	0
Melbourne	4	3	3	2
Adelaide	6	6	5	2
Perth	4	4	3	2
Coolgardie	6	6	6	5
Hobart (Tasmania)	2	2	1	0
Jamaica (Kingston)	9	3	0	0
Toronto	1	0	0	0
Fredericton	1	1	0	0
Blömfontein	5	2	0	0

on the basis that it is to be a value that shall *never* be even *slightly* exceeded. The reference value adopted must rest upon an assumption and it is important that the assumption shall be conservative. In the rules of the Verband Deutscher Elektrotechniker the ambient temperature of reference is 35 deg. The precise statement in this respect as set forth in the V. D. E. rules is as follows:

"It is assumed that the temperature of the surrounding air will not exceed 35 deg."

In the British, American and Italian rules, it is assumed that the temperature of the surrounding air will not exceed 40 degs. It is probable that in the neighborhood of electrical machinery, *i. e.*, at a distance of 1 to 2 meters from the machine, as set forth in Section 314 of the American rules), the temperature of the air at some time during the year exceeds 35 deg. in the majority of cases and there is often a considerable probability that the ambient temperature near electrical machinery will occasionally rise a few degrees above 40 deg. But by the adoption of 40 deg. as the ambient temperature of reference there will for almost all installations of electrical machinery in the temperate zone probably be a margin of a few degrees during 99 per cent of the year. For such an indefinite state of affairs, it is reasonable to adopt a value which offers some probability that there will be such a margin. It is not possible to predict the maximum ambient temperature in the neighborhood of an electrical machine within several degrees even when the machine is not running, and the value to which the ambient temperature is likely to attain when the machine is in operation is still more indefinite. The records of the official shade temperature for any given locality are of little or no service. Indeed the temperatures maintained within buildings are apt to be fully as high in cold climates as in warm climates. In view of the indefiniteness inherent to the subject, and of the importance of taking a conservative value, it would appear that the reference value of 40 deg. for the ambient temperature in regions in temperate climates is certainly not too high and reasonably might be criticized as too low. From whatever way the matter is approached there is obviously a 5-degree-greater factor of safety, (in other words, a more conservatively rated machine), when the rating is based on an ambient temperature of reference of 40 deg., as in the British, Italian and American rules, than by basing it on 35 deg.

A distinct commercial value attaches to the provision of means for maintaining at a reasonably low temperature the premises in which electrical machinery is operated. If a temperature of 30 deg. on these premises is never exceeded at any time during the year, then the maximum temperature ever occasioned in the electrical machinery when operating at its rated load is 10 deg. below the approved limits and the margin of safety is very much greater.

The Ambient Temperature During Acceptance Tests

In determining the ambient temperature on the occasion of acceptance tests in the case of rotating machines cooled by forced draft, it is provided in Section 311 of the American rules that "a conventional weighted mean should be employed, a weight of *four* being given to the temperature of the circulating air supplied through ducts and a weight of *one* to the surrounding room air." Thus, for example, if, on the occasion of an acceptance test, the circulating air is taken from outside the building and has a temperature of 14.0 deg. at the intake of the machine, while the temperature of the air in the room is 24.0 deg., the ambient temperature, from which the temperature rise is determined, should be taken as:

$$\frac{4 \times 14.0 + 1 \times 24.0}{5} = 16.0 \text{ deg.}$$

If the temperature of the machine at the end of the heat run is 70 deg., then we have:

Temperature rise *in accordance with the American rules*
$= 70 - 16 = 54$ deg.

Temperature rise *above room temperature*
$= 70 - 24 = 46$ deg.

Temperature rise *above inlet temperature*
$= 70 - 14 = 56$ deg.

While, strictly speaking, the weights given for the two air temperatures should depend upon the characteristics of the particular machine under test, the correction is of such moderate amount that it has been desirable in the interests of simplicity and definiteness to standardize the weighting of the two temperatures.

It is further to be noted (from Sections 314 and 315) that the room temperature is to be taken as the mean of "several thermometers placed at different points around and half way up the machine, at a distance of one to two meters," and that the value to be employed shall be the mean of the readings of these thermometers taken at equal intervals of time during the last quarter of the duration of the test.

The temperature of a large machine will not at all promptly follow the changes which are always taking place in the temperature of the premises where a heat run is being made. Consequently, if no appropriate provision be made, a greater temperature rise will usually be recorded if the heat run concludes shortly after midnight, when the air temperature in a large factory building is usually falling, than if the heat run is concluded in the middle of the forenoon, when the air temperature of such a building is usually rising. Errors from this source are decreased by complying with the requirement in Section 316 that "the thermometer for determining the ambient temperature shall be immersed in a suitable liquid, such as oil, in a suitable heavy metal cup." With a falling room temperature, a mercury thermometer exposed to the room air might read at least a couple of degrees lower than an identical thermometer with its bulb immersed in oil in one of these metal cups.

To those who have not had extensive experience in testing large generators, these various precautions may seem trivial. As a matter of fact they ensure immunity from errors which may easily amount to several degrees difference in the result obtained for the temperature rise.

The British, Italian and American rules are now in agreement in providing that for rotating machinery no correction is to be made in the temperature rise on account of the particular value of the ambient temperature on the occasion of the test. The British and American rules simply suggest, (Section 320 of the American rules), that "tests should be conducted at ambient temperatures not lower than 15 deg." The corresponding Italian rule is as follows:

> "For ambient temperatures lower than 40 deg. during the tests, no correction shall be applied to the results of the measurements so long as the temperature does not fall below 10 deg.; however it is not convenient that tests should be carried out at temperatures below 10 deg."

This plan of omitting any corrections is a decided improvement over the old plan of applying to the observed temperature rise, a correction which was a function of the ambient temperature at the time of the test. Careful tests have shown that the temperature rise of the average machine is not very dependent upon the temperature at the time of the test and that the reliability of the result cannot be increased by means of any simple corrections. Elaborate tests have been made with the object of clearing up this matter by making heat runs in a room maintained successively at low and high temperatures. The rise with low room temperatures averaged as great as the rise with high room temperatures, the inverse change in core and copper loss with change in temperature combined with the very rapid increase in radiation at high temperatures tending to render the result independent of the room temperature.

Another progressive ruling which is identical in the British and American rules is that relating to the duration of heat runs. It is to the effect that:

"The temperature test shall be continued until sufficient evidence is available to show that the maximum temperature and temperature rise would not exceed the requirements of the rules, if the test were prolonged until a steady final temperature were reached."

For conditions where the temperature of a part cannot be obtained until the machine is shut down, (for example, the resistance of the stator windings of a polyphase generator), the rules make the following provision:

"Whenever a sufficient time has elapsed between the instant of shut-down and the time of the final temperature measurement, to permit the temperature to fall, suitable corrections shall be applied, so as to obtain as nearly as practicable the temperature at the instant of shut-down. This can sometimes be approximately effected by plotting a curve, with temperature readings as ordinates and time as abscissas, and extrapolating back to the instant of shut-down. In other instances, acceptable correction factors can be applied."

As to these *acceptable correction factors*, it may be said that from the many test results available on the records of manufacturers, it will be known generally that, for a particular type of machine, the cooling of the hottest-spot will be approximately at some particular rate per minute for the average of the first three or four minutes after shut-down. At the time of the acceptance tests, both parties to the transaction usually will readily arrive at a satisfactory agreement that for any particular machine under test a certain number of degrees shall be added to the temperature determined by resistance measurements made within a given number of minutes of shut-down. It rarely would be worth while to encumber the specifications and guarantees with a clause setting forth the amount of this correction, but it is simple enough to do so when it is considered that it is of sufficient consequence to have the amount definite y stipulated.

Embedded Temperature Detectors

The American rules (Section 355) require that for the purposes of acceptance tests, the temperatures of the stators of large generators shall be determined by means of embedded temperature detectors, several of which shall be employed. These are to be so located as to disclose as nearly as possible the temperature of the hottest spot existing anywhere in the machine. These embedded temperature detectors consist of thermocouples or resistance coils. An extensively employed design of embedded temperature detector of the resistance type, has a length of about 10 in. (25.4 cm.), and, at a temperature of 25 deg., its resistance is just 10 ohms. In Fig. 1 are shown sections through slots for two types of slot windings usually respectively designated two-layer and single-layer windings. It is required in Sections 353 and 354 of the American rules that "a liberal number" of temperature detectors shall be placed in the locations designated in Fig. 1 as *A* and *B*, for two-layer windings, and *B* and *C* for one-layer windings.

THE HOTTEST-SPOT TEMPERATURE

The rules stipulate that for machines with two-layer windings, the hottest-spot temperature shall be considered to be 5 deg. greater than the highest reading obtained by any of the embedded temperature detectors; and that in single-layer windings the hottest-spot temperature shall be that obtained by adding to the highest reading 10 deg., plus 1 deg. per 1000 volts above 5000 volts of terminal p essure.

These corrections are brought together in the following table:

For two-layer windings.	Add 5 degrees to the highest reading.
For single-layer windings for 5000 volts or less.	Add 10 degrees to the highest reading.
For single-layer windings for more than 5000 volts.	Add to the highest reading 10 deg., plus 1 deg. for every kilovolt by which the voltage between the terminals of the machine exceeds 5 kv.

Thus for a three-phase machine with an 11,000-volt single-layer winding, the correction to be added to the maximum observable temperature in estimating the hottest-spot temperature, is 16 deg.

Usually the hottest-spot results derived from the indications of the embedded temperature detectors are the most satisfactory. It is, however, quite possible that the temperature rise derived from measurements of the resistance of the stator windings at the conclusion of the heat runs sometimes may be greater than the temperature rise determined from the embedded detectors. Consequently it is provided in Section 352 of the American rules that when the embedded-detector method is used, the results shall, *when required*, be checked by the results obtained from measurements of the resistance of the stator windings, and "the hottest spot shall then be taken to be the highest value by either method, the required correction factors being applied in each case." By correction factor is meant the number of degrees which shall be added to the observed temperature to obtain the hottest-spot temperature. For the resistance method the correction factor is 10 deg.

As regards the so-called correction factors[3] established in the American rules, it would appear that the hottest-spot temperature determined by adding to the observable temperature the *stipulated* correction factor shall constitute the criterion and that a machine could not be rejected on the ground that other evidence demonstrated that a still-greater temperature existed at some point of the winding. For example, for purely research purposes it would be practicable to locate temperature detectors

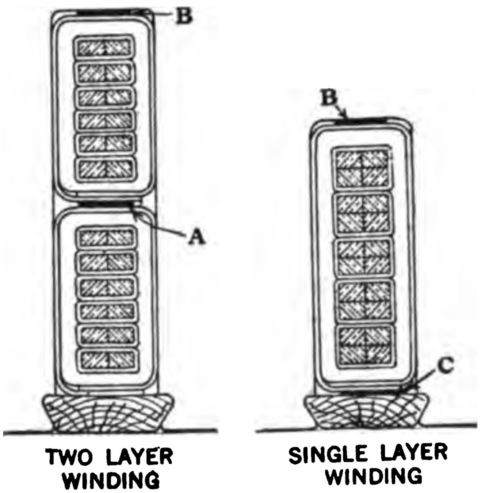


Fig. 1

actually against the copper of a high-pressure winding. In some special cases such temperature detectors might disclose temperatures exceeding those obtained by adding the conventional correction factors to the observable temperatures. Since the conventional correction factors have been established with every intention that they shall be liberal and since definiteness in contracts is essential, the hottest-spot temperatures obtained by complying with the methods approved in the American rules should be taken as final, irrespective of evidence of the existence of higher temperatures. It is believed that it would be only in exceedingly rare instances that higher temperatures could be

3. These are not factors. Some better designation should be substituted.

found and that they would exceed the conventional hottest-spot temperatures by immaterial amounts. However, in so far as the rules on this point may be obscure in the least, it would seem to be very important to make their intention unmistakably evident.

The use of embedded temperature detectors has been demonstrated to be of great advantage. When only required for the acceptance tests the leads from the detectors may, at the conclusion of the tests, be cut off, and the detectors abandoned. But it is of decided advantage, in the service operation of large generators, to be able, at any time, to ascertain the internal temperatures from the direct readings of switchboard instruments. This practise is now very customary.

It has been mentioned that the hottest-spot temperatures indicated by embedded detectors may in rare instances be less than the hottest-spot temperatures indicated by measurements of the resistance of the stator winding of a generator. Moreover since the resistance measurements of a winding only disclose *average* temperatures, occasions will arise where a suitably-located surface thermometer may indicate a temperature in excess of that indicated by the resistance measurements. A liberal number of surface thermometers ought, therefore, also to be employed when making heat runs. The author of the present paper is of the opinion that one of the chief advantages of embedded temperature detectors of the resistance type relates to the ability to employ a resistance of a magnitude which can be measured readily with accuracy, and to the reliability with which its resistance at any time can be taken to indicate a definite temperature. The temperature rise obtained from the increase in the resistance of an armature or field winding would be of distinctly greater value were it practicable to know accurately the temperature of the winding on the occasion of the measurement of the cold resistance. It is rarely practicable to incur the delay before commencing a heat run, which would be necessary to ensure that an armature or field winding is within a couple of degrees of the surrounding temperature. Often when it is assumed that the winding's temperature is substantially identical with that of the surrounding air, there is actually a difference of over five degrees and consequently the measured cold resistance is associated with a temperature over five degrees different from its actual temperature and a corresponding error is incurred in deducing from its hot resistance the temperature of the winding at the end of the heat run.

Some such plan as that set forth in the following clause, if the conditions of practise should permit of its adoption, would provide a way out of the difficulty and much increase the value of temperature determinations by measurements of the resistance of the main windings:

"In order to avoid protracted delays in the testing of a machine, in bringing the temperature of its windings into accord with the ambient temperature, the resistance of the windings of a machine, reduced to 40 deg., should be made a matter of factory record for all machines subject to temperature measurement by resistance under these rules."

In general, the author's opinion in this matter is that the methods of obtaining temperatures by surface thermometers and by measurements of the resistances of the main windings should not be discarded in favor of the newer method by embedded temperature detectors, but should continue to be employed *in addition thereto*. Indeed the careful tests made on a large machine, which are described later, showed, as may be seen from the last Table in the paper proper, that in two out of the three heat runs, the temperature rise *of the hottest spot* as deduced from measurements of the resistance of the stator windings was greater than the temperature rise *of the hottest spot* deduced from the readings of temperature detectors, and that in the remaining heat run the temperature rise *of the hottest spot* was the same by both methods. Furthermore the readings of mercury thermometers placed against appropriate parts of the surface of the rotor winding disclosed higher temperatures than were obtained by means of measurements of the resistance of the rotor winding. The results in these tests were especially reliable since the cold resistances were measured with the greatest care after the machine had been standing idle for two days, so that its windings at the time of measuring their resistances before beginning the heat run, should be at the same temperature as the surrounding air.

A recommendation to take advantage of all three methods, that is to say, Method I, surface thermometers, Method II, main-winding resistance measurements, and Method III, embedded detectors, might at first sight be condemned as impracticable on all except large, valuable machines, on the ground that the expense of making such thorough tests would be prohibitive. Were it necessary to make these measurements on each and every machine, such a criticism would be well founded. But the author of this paper holds the opinion which, in another publication, he has expressed as follows:

"Although the rules contain no explicit statement to that effect, it may doubtless be understood that it is not intended that a test by the prescribed method need necessarily be made upon every individual machine comprised in a transaction. The simplest method, as above explained, is usually Method I, and in the interest of avoiding needless expense, it should often be practicable to arrange for a judicious employment of Method I for most of the machines of a given size, employing Method II or III, as the case may be, on a few of the machines, and thereby arriving at a factor by which the results obtained by Method I require to be multiplied in order to arrive at the results which *would have been obtained* on those particular machines had Methods II and III been employed. In other words, it should not be concluded that the less simple measurements will necessarily be made on every machine, but rather that conclusive evidence shall be provided to insure that *had the measurements been made*, the temperature would have been within the required limits."

Further Consideration of the Hottest-Spot Temperature. The American rules lay emphasis on the hottest-spot temperature. Limiting approved values for the hottest-spot temperatures are set forth. The limiting values depend chiefly upon the class of insulating material employed. Insulating materials are divided into three classes, *A*, *B*, and *C*. These classes are defined as follows in the American and British rules:

Class of insulation	Description of insulating material
A	Cotton, silk, paper and similar materials when so treated or impregnated as to increase the thermal limit, or material permanently immersed in oil; also enamelled wire*
B	Mica, asbestos and other materials capable of resisting high temperatures, in which any Class A material or binder is used for structural purposes only, and may be destroyed without impairing† the insulating or mechanical qualities of the insulation.
C	Fireproof and refractory materials, such as pure mica, porcelain, quartz, etc.

*For cotton, silk, paper and similar material, when *not* treated, impregnated or immersed in oil, the highest temperatures shall be 10 deg. lower than the limits given above for Class A.

†The word impair is here used in the sense of causing any change which would disqualify the insulation for continuous service.

No limit is placed upon the temperature of Class C insulation. The permissible temperatures and temperature rises of electrical machinery at present are based chiefly upon the characteristics of Class A and Class B insulations. The British and American rules agree in adopting 105 deg. and 125 deg. for the limiting hottest-spot temperatures for these two classes of insulations. The author believes that it may be of some interest for him to state that he shares with many other engineers, the opinion, based on extensive tests, that 105 deg. for Class A insulations and 150 deg. for Class B insulations are both thoroughly conservative limits, when all the designing and manufacturing processes are carried out with due regard for numerous important details. But, failing the availability and application of skill and experience, even much lower temperature limits for Class A and Class B insulations will not ensure a satisfactory product. It is difficult to see how any Standardization rules can afford the necessary assurance in this respect. The successful withstanding of acceptance tests does not necessarily constitute evidence that the insulations will endure the stipulated temperatures (and other deteriorating influences which vary from instance to instance), for a satisfactory term of years. Fortunately the manufacturer's interest in the success and reputation of his product usually affords the required assurance. Indeed there is usually a strong tendency on the part of the manufacturer to refrain from taking advantage of temperature limits of established practicability until years of study by tests on samples and on experimental machines have established beyond all reasonable doubt the appropriateness of the higher limits. It is, however, important to the industry to take advantage of higher limiting temperatures as soon as a reasonable amount of experience is gained, since this permits of reduced capital costs for machinery and rarely affects prejudicially the working costs except where the action is premature. The adoption of new limits by bodies of the standing of the British and American Standards Committees is ample proof that the evidence in the case has been carefully sifted and that the time is ripe for the modification. While the temperature limits for Class A and Class B insulations can both be safely exceeded for short periods, it is in the interests of reserving reasonable factors of safety to establish them (as is expressly emphasized in the British and American rules) as limits which shall *never* be exceeded. In the British and American rules the limit at present standardized for Class B insulations is 125 deg. but there is a well-developed opinion in America that since there is now a great deal of experience on which to base the action, the limit for Class B insulations could with advantage be raised to 150 deg.

Intensified Aging of Insulations

Reference has been made to the impossibility of framing rules to ensure that the insulations employed have satisfactory longevity. Naturally, however, the aging of insulating materials is a matter of great importance to the manufacturer. The author has been much interested in some elaborate series of tests of this character. The point of most importance to decide is that of the temperature which can be withstood for 10 to 20 years by an insulating material. It might be supposed that subjection to super-temperatures for brief periods would permit of forming an opinion regarding the life corresponding to lower temperatures. To a certain extent brief tests for short periods at super-temperatures are useful but conclusions drawn therefrom must, at the present state of affairs, be regarded as only of the nature of very rough evidence. For some Class A insulations, values of the order shown in the following table are indicated:

Temperatures which can be withstood successfully, not only electrically but physically by approved Class A insulations:	
For seconds	250 degrees
" minutes	200 "
" hours	170 "
" days	150 "
" weeks	130 "
" months	115 "
" years	105 "

A very slight modification in the composition or construction of the insulation, however, might completely disqualify it for withstanding any considerable super-temperatures, even for brief periods. Tests on various approved Class B insulations lead to values which, while quantitatively higher by a matter of some 50 deg., are qualitatively very similar.

Reasonable factors of safety must, however, be reserved. This is realized by the British, American and German Standards Committees and no recognition whatsoever is extended to the ability of insulations to successfully withstand super-temperatures for brief periods. Thus in the American rules we have Section 305 A, to the following effect:

Section 305 A. Whatever may be the ambient temperature when the machine is in service, the limits of the maximum observable temperature

and of temperature rise specified in the rules should not be exceeded in service; for, if the maximum temperature be exceeded, the insulation may be endangered, and if the rise be exceeded, the excess load may lead to injury, by exceeding limits other than those of temperature; such as commutation, stalling load and mechanical strength. For similar reasons, load in excess of the rating should not be taken from a machine.

It is thus clear that in the interest of securing a liberal margin of safety we must forego rigorously the temptation to expose the insulation of machinery, even for brief periods, to temperatures in excess of the limits approved in the American rules.

This practise is in striking contrast to that underlying the older Standardization rules which authorized higher temperatures for short periods. Probably the credit for the modern departure belongs to the German Standards Committee, which, for some years, has employed the plan of permitting overloads with the same temperature limits as for the rated load. The following clauses are from the German standardization rules:

Overloading. **With the limitation that the overloads only are carried for so short a time, or only occur under such temperature conditions of the machines and transformers that the highest permissible temperatures are not thereby exceeded, machines and transformers must be capable of carrying the following overloads:**

Generators Motors Synch. conv. and motor-generators Transformers	25 per cent during one-half hour
Motors Synch. conv. and motor-generators Transformers	40 per cent for 3 minutes

Section 305 A of the American rules, however, contains the restriction that "loads in excess of the rating should not be taken from the machine," lest limits other than those of temperature, such as commutation, stalling load and mechanical strength should be exceeded.

Nevertheless the American rules provide for the case where a machine is required to carry very heavy loads for brief periods. Such a case is met by giving a machine more than one rating. Thus amongst the machinery recently supplied to the Chicago, Milwaukee and St. Paul Railway are some couple of dozen 2000-kw. motor-generator sets for use in substations. These sets have the following three ratings:

Continuous rating....................	2000 kilowatts
Two-hour rating......................	3000 "
Five-minute rating...................	6000 "

The mechanical strength and the commutating requirements for the five-minute rating are far in excess of those for the continuous rating. But the temperature attained with the continuous rating exceeds that attained with the five-minute rating.

This plan may be employed whenever it is necessary to provide for peaks of load, as in the case, for instance, of crane motors. Knowing the typical duty cycle, we may prescribe a *short-time* rating sufficient to ensure that the motor shall have ample mechanical strength as well as sufficient margin in the matter of commutation, and that it shall not stall with the greatest load which it ever will be called upon to carry. Knowing also the average load, we may prescribe a *continuous* rating which will ensure that approved temperatures shall never be exceeded. Two ratings should suffice, a continuous rating to ensure the non-exceeding of approved temperatures and a short-time rating to ensure the required capacity for the intermittently occurring peaks of load, as regards commutation, stalling load and mechanical strength.

On the whole, while as already stated, we owe the conception of modern ratings to the German Standards Committee, the way in which the American Committee has fitted the conception to the requirements of practise, would appear to be distinctly excellent.

Low-Temperature Circulating Air

For small machines built in large quantities for stock, the ultimate destination is unknown. In normal times a motor driving a printing press in Bombay or Pekin or Moscow is about equally likely to have been built in Berlin or Manchester or Milan or Schenectady. Even if the ultimate destination may be ascertained it is not practicable to countenance departures from the strict letter of the Standardization Rules in the case of small machinery.

But for large machines worth many thousands of dollars apiece and operated under skilled supervision, it would be wasteful to forego any economic advantage compatible with sound engineering practise. As a concrete case let us assume that a large operating company is purchasing a 20,000-kv-a. generator which will be cooled by circulating through it every minute 50,000 cu. ft. (1420 cu. m.) of air taken from outside the building. In the summer, on days when the humidity is high, the circulating air's temperature, even after passing through the air washer, may sometimes be nearly 40 deg. But the nature of the load may be such that the station's peak in summer is half of its mid-winter peak, or even much less. It may be practicable to rely on 15-deg. circulating air for the mid-winter peak. For the limiting temperature for Class A insulation, (105 deg.), this represents 90 deg. " hottest spot " rise as against 65 deg. " hottest spot " rise in the summer. By temperature coils in location A of Fig. 1, the *observable* rises are:

Summer—(105—5—40) = 60 deg.
Winter— (105—5—15) = 85 deg.

Consequently, if the machine has ample margin as regards mechanical strength and if the prime mover is adequate, advantage ought to be taken of its increased capacity in winter which would be of the order of 25 or 30 per cent.

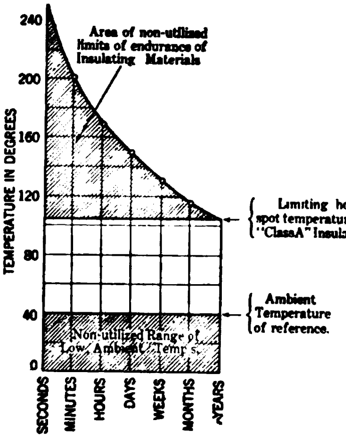


FIG. 2

Three such 20,000-kv-a. machines, operated on the basis of loading them up to their capacity as indicated by embedded temperature detectors, would do the work of four machines operated in strict accordance with Section 305 A of the American rules, and the saving in the capital component of the total cost of manufacturing electricity would be quite appreciable.

Such a case would be met by some such clause as follows:

"Contractors will be required to guarantee that the machine shall be in all respects in strict accordance with the 1916 edition of the American rules with the following exception:

Exception. The machine shall have ample mechanical strength and shall be in all other respects adequate to carry the increased load which with a circulating-air temperature of 15 deg., may be carried without occasioning hottest-spot temperatures in excess of those set forth in the American rules as approved for the class of insulation employed. For the acceptance tests, the embedded-temperature-detector method supplemented by measurements of the resistances of the main windings and by surface thermometer measurements, shall be employed for determining the temperature attained.

MARGIN OF SAFETY

Adherence to the recommendations in the British and American Standardization Rules ensure very liberal margins of safety. This is apparent from Fig. 2 in which the shaded areas indicate respectively for machines with Class A insulation, the temperature ranges above the permitted hottest-spot temperature of 105 deg. which technically are available but which are not allowed, and the temperatures below the reference ambient temperature which are liable to exist in most locations during certain seasons of the year. The unshaded area represents the temperature range, utilization of which is approved in the American rules. There is no disposition to suggest encroachment upon these liberal margins of safety; they are simply in accordance with the best and most valued traditions of the engineering profession.

EQUIVALENT TESTS

We now arrive at a matter with which the Standardization Rules do not yet deal, at any rate with any approach to thoroughness. The deficiency relates to indicating the nature of the

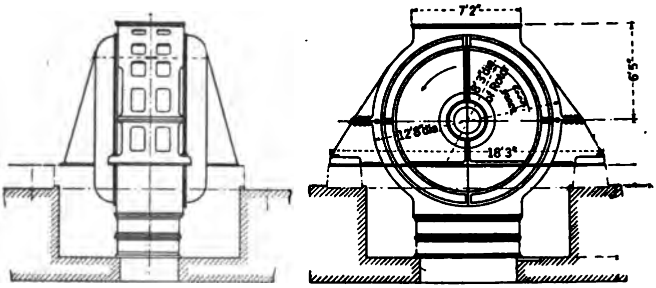


FIG. 3—TWELVE-POLE—8750-KV-A.—6600-VOLT—500-REV. PER MIN.—THREE-PHASE GENERATOR

tests which shall be regarded as satisfactory criteria for determining the temperature rise. Several methods are in vogue, but for testing a single large machine, no method in common use is thoroughly satisfactory. Doubtless the matter will be given very careful consideration by the Standards Committees before rules are adopted.

The author has already mentioned some large waterwheel generators which he recently tested. These were 500-rev. per min., 50-cycle three-phase generators with a rating of 8750 kv-a. These machines were of the design indicated in Fig. 3. Advantage was taken of the opportunity to employ for the heat test a method which may be termed a cyclic heat run.* It appears to

*This cyclic method of testing electrical machines was first described in an article by Hobart and Punga in the *Electrical World* for April 22, 1905.

See also an article by the author in the *General Electric Review* for November 1911, entitled "A Method for Testing the Heating of Large be especially well adapted to a machine of the kind tested. The test consisted in operating the machine for alternate 15-minute periods on open circuit with super-normal pressure and on short circuit with super-normal current. The degree of the super-normality was so selected as to occasion in each complete half-hour cycle, as nearly as practicable, the conversion into heat of the same amount of energy in each part of the machine as would be occasioned in each part were the machine to deliver the actual load which it was the object of the test to investigate. The normal pressure of the machine was 6600 volts between terminals. (3800 volts per phase) and heat tests were required at each of the three different loads set forth as follows:

Designation of heat run	Kilovolt amperes	Power factor	Current per phase	Terminal pressure
I	7,000	1.00	614 amperes	6600 volts
II	8,750	0.80	766 "	" "
III	10,937	0.80	960 "	" "

For each of the three heat runs it was desired to provide heating conditions equivalent to the loads just set forth. This was accomplished by cyclic tests with the following conditions:

Designation of heat run	I	II	III
For the short-circuit periods			
Rotor excitation (amperes)	119	148	185
75-deg. rotor I^2R loss (kw.)	5.10	7.9	12.4
Stator current (amperes)	854	1070	1344
75-deg. stator I^2R loss (kw.)	24.0	37.8	60.0
Stray load loss (kw.)	18.0	25.5	42.3
For the open-circuit periods			
Rotor excitation (amperes)	327	327	324
75-deg. rotor I^2R loss (kw.)	38.5	38.5	38.0
Terminal pressure (volts)	8420	8420	8350
Core loss (kw.)	270	270	260

Before these values were determined upon, curves of no-load excitation, short-circuit excitation, core loss and stray-load loss

Alternators." On February 28, 1913 this and other "Methods of Testing Apparatus for Performance" were discussed at the Midwinter Convention of the A. I. E. E. For this discussion see pp. 714 to 721 of Vol. XXXII of TRANS. A. I. E. E.

had already been taken. These are reproduced in Figs. 4, 5, 6 and 7. The resistances of the windings had also been measured and reduced to the 75-deg. reference values.† The resistances were:

Stator winding per phase....................	0.0110 ohm
Rotor winding............................	0.360 ohm

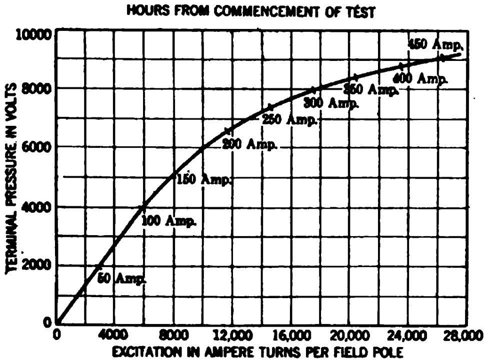


FIG. 4—NO-LOAD SATURATION CURVE OF 12-POLE—8750-KV-A.—6600 VOLT—500-REV. PER MIN.—THREE-PHASE GENERATOR

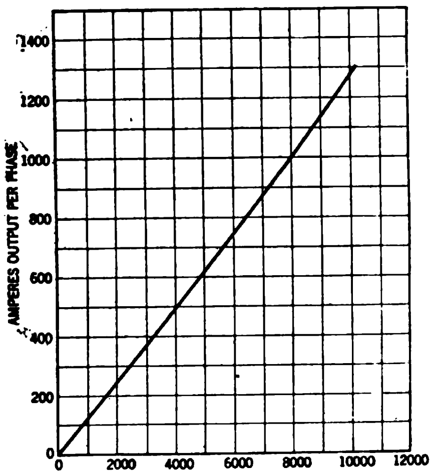


FIG. 5—SHORT-CIRCUIT EXCITATION CURVE OF 12-POLE—8750-KV-A.—6600-VOLT—500-REV. PER MIN.—THREE-PHASE GENERATOR

The value of the internal windage was estimated to be 30.0 kw.

The extent of the equivalence to the actual losses for the three loads is seen from the data in the following table:

†Section 432 of the American rules is to the effect that "the efficiency, of all loads, of all apparatus, shall be corrected to a reference temperature at 75 degrees."

HEAT RUN I

	Losses during the:		Average losses during cyclic test	Losses corresponding to actual load of 7000 kv-a. at at P.F. = 1.00
	Open-circuit half of the cycle	Short-circuit half of the cycle		
Stator $I^2 R$	0	24.0	12.0	12.5
Rotor $I^2 R$	38.5	5.1	21.8	17.8
Core loss	270.0	0	135.0	119.0
Stray-load loss	0	18.0	9.0	11.5
Internal windage	30.0	30.0	30.0	30.0
Total loss =			207.8 kw.	190.8 kw

HEAT RUN II

	Losses during the:		Average losses during cyclic test	Losses corresponding to actual load of 8750 kv-a. at P.F. = 0.80
	Open-circuit half of the cycle	Short-circuit half of the cycle		
Stator $I^2 R$	0	37.8	18.9	19.4
Rotor $I^2 R$	38.5	7.9	23.2	27.9
Core loss	270.0	0	135.0	119.5
Stray-load loss	0	25.5	12.8	15.3
Internal windage	30.0	30.0	30.0	30.0
Total loss =			219.9 kw.	212.1 kw.

HEAT RUN III

	Losses during the:		Average losses during cyclic test	Losses corresponding to actual load of 10937 kv-a. at P.F. = 0.80
	Open-circuit half of the cycle	Short-circuit half of the cycle		
Stator $I^2 R$	0	60.0	30 0	30.5
Rotor $I^2 R$	38.0	12.4	25.2	32.6
Core loss	260.0	0	130.0	120.0
Stray-load loss	0	42.3	21.2	21.5
Internal windage	30.0	30.0	30.0	30.0
Total loss =			236.4 kw.	234.6 kw.

The temperatures of the circulating air were determined at the inlet and outlet from the mean of the readings of several thermometers. The results and the "loss per degree air rise," are given as follows:

Designation of heat run	Total loss in machine	Air rise in machine	Loss per degree air rise
I	208 kw.	12.4 deg.	16.8 kw.
II	220 kw.	13.0 "	16.9 kw.
III	236 kw.	15.5 "	15.3 kw.
Average value for loss per degree air rise			16.3 kw.

It can fairly be assumed for this particular design that the heat corresponding to 90 per cent of the loss in the machine is

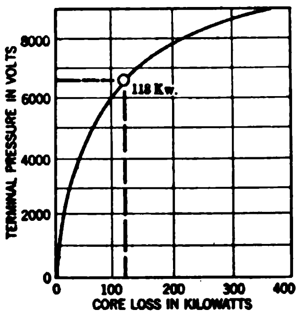


FIG. 6—CURVE OF CORE LOSS OF 12-POLE—8750-KV-A.— 6600-VOLT —500-REV. PER MIN. THREE-PHASE GENERATOR

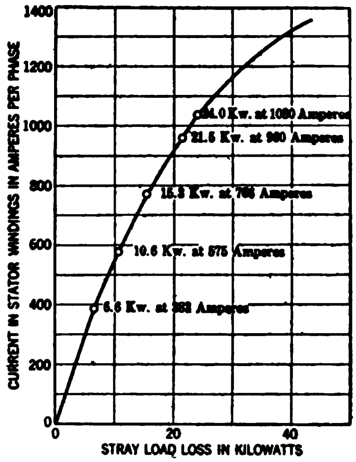


FIG. 7—CURVE OF STRAY LOAD-LOSS OF 12-POLE—8750-KV-A.—6600-VOLT—500-REV. PER MIN.—THREE-PHASE GENERATOR

carried off by the circulating air, the remaining 10 per cent being dissipated from the surfaces of the machine.

Therefore we have, as carried away by the circulating air:

$$16.3 \times 0.90 = 14.7 \text{ kw. per degree rise.}$$

One kilowatt raises the temperature of 1000 cu. ft. of air per minute (0.47 cu. m. per second) by 1.78 deg., or:

A temperature rise of 1 deg. will be occasioned by a loss of 1 kilowatt for a circulation of 1780 cu. ft. per min.(0.84 cu. m. per second).

Consequently we have:

Quantity of circulating air = 14.7 × 1780 = 26,200 cu. ft. per min. (12.4 cu. m. per second).

In the following table are brought together for the three heat runs the results obtained by the embedded temperature detectors in the locations designated by A and B in Fig. 1, and also the results for the mean of A and B.

Designation of heat run		I	II	III
Total loss in machine		208 kw.	220 kw.	236 kw.
Temperature rises by embedded detectors	Location-A.	33.0 deg.	36.0 deg.	41.5 deg.
	Location-B.	26.3 "	28.8 "	29.3 "
	Mean of A & B.	29.7 "	32.4 "	35.4 "
Loss per degree of mean rise		7.00 kw.	6.80 kw.	6.70 kw.
Average for the three heat runs for the loss per deg. of mean rise		6.83 kilowatts		

It is to be noted that by mean rise by embedded detectors is meant the mean of the two maxima, the one being the maximum for location A and the other being the maximum for location B.

The results for these three heat runs by the cyclic method deviate from the average result by less than 3 per cent in the case of the "loss per degree mean rise by embedded detectors" and by only 6 per cent in the case of the "loss per degree air rise in machine." These values speak well for the accuracy of the cyclic test.

These and the temperature rises obtained at other parts are brought together in the following summary in which the results from which the highest "hottest spot" temperatures are deduced, are in heavy type.

Designation of heat run		I	II	III
Kilovolt amperes		7000	8750	10937
Power factor		1.00	0.80	0.80
Terminal pressure (volts)		6600	6600	6600
Current (amperes)		614	766	960
Maximum observed rise by temperature detectors		**33.0**	36.0	41.5
Observed by temperature detectors	In location "A"	33.0	36.0	41.5
	" " "B"	26.3	28.8	29.3
	Mean of A & B	29.7	32.4	35.4
Maximum observed rise of rotor wind-winding		19.0	19.0	20.5
Observed rise stator winding by resistance		**28.0**	**34.5**	**42.0**
Air rise in machine		12.4	13.0	15.5
Deduced hottest-spot temperature corresponding to ambient temp. of reference		78.0	84.5	92.0

It is interesting to note that in heat runs II and III the hottest-spot temperature corresponds to the observations of the rise of

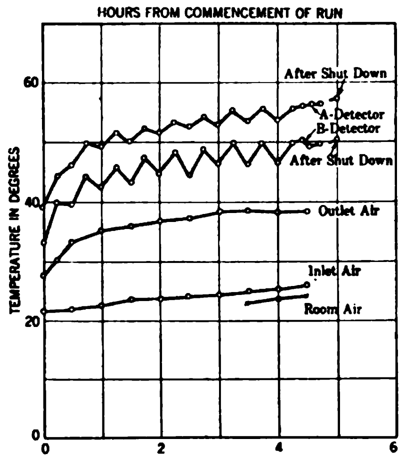


FIG. 8—TEMPERATURE-TIME CURVES FOR CYCLIC HEAT RUN EQUIVALENT TO 7000 KV-A. AT POWER FACTOR = 1.00

the stator winding by resistance and not to the results obtained by the embedded detectors. This is for the reason that the Standardization Rules require 10 deg. to be added to the observed

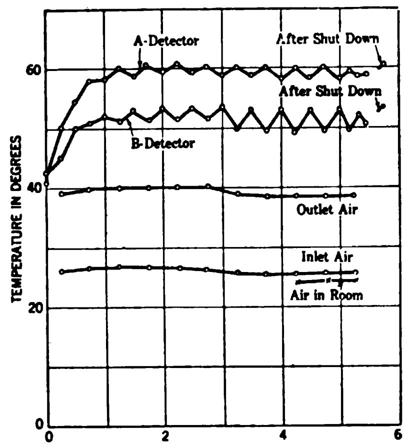


FIG. 9—TEMPERATURE-TIME CURVES FOR CYCLIC HEAT RUN EQUIVALENT TO 8750 KV-A. AT POWER FACTOR = 0.80

temperature as determined by the resistance method and require 5 deg. to be added to the observed temperature as determined from the highest reading of any of the embedded detectors. Such results may occur in machines so designed that no part of the stator winding is much hotter or cooler than the *average* temperature of the stator windings.

In Figs. 8, 9 and 10 are given curves showing the progress of the heating during the cyclic tests.

It should be understood that this paper has been chiefly confined to a discussion of those parts of the temperature sections of the rules which deal with rotating machinery and that even in this small portion of the rules there are various matters of interest and importance which have not been considered. On

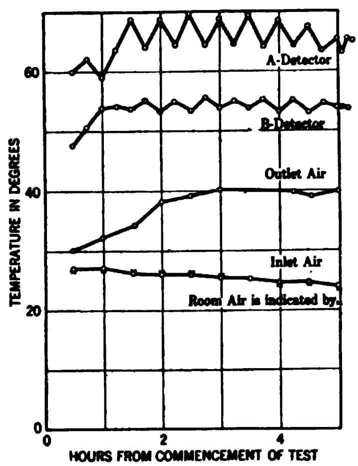


FIG. 10.—TEMPERATURE-TIME CURVES FOR CYCLIC HEAT RUN EQUIVALENT TO 10,937 KV-A. AT POWER FACTOR =0.8

the subject of transformers there are further matters of importance in the temperature sections. The sections on dielectric tests and those on efficiency and regulation present features of at least equal importance as regards both rotating machinery and transformers.

The author entertains the hope that his paper soon may constitute one of several papers by others along these general lines and that by making this beginning he may have promoted in some measure the important undertaking of standardization of electrical machinery.

APPENDIX

A Comparison of the Temperature Limits in the British and the American Rules for Electrical Machinery

In the following collection of Tables the three methods of determining the temperature are designated I, II and III, following the arrangement in the American rules. Briefly these methods are defined in the American rules as follows:

Designating number of method	Designating name of method	Description of method
I	Thermometer method	This method consists in the determination of the temperature, by mercury or alcohol thermometers, by resistance thermometers, or by thermocouples, any of these instruments being applied to the hottest accessible part of the *completed* machine, as distinguished from the thermocouples or resistance coils *embedded in* the machine as described under Method No. III.
II	Resistance method	This method consists in the measurement of the temperature of windings by their increase in resistance, corrected to the instant of shut-down, when necessary. In the application of this method, thermometer measurements shall also be made whenever practicable without disassembling the machine, in order to increase the probability of revealing the highest observable temperature. Whichever measurement yields the higher temperature, that temperature shall be taken as the "highest observable" temperature.
III	Embedded-temperature-detector method	This method consists in the use of thermo-couples or resistance temperature detectors, located as nearly as possible at the estimated hottest spot. When Method No. III is used, it shall, when required, be checked by Method No. II; the hottest spot shall then be taken to be the highest value by either method, the required correction factors being applied in each case.

1.—Limits of Observable Temperature for Class A Materials When Methods I and II are Employed

For these cases the limits are set forth on the first insert herewith.

2.—Limits of Observable Temperature for Class B Materials When Methods I and II are Employed

The second insert sets forth the limits for these cases.

LIMITS OF OB[illegible]

BROAD DESCRIPTION OF THE PART OF THE MACHINE	
Stationary and rotating d-c field coils	[illegible]
Rotating armatures with commutators	[illegible]
A-c. windings in slots (of the ratings for which method III is not required)	[illegible]
Short-circuited windings	[illegible]
Air-cooled transformers	[illegible]
Oil-immersed transformer	[illegible]
Induction regulators	[illegible]
Iron cores	[illegible]

NOTE. Both th[illegible] temperature limits [illegible]

3.—Limits of Observable Temperature for Class A and Class B Materials When Method III is Used

When Method III is used, the limits set forth in the British and American rules are identical and are set forth below for machines of various voltages.

Voltage of Machine	Permissible limits of temperature as measured by embedded temperature detectors			
	Temperature detectors located between top and bottom coil-sides in two-layer windings		Temperature detectors located between coil-side and core and between coil-side and wedge	
	Class A	Class B	Class A	Class B
Not over 5000 volts	100 degrees	120 degrees	95 degrees	115 degrees
Between 5000 & 6000 volts	100 "	120 "	94 "	114 "
" 6000 & 7000 "	100 "	120 "	93 "	113 "
" 7000 & 8000 "	100 "	120 "	92 "	112 "
" 8000 & 9000 "	100 "	120 "	91 "	111 "
" 9000 & 10000 "	100 "	120 "	90 "	110 "
" 10000 & 11000 "	100 "	120 "	89 "	109 "
" 11000 & 12000 "	100 "	120 "	88 "	108 "

Note: Method III, (Defined and discussed in sections 352 to 356 of the American Rules) is, in the American Rules, mandatory for all stators of machines (exclusive of induction regulators) with cores having a width of 50 cm. (20 inches) and over, and also for all machines of 5000 volts and over, if of over 500 kv-a., regardless of core width. The method is not mandatory in the British Rules but section 63 of those rules states that: "When so specified with the inquiry, embedded temperature detectors shall be employed in the case of a machine of over 3000 kilowatts if wound for a rated pressure exceeding 3300 volts."

Presented at the 325th meeting of the American Institute of Electrical Engineers, Philadelphia, Pa. October 13, 1916.

THE POWER COMPANY'S PROBLEM IN THE ELECTRIC SUPPLY FOR LARGE SINGLE-PHASE LOAD

BY WILLIAM C. L. EGLIN

ABSTRACT OF PAPER

The position taken by the power company is that it should be able to supply all needs of energy in the community whether for industrial, street railway or trunk railroad use. The power company must also be able to supply energy of uniform pressure whether single-phase, two-phase or three-phase, at whatever voltage best suits the consumer. These conditions are best met by polyphase generating units, and three-phase units are almost universally adopted on account of the economy in transmission which they permit.

When the demand for single-phase current is heavy enough to produce an unbalance, some means of balancing must be provided in order to prevent reduction in the output of the generator, and also to maintain uniform voltage on all phases. Three methods of balancing are discussed; first, by equipping the generator field with damping devices; second, by the use of a separate machine similar to the three-phase induction motor; third, by means of a synchronous phase-balancer consisting of a two-unit machine, one of which transfers energy between phases and the other balances the voltage. Correction for power factor on each individual large consumer's line is suggested.

FUNDAMENTALLY, the power company should be prepared to supply electric energy for all the uses required in the territory which it serves. The greater the variety of utilization of the power company's service, the greater is the diversity factor—the non-coincident demands within a twenty-four hour period or within the yearly period of operation—which increases and improves both the daily and the yearly load factors, and enables the generating plant to operate more efficiently.

In order that it may furnish service in the simplest way, it is the policyand aim of the power company to select such voltages and frequencies for the generating equipment as are best adapted to meet the requirements of its consumers' apparatus. Practically without exception in this country at this time, the main generating stations of large power companies are equipped to supply polyphase alternating currents, at high voltages and at frequencies of either 25 cycles or 60 cycles.

A word in retrospect:

The power companies' principal business in their earlier period was lighting. The use of lighting is restricted usually to the hours of darkness, so that the period of maximum load was a relatively small percentage of each twenty-four hours. The diversity factor of this load, due to the combination of stores, residences and factories, did not improve the load factor very materially, on account of the occurrence simultaneously of these loads between the hours of four and six p.m., forming a very abrupt peak in the load diagrams, especially during the winter months. The value of a motor load was therefore recognized, because it would be more continuous and because its requirements for power would increase very considerably over the requirements for lighting.

The next logical step in increasing the load factor was the broad position taken by the power company, to supply all of the needs for energy in the community; first, by supplying energy to large industries; then, to the street railways; and finally, to the steam railways in its territory.

Another important and very obvious consideration, from the power company's standpoint, is to operate the plant at its maximum efficiency. This means loading the generating units with the load which will produce the maximum *steam economy* in a steam generating station and entail the minimum investment in plant.

The generating apparatus must be capable of delivering to the consumers, energy of uniform pressure, irrespective of the demands, and the power company must stand ready to supply single-phase, two-phase and three-phase current at any voltage that best suits the individual consumer. These conditions are best met by polyphase generating units; and on account of the economy in transmission, three-phase units are being universally adopted.

The power requirements of individual consumers in a large territory, are of a varied character, demanding a close regulation of pressure through a range of their loads from no-load to full load.

With the balanced three-phase load of a consumer there are no serious difficulties involved, and even with the two-phase load which can be partially balanced by means of T-connected transformers, the difficulties are of little importance, and can be taken care of either by individual automatic regulators on the feeders supplying the consumer, or by regulation of the generated voltage, or by both.

When the demand for single-phase load is heavy, and especially when it produces an unbalance—*i.e.* when a single consumer requires a large amount of single-phase load and it cannot be balanced by other consumers also requiring single-phase load, a number of new problems are presented: The capacity of the generating apparatus is materially reduced, on account of the load being limited by the carrying capacity of the windings in the heavily loaded phase, so that the first problem is to provide some means of balancing the single-phase load, or splitting the single-phase load on the generators, to enable the generator to be operated at its normal output. The second problem is to maintain uniform voltage on all phases irrespective of the unbalancing. There are several methods by which this may be partially accomplished:

First, by equipping the field of the generator with damping devices, which consist of copper conductors imbedded in the core and short-circuited at their ends; this enables the transfer of energy from the heavily-loaded phase to the under-loaded phase. It, however, cannot be an exact balancing of the load and does not permit of the balancing of potentials. When the unbalance exists only in one phase and is fixed, some adjustments can be made which will approximate uniform voltage upon all three phases. The addition of dampers to the generator, however, reduces its efficiency and adds to its size and necessarily to its first cost, and it would probably be necessary to equip all generators in this way. On the other hand, the balancer capacity is added only for the amount of unbalanced single-phase load.

Second, by the use of an external machine connected to the generator, similar in all respects to the three-phase induction motor. By the addition of boosters on each phase, regulation of voltage and also a balance may be effected. When the unbalance exists on one phase and it is known that this will always be the heavily-loaded phase, adjustments can be made in the windings of this rotating machine so as to obtain an average of balance of load and an average of balance of voltage.

Third, by means of a synchronous phase balancer, which consists of a two-unit machine, the function of one unit of which is principally to transfer energy between phases; the other unit is a boosting set with two fields at right angles to each other, which balances voltage. Thus, by use of the combination, there are maintained, uniform energy balance and uniform voltage balance. These fields may be controlled by automatic regulators, and a balanced voltage under wide variations from zero to the full range of the balancer set, may be obtained. Variations in load may occur on any phase, without in any way affecting its satisfactory operation. The operation of the balancer set does not, in any way, affect the economy of the generator. It does permit the generator to be operated at its most efficient load and to carry a full load, irrespective of the unbalance, up to the capacity of the balancer set.

The losses in the synchronous phase-balancer and booster are the usual losses in rotating synchronous apparatus, consisting of the losses in the windings and fields, windage and friction of its bearings. The efficiency of a machine of 5000 kw. is approximately 94 per cent.

As previously noted, two single-phase loads may be partially balanced by T-connected transformers, and naturally three or more single-phase loads may be distributed on the three phases so as to produce the best balancing effect; so that with the increased demands for single-phase load, additional balancer capacity may not be required in a large generating station.

Because of the fact that the balancer apparatus is a synchronous machine, the portion of the unit which is designed to transfer energy, will be made somewhat larger and could be used as a synchronous condenser to improve the power factor of the system.

The principal demand from large consumers is alternating current, either single-phase, two-phase or three-phase, at some predetermined, practically uniform voltage. With varying demands from no-load to full load, good regulation may be obtained by the various automatic devices to regulate the generating voltage on individual feeders. Variation in voltage upon feeders, however, may become excessive with inductive loads. These loads may also produce at the generating station a low power factor, with a consequent under-loading of the generators, reducing their capacity and possibly necessitating their operation at some point lower than their maximum steam economy.

There are great variations in the power factors of individual consumers, depending upon the nature of their loads. As this also prevents the economical loading of the generating units. some means should be provided to correct for power factor, and I believe that each individual large consumer should be corrected for practically unity power factor, and to do this the proper synchronous condenser capacity should be introduced at some point in the consumer's line where the most economical results can be obtained. This, however, will vary very largely with each individual consumer and must be studied in each case.

Presented at the 325th meeting of the American Institute of Electrical Engineers, Philadelphia Pa., October 13, 1916.

SUPPLY OF SINGLE-PHASE LOADS FROM CENTRAL STATIONS

BY PHILIP TORCHIO

ABSTRACT OF PAPER

American central stations, contrary to European practise, have extensively adopted single-phase distribution from polyphase stations, balancing the loads among the different phases by grouping of the single-phase feeders or the distributing substations. Voltage regulation for lighting circuits has been supplemented by individual regulators. Generators with good single-phase characteristics were sometimes employed. In other cases generators were installed of larger kilovolt-ampere rating than the kilowatt capacity of the steam unit.

Large customers, using electric welding machines, electric furnaces, etc., assist the balancing by dividing their load between the two or three phases.

In cases of railroad companies' generating stations, the single-phase power is furnished from three-phase generators of special design. In cases of purchased power from central stations, different methods of supply may be available.

In connection with the supply of service to the Western portion of the New Haven Railroad electrification by the New York lighting companies, four methods were considered contemplating the supply of power—(1) directly from the 25-cycle system busbars; (2) from a separate section of the 25-cycle system busbars; (3) from a 60-cycle station with frequency changers at the delivery point; (4) from special 25-cycle generators installed in the latter station. On account of the requirement of parallel operation with the railroad power plant, the first method would not give the necessary load control. The second method was dismissed on account of the requirements of balancers and also longer transmission lines than the other methods. The third plan necessitated a large investment in special apparatus and gave poor efficiency of conversion. The fourth method was adopted as it gave complete control of the load and voltage, and maximum efficiency of transmission. The larger original investment in new generator capacity was partly compensated for by its value to the companies as a standard equipment for supplying their future demands and other three-phase existing loads in the immediate districts. The equipment is described.

CONTRARY to European practise, the distribution of single-phase currents from polyphase stations is very common in American central station practise. The balancing of loads among different phases has been accomplished by grouping of single-phase feeders on different phases. The exacting requirements of regulation for lighting circuits have been met by supplementing the regulation obtained from the main supply with individual regulators on each single-phase feeder circuit. These circuits feed different districts.

Where the distribution is done from different substations, fed from a generating station, the transmitting lines between generating station and substations may be two- or three-phase, one of the phases carrying the heavy lighting load in addition to its share of the power load, which is equally divided among the phases. In such cases the substations are divided into two or three groups, each group having the heavily loaded phase connected to a different phase of the generating station, so that the loads of all phases are approximately equally divided.

The operation of such systems has never given any inconvenience. In the early years the distributing stations and the individual customers' loads were small, so that there were not presented great difficulties in balancing the load among different groups of feeders connected to different phases. With the growth of the system and the introduction of distributing substations, fed from a generating station, the unbalancing of phases became a problem, because it was not possible to maintain always balanced loads on different phases, notwithstanding the care taken in the grouping of different substations. In such cases generators were secured with suitable field windings and additional copper in the armature to give good single-phase characteristics; in other cases the generators were also built of greater kilovolt-ampere rating than the kilowatt capacity of the steam unit.

As an illustration of the former case, we may cite the 14,000-kw. three-phase, 10,000-kw., single-phase, 60-cycle generator installed in 1906 in the Waterside station of the New York Edison Company. As illustrations of the second case are the three 19,000-kv-a., 60-cycle generators driven by 15,000-kw. turbo units installed in 1913 in the 201st Street station of the United Electric Light & Power Company of New York. In this case the fields of the generators were also provided with damper windings which would permit them to carry 7500 kv-a., single-phase load. With this precaution taken, the station output is not handicapped by low power factor or unbalanced loads, and is capable of taking on a comparatively large single-phase customer without handicapping the generating capacity.

Usually the load unbalancings are only temporary and of relatively high power factor and, therefore, they do not present the same difficulties as when large single-phase loads, often of fluctuating character, are to be supplied. In such cases the customer can greatly assist the central station by dividing his load as nearly as possible between the two or three phases, as it will give a better balanced voltage condition. This is especially true in electric welding, electric furnaces and possibly in single-phase railroad supply. This division of load has been accomplished to good advantage in cases of large industrial installations.

When large amounts of single-phase railway load supply are to be furnished, the railroads have, from the beginning, established the practise of installing three-phase generators to furnish the bulk of the power single-phase, direct from the generators. The generators are of special design. In cases of purchased power from central stations, it may be possible to do away with the special design generators and supply the single-phase loads from the main buses of the power company, if of sufficient capacity, or with the aid of phase balancers or possibly by sectionalizing, on different phases, the railway load.

A very careful study of the most advantageous method of supplying a large single-phase railroad load was made in connection with the negotiations of the New York lighting companies for supplying the New York, New Haven & Hartford Railroad Company with the power for its western end. The conditions of service required the supply of a minimum guaranteed maximum (hourly) load of single-phase power of 6500 kw., at 70 per cent power factor, with momentary peaks of 250 per cent of this load. The supply was to be paralleled with the 35,510-kv-a., single-phase generating station of the New York, New Haven & Hartford Railroad Company at Cos Cob. Conditions for parallel operation were rendered favorable by the existence of two three-phase 11,000-volt lines over which a maximum synchronizing power of 10,500 kw. could be supplied to the lagging station, with approximately 23,500-kw. of power supplied from the leading station.

The supply was to be 25-cycle and capable of controlling its load to maintain a load factor as desired. In addition, the control was to be such as to divide the peak loads with the Cos Cob power station in proportion to the maximum one hour load taken from the respective sources.

The power was to be supplied at the West Farms Junction

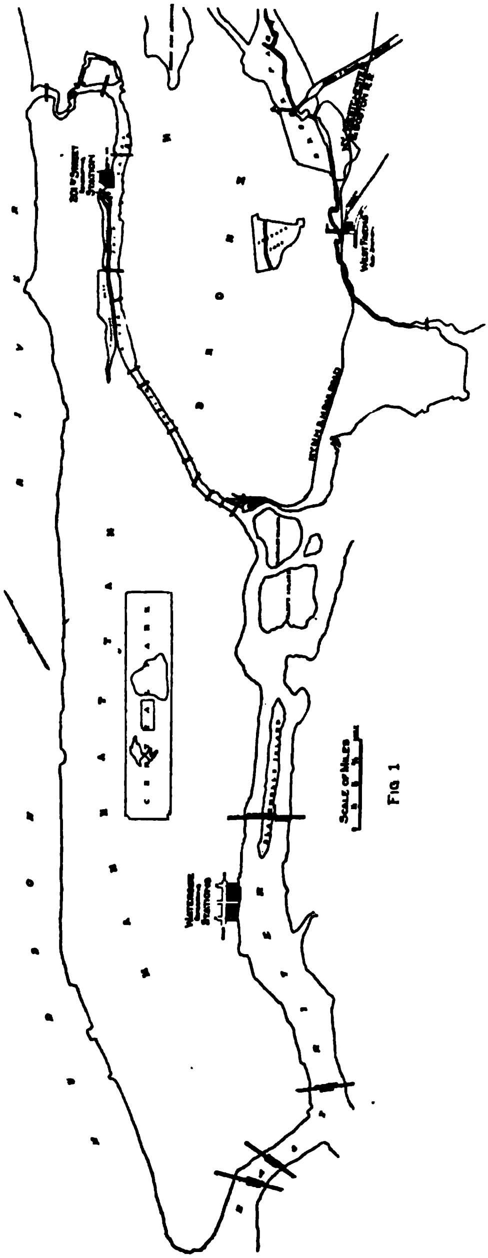


FIG. 1

of the New York, New Haven & Hartford Railroad Company at 22,000 volts, single-phase, with the neutral grounded to the rails, and 11,000 volts, three-phase, for the synchronizing ties. The voltage was to be maintained at this supply point within the limits of 10,500 to 11,500 volts under all conditions of load. The generating capacity that was available for supplying this load at the time of these negotiations was 237,000 kw., 25 cycles, and 22,500 kw. 60 cycles, at the Waterside stations No. 1 and No. 2, located at 40th Street and East River, and 45,000 kw. 60 cycles at the 201st Street station, located at the Harlem River.

The accompanying map, Fig. 1, shows the relative locations of these stations to the proposed point of supply at West Farms. The distance over available duct routes from Waterside station is 9.5 miles, and from the 201st Station 4.5 miles.

With these stations available, the following methods of supply were considered:

I. Power supplied from the Waterside 25-cycle bus which has a generating capacity of 237,000 k.w. operating in parallel. Here the total capacity of the generators would be capable of absorbing the single-phase power without undue heating of the generators.

II. Power supplied from a section of the Waterside 25-cycle bus. In this case the generating capacity operating on this bus section would be comparatively small and phase balancers would be required to balance the load between the phases as the generators were not constructed for supplying a single-phase load greater than 10 to 15 per cent of the capacity of the machines.

In both propositions I and II, the voltage would be stepped up by means of transformers from 6600 to 24,000 volts in Waterside and transmitted at this voltage over 24,000-volt cables to the West Farms Junction of the New York, New Haven & Hartford Railroad.

III. Power supplied from the 201st Street 60-cycle station transmitted at the bus voltage of 7800 volts, three-phase to the West Farms Junction where it would be converted by means of frequency changers to 11,000 volts, 25 cycles.

IV. Special 25-cycle generators installed in the 201st Street station which would be capable of giving the required single-phase load in addition to supplying other 25-cycle load in this territory. Here the voltage would be stepped up to 24,000 volts and transmitted at this voltage to the West Farms Junction of the New York, New Haven & Hartford Railroad.

On studying these four propositions it was found that the first method would be impracticable as it would not give the necessary speed control for division of loads with the Cos Cob

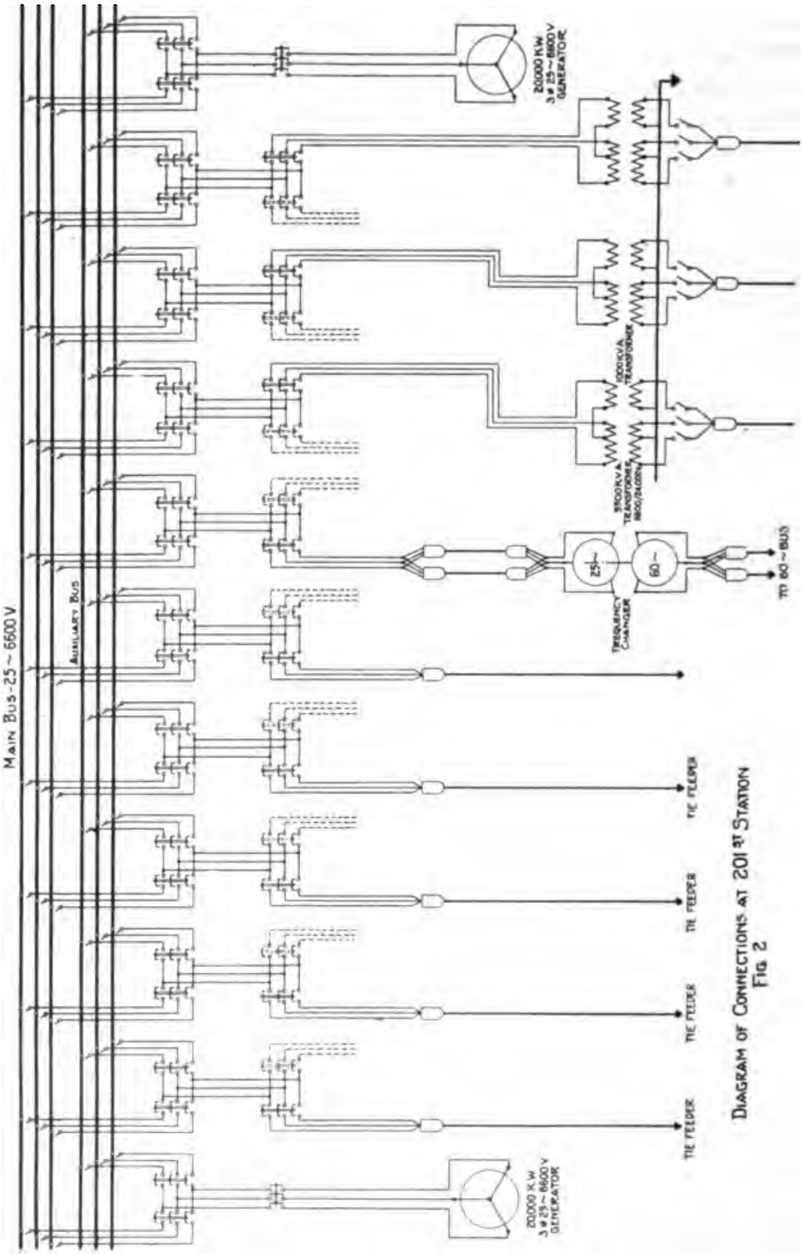


Diagram of Connections at 201st Station
Fig 2

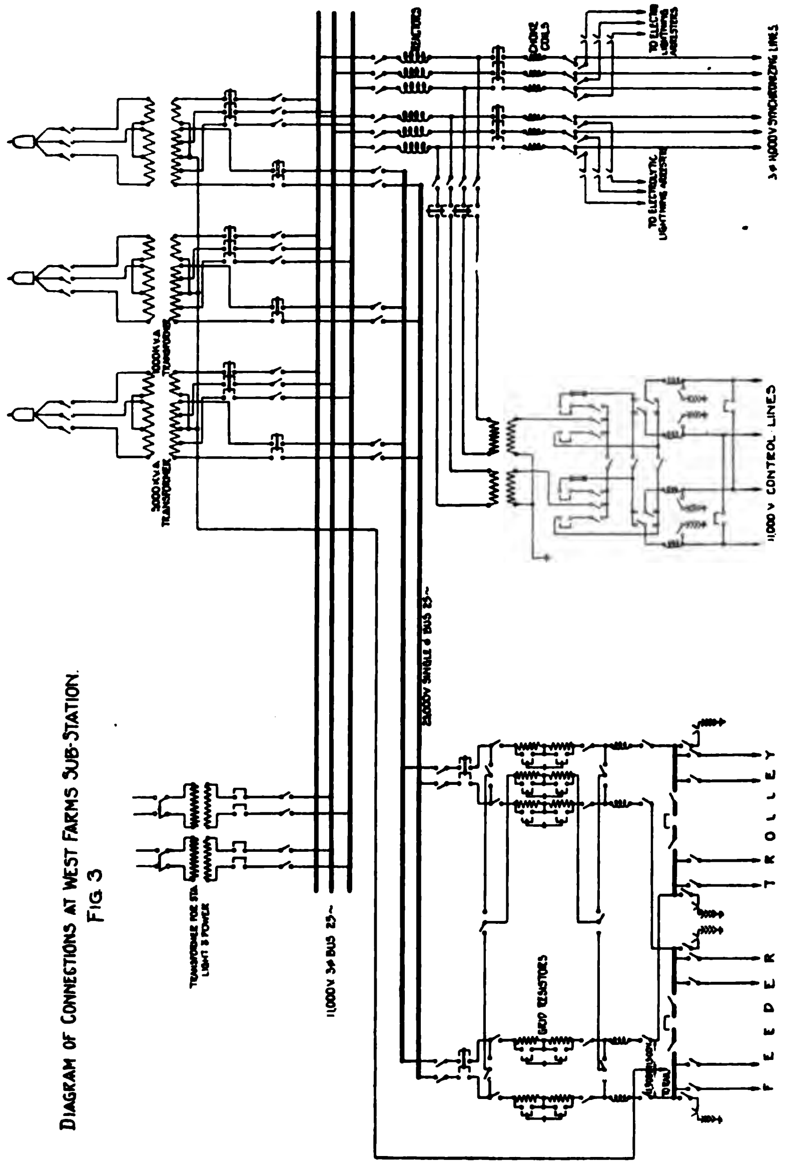


DIAGRAM OF CONNECTIONS AT WEST FARMS SUB-STATION.
FIG 3

station. It would also not be possible to regulate the voltage supplied without the installation of an expensive regulator for this purpose.

Method II required the installation of phase balancers which was a new type of apparatus and had not been worked out by any manufacturer. The cable lines would be very long and expensive, and there would be no available space in the Waterside stations for installing the transformers and phase balancers.

The layout in method III had the advantages of taking three-phase power from the existing buses and therefore involving the minimum station investment, but the frequency converters would be costly and uneconomical, and limited in application exclusively to this service. In addition they would require an expensive substation for their installation at the West Farms Junction. Also, in order to give the load control, it would be necessary to have the motor of these frequency changers variable speed with certain specific drooping characteristics for dividing the load in the desired proportions with Cos Cob. Regenerative synchronous converter speed control in connection with rotor-wound induction motors was considered for this purpose in order to increase the efficiency of the conversion. This introduced a complicated and rather expensive system of supply.

Method IV seemed to offer the greatest number of advantages as it would give complete control of the load and voltage with a short transmission cable line. While the cost of the new generator capacity required involved a much larger outlay, still it was considered that ultimately such equipment would be utilized both for the railroad load as well as for the company's increasing demands. For this consideration the method proved to be the cheapest when the net results of capital outlay and transmission and transformation losses were considered as part of the cost.

Therefore, when the contract was signed for supplying the New York, New Haven & Hartford Railroad single-phase load, two 25-cycle, 6600-volt, three-phase turbo generators, having a high single-phase rating, were installed in the 201st Street generating station. These generators were rated 20,000 kw., three-phase, at unity power factor, with additional single-phase guarantees of 14,300 kv-a. continuous, after which 17,600 kv-a. can be supplied for seven minutes with a momentary peak of 21,000 kv-a. for two minutes.

The heavy single-phase rating of these generators was made possible by the use of special damper windings in the field poles. These windings were necessary in order to neutralize the pulsating armature reaction of single-phase load. The voltage of these generators was made 6600 volts, this being the company's system voltage.

In addition to the supply from these two generators, a frequency changer was connected between the 25- and 60-cycle buses in the 201st Street station. This 25-cycle bus can also transmit or receive power from the Waterside station through four 6000-kv-a. existing tie lines supplying power in the neighboring territory.

The power is stepped up in the 201st Street station to 24,000 volts by three 5500-kv-a., single-phase transformers, with 1000-kv-a. teaser transformers supplying the third leg. This gives a capacity of 11,000 kv-a., single-phase, with one bank and cable out of service, with sufficient three-phase capacity for holding the two generating stations in step during times of trouble on the single-phase lines. All transformers and cables are capable of giving 50 per cent overload for one hour following the full-load run, with a final 100 per cent overload for seven minutes and 150 per cent for one minute.

Figs. 2 and 3 show diagrammatically the method of connections in the 201st Street generating station and the West Farms substation where the connections are made to the New York, New Haven & Hartford Railroad lines.

This supply has now been in operation for fourteen months and has been continuous from the start without any interference or difficulty.

The above description of this supply is made very general as the details have already been published in the technical press.*

*_Electrical World_, Vol. 66, No. 24, 1915, Page 1300 and Vol. 66, No. 25, 1915, Page 1365.

Electric Railway Journal, Vol. 46, No. 25, 1915, Page 1200.

DISCUSSION ON "THE POWER COMPANY'S PROBLEM IN THE ELECTRIC SUPPLY FOR LARGE SINGLE-PHASE LOAD" (EGLIN), "SUPPLY OF SINGLE-PHASE LOADS FROM CENTRAL STATIONS" (TORCHIO), PHILADELPHIA, PA., OCT. 13, 1916.

W. S. Murray: In the days of the not distant past, there can be found commentary very unfavorable to the system of single-phase traction, based upon whether that power, supplied from central stations of polyphase design, brought about unbalanced bus-bar voltages.

My negotiations for the 40,000,000 kw-hr. of single-phase current now supplied by the New York Edison Company to the New Haven road, were effected through Mr. Torchio, and the electrical construction details necessary to such a supply were perfected under joint co-operation of the engineering departments of the two companies. There have been no disappointing features in practical operation to mar the excellent operating results which we anticipated, and as outlined in the contract guarantee of power supply.

The safe and sane construction and regulation features of the power supply, bearing in mind the necessity of perfect continuity of service, in combination with synchronous operation with our own power station, have made this western supply to our electrification zone a most valuable adjunct.

Ten years ago the New Haven engineers elected the single-phase system of propulsion as properly applicable to the New Haven conditions and at that time it, of course, was necessary to decide on the phase characteristics of the generators to be installed in the power station, its location at Cos Cob, Conn., having been determined as the economic point for power distribution. In these earlier days the copper clad dampened field was not in vogue and as pointed out before, central stations would have looked askance at the proposition to furnish from their bus bars, a single-phase load in the amount necessary to the New Haven's requirements, on account of its unbalancing terminal voltage effect. The New Haven, therefore, had to solve this problem incident to its own power generation, and I think I can say that the cost to us of its solution was, for our own and for posterity's sake, a valuable investment. At this point it is of interest to say that what was immediately apparent to the engineers of the New Haven Road was the fact that the best economies of power house generation demanded balanced loads in the phases of the generators, while the exact reverse and controlling condition prevailed outside of the power house, in that the most economical distribution of line load could be effected by maintaining one phase over the entire system; thus the power house had to bow to the line.

The interesting step, however, that followed was not the selection of single-phase generators, but three-phase generators. I will not repeat here, what may be found in the archives of other papers in the Institute, regarding our early troubles incident to the unbalanced effect of single-phase generation by polyphase machines; these have been conquered by the copper clad field, and notwithstanding our three-phase machines are loaded to the extent of 80 per cent single-phase current, they are at the same time distributing three-phase current with terminal voltages, the maximum unbalancing of which is not greater than 15 per cent under average conditions. Anticipating that you may be interested in what the actual unbalances are, there follows readings which I had taken this week at Cos Cob station.

Cos Cob Peak Loads

Time	Phase Voltages			Load kw.
	1-2	2-3	1-3	
5:33 P. M.	12200	11600	13400	16000
5:36 "	12100	11600	13400	16500
5:38 "	12100	11700	13700	17000
5:42 "	12100	11600	13600	18000
5:48 "	12100	11500	13700	18000
5:54 "	12200	11600	13800	19000
6:08 "	12100	11500	13800	21500
6:16 "	12200	11500	13800	20000
6:22 "	12200	11500	13800	20000
6:39 "	12200	11500	13900	24000
		Cos Cob Low Loads.		
1:42 A. M.	11700	11800	13500	5500
2:02 "	11900	11500	13300	4500
2:08 "	11900	11600	13000	2700
2:13 "	11900	11700	13100	3800
3:21 "	12300	11500	13000	2900
3:25 "	12300	11600	13000	3300
3:38 "	12300	11700	13000	2900
3:46 "	12300	11700	13000	3300
3:49 "	12200	11600	12900	3400
3:57 "	12300	11600	13100	3000

As Mr. Torchio has pointed out, the matter of unbalanced effects due to the supply of single-phase loads is no longer of real moment. There are many situations where the unbalancing effect (as in the case of the New Haven supply), without any other correction than that resulting from the operation of copper clad fields, is entirely satisfactory. For example, the three-phase current as supplied from our generators previously described, is used in lighting our stations and for the operation of synchronous motors and converters, operating in the substations of railway and lighting companies adjacent to our property.

If further refinement, however, in regard to unbalanced voltages is required, static or rotary balancers may be used. In every instance, however, the conditions of power supply should be especially studied. While making a special installation for the New Haven conditions, it is pointed out that this same equipment is practically standard and applicable to placing power on the buses of the station for general distribution, as demand may require. Other stations might demand a more perfect balance of terminal voltage on the three phases to be continually maintained on the busses of the power station, while supplying single phase from two of the phases. This can be accomplished through the medium of a balancer as brought out in Mr. Eglin's paper.

Peter Junkersfeld: I would like to call particular attention to the first paragraph in Mr. Eglin's paper, and particularly the first sentence.

He says, "fundamentally the power company should be prepared to supply electric power for all the uses required in the territory which it serves."

The remainder of his paper, and also Mr. Torchio's paper, shows one notable instance in which that has been done, and also points out the four different methods that were considered and the reasons that govern the final adoption of the one that was selected.

The general public who ride on the steam cars, who ride on the surface, elevated and subway cars, and who use electric service for light and power, are, after all, in the last analysis very largely one and the same; so that, if anything is done in an uneconomical manner, in any one of those branches, it to a certain extent involves the same people.

Certain of these uses for electric service come at one hour of the day and month, and certain other uses at another time of day and month; so that, if the fundamental statement that is made here is followed out, and followed out to the full, it results in the best economy for all concerned. That applies not only to the particular engineer who buys and installs the equipment, but also to the engineer who designs and manufactures the equipment.

These papers refer principally to the supplying of railway power in large centers from very large stations.

I think we all feel that ultimately the use of electric power will be very extensive, and that power will have to be supplied through widley scattered areas; and also that full consideration must be given to the dollars already invested, and these dollars used as far as practicable:

That, then immediately brings up certain further questions in the design of apparatus and the design and construction of lines. It will probably resolve itself into practically state-wide transmission.

In state-wide transmission it will be possible to connect up large sources of power, and take advantage of another fundamental factor, which, for the moment, we might call "capacity diversity," particularly in a large territory where there is a certain source of steam power or water power available.

There are a great many areas in this country where the water-power supply in the summer is very low, possibly within 50 or 100 miles (80.4 km. or 160.8 km.) of some place where there is a certain source of steam power supply, which has an excess of supply in the summer and a shortage in winter. Those two sources should help each other. The state-wide transmission lines, it might be conceived, could be used for the purpose of interchanging power between sources as well as delivering power to the steam railroads along their route.

That will mean that the balancing machines would probably have to be put at the points where the steam railroad supply is taken off and taken away from the state-wide transmission line.

D. B. Rushmore: The necessity for single-phase railway loads is an open question. There are, however, other single-phase loads which, under present conditions, are inevitable, and amongst the most important of these is the electric furnace. It would be interesting to hear from Mr. Eglin and from Mr. Torchio, what on their respective systems they would consider the maximum capacity of single-phase arc furnaces which would be permissible, these having a power factor of between 75 and 85 per cent.

The two systems outlined in the papers are different in respect to the overlapping of loads. Where single-phase generators are used the overlapping of loads comes only on the boiler equipment. On the other system, the single-phase electric load is transformed into a three-phase load on the electric circuits, and the possibility of obtaining desirable overlapping is very much greater.

It will also be interesting to know what is the minimum load for which single-phase generators would seem desirable.

L. E. Imlay: We have no single-phase problem at Niagara Falls. We have no single-phase railways.

It is true that we operate a number of furnaces on single phase, perhaps 2000-kw. capacity is the largest, but our sub-stations and our switch stations are so arranged that these furnaces can be changed from one phase to another.

Our customers are so glad to get power that they are willing to take it not only when we want them to, but they are glad to put it on any phase that we ask them to put it on, so that, we have had no trouble whatever from unbalanced loads.

H. R. Summerhayes: While 2000 kw., as mentioned by Mr. Imlay may not be a large single-phase load to put on the Niagara system, it would be a very large load, and rather disconcerting in its effect on a small system; and it is quite possible that a balancer of the type used in Philadelphia could be applied with good effect where a single-phase load of 2000 kw. was to be taken from a comparatively small system.

When we get to as small a load as 2000 kw., however, the question of the comparative cost of the balancer and of the single-phase motor generator becomes interesting, and I should say that at that point there would be considerable question whether the balancer would generally be cheaper than the motor, The balancer, however, would probably be more efficient, even in that size.

In larger sizes I believe that Mr. Doherty intends to present some figures indicating that the balancer is both cheaper and more efficient, hence its adoption by the Philadelphia Electric Company for this single-phase railway problem.

The balancer will have an application also in this way: that furnace loads need no longer be limited to 2000 kw.

Larger single-phase furnaces may be used if machines of the character of this balancer are used with them.

In Mr. Torchio's paper, this explains very clearly the reasons why single-phase generation was adopted, and there are undoubtedly advantages in having these single-phase systems entirely separate from the general three-phase supply of the New York Edison Company.

It is possible, however, that by the addition of a balancer, the two systems could be tied together, gaining somewhat in load factor. That is, the diversity factor would be improved.

N. W. Storer: It is very gratifying to note that the problem of applying single-phase power which has been presented to the central station companies has been met so satisfactorily.

We have two instances here, one in New York and one in Philadelphia, where the same problem has been met in two different ways, and both of them are giving entire satisfaction to the power users, and to the central station companies.

The question that is going to be the most interesting to the future users of power is, what is it going to cost to produce single-phase power in large blocks?

Is it going to cost more than three-phase power, and if so, how much, and at what load does this different cost begin?

E. H. Martindale: I would like to ask what power factor is obtained on single-phase railway load, with and without the balancing set, and also whether the use of damping coils has any effect on the power factor?

E. F. W. Alexanderson: If I understand the question correctly, it is whether the use of a balancer improves the power factor of the single-phase load, so as to make it more adaptable to the three-phase power system.

If desired, the balancer can be made to act as a synchronous condenser.

That question was considered in designing the balancer for Philadelphia, and it was concluded that it was better to design these machines exclusively as balancers; in other words, having the function only of converting power from single phase into polyphase, but not to correct power factor.

The power factor correction is being accomplished on the single-phase line with condensers when the load is high enough to require it.

John L. Harper: In the days when property existed in water rights, and water power was available at Niagara Falls, New

York, for the benefit of industrial interests of the country, we used to sell power for $20.00 per horse power per year.

Within the last few months we had calls for amounts of power ranging from 5000 to 25,000 horse power, which we could not furnish. Power asked for in some previous calls has now been obtained in other places, because we could not furnish it in a single-phase form.

The motor-generator set would impose relatively high losses upon a customer in making the change, and certainly much greater loss than would have been obtained if the power were changed by this new system of phase rearrangement. I understood the previous speaker to say that 94 per cent efficiency could be obtained, or a maximum loss of 6 per cent would be the greatest that could occur in an apparatus of this new form and, if such is the case, it would mean that a customer purchasing power from us would now only be under a handicap of $1.20 per horse power for getting his energy changed from three-phase to single-phase. At least in one case within my knowledge, a customer has gone elsewhere for power, where, it is reported, he could get it for $21.60 per horse power.

If this new apparatus really shows the efficiency that has been stated here, this customer could have stayed at Niagara Falls and received the benefit of a lower price than he could get if he moved elsewhere, and would not have had to duplicate his plant.

The large amounts of electric furnace power that are now being demanded, especially in the production of artificial abrasives, make this problem not only of interest from an engineering, but also from a financial standpoint.

H. W. Buck: I would like to ask whether it was not possible for the prospective customer to balance his load between the three phases. Why was it necessary to put the whole load on a single phase?

John L. Harper: The power which was demanded from us could not be used in three separate loads; the customer wanted only power enough to begin with to take up one or two of the three phases. To make the balance delivery from our lines, in this case where the customer's furnaces were approximately 2000 kw., it would have required the customer to have always increased his use of power in blocks of 6000 kw., which is much greater than the ordinary industrial development wishes to take at one time, preferring rather to enlarge in smaller increments.

H. W. Buck: It seems to me, in this connection, that with the rapid development of the electric furnace and furnace loads on central stations, power companies should take a very strong stand in insisting upon the balancing of such furnace loads between the various phases of the power system, and should try and force the electrochemical customer, as far as possible, to adopt this method of operation.

If the power companies simply swallow any single-phase proposition, however large, which may be thrown on one phase of their system by a customer, and then undertake to overcome it by installing a complication of balancers, trouble will result from the additional expense and additional complications. These balancers should be avoided wherever possible.

J. E. Kershner: I would like to ask for a little information on the manner of balancing fields controlled by automatic regulators.

I did not see how you could take fields of different phases and balance them—just what does that mean? You could not very well do that on an ordinary generator.

C. F. Scott: Something has been said of rather taking it for granted that the balancer is needed.

Looking at the question broadly, is the balancer needed?

Is it a universal panacea, or does it apply to certain specific cases?

The problems that have been presented are those of the larger sort. Most of the gentlemen who have spoken have been connected with three of the largest central stations in the country or with Niagara Falls, or the largest single-phase railways.

What may apply there, and some of the recommendations that Mr. Eglin has made, I think will be found to apply to the larger consideration of power and its distribution.

Broadly speaking, and to take a different position from the position which has been presented, is it not better to do away with balancers and auxiliaries and to meet the single-phase requirement in the generator itself?

As an illustration of what I mean, the synchronous condenser for power-factor correction has been looked upon as a great thing for increasing the capacity of a generator.

If for example a certain load is 1000 kv-a. at 60 per cent power factor, we have two alternatives, (a) a 1000-kv-a. generator to operate at 60 per cent. power factor or, (b) a 600-kw. generator supplemented by a 800-kv-a. synchronous condenser. In the latter case the aggregate capacity is 1400 kv-a. If there be a transmission line, its cost will be less if the synchronous condenser is placed at the load end, thus compensating for the extra cost of machinery.

If we can, by increasing the size of the generating unit, secure the capacity for supplying single-phase power, will not that be simpler than the addition of auxiliary apparatus?

We will be adding to the size of an already large unit where the cost for the additional kilowatt capacity is relatively small.

The power lost in a single power generator will generally be less than is required when there is auxiliary smaller apparatus. The attendance is less.

These remarks may not apply to the specially large cases which have been mentioned, but they certainly, I believe, will be applicable to smaller stations and smaller power units.

Again, two distinct cases arise, reconstruction and new construction. If a generator is now installed its capacity may be increased in the simplest way by the addition of a synchronous condenser or by a phase balancer; but if the construction is not new, it might be simpler to simply add to the size of the initial machine.

Take the cases brought out at Niagara Falls; The present generators are inadequate for a certain single-phase load. Those generators might be aided by auxiliary apparatus, but for new construction, would it not be simpler to add fifty per cent or whatever might be necessary to the size of those generators for the single-phase capacity required.

Fluctuation of the single-phase load is a factor which has not been brought out. The loads to which Mr. Imlay referred, which ran along so quietly, may relate to a certain type of furnace, which takes a substantially constant output for 24 hours.

Mr. Murray does not supply that kind of load. His is the other kind, up and down, in which the kind of regulation and method of providing the generating apparatus might be quite different.

Mr. Eglin suggests that each customer might be required to provide a power-factor regulator, so that there would be 100 per cent power factor to each individual customer.

There again, you must be implying customers who require a very large amount of power on a very large scale; and even then it seems to me it would be open to question, without an examination of the particular circuits, whether it would not be better in the central station to provide for supplying certain loads at the lower power factor than it would be to add synchronous apparatus over the system on each customer's premises for the adjustment of power factor.

Unless units are quite large it would certainly be better to have that general control in the hands of the central station than to have the regulation of the system somewhat under the control of each individual customer.

W. C. L. Eglin: Mr. Summerhayes says that there is a possibility of the motor-generator set being substituted for the balancer set. We do not believe that, from a central power company standpoint.

Mr. Junkersfeld stated that the power company must be ready to supply customers with any kind of requirement, whether they are big, or whether they are little. If we could have all of the load at unity power factor the balancing feature would be very small; that is, our troubles would be about cut in two, or probably more.

A central station power company has two things to consider; first, that it has got to buy its apparatus at the lowest price; second, it has got to get the most economical apparatus.

Now, Mr. Torchio just hinted at the possibility of designing generators for something less than unity power factor. If you do that, somebody will want a factor of 50, 60 or 70. You will have no uniformity, and no standard at all. You have got to begin somewhere, and the right place to begin it seems to me is at 100 per cent power factor, so that you can specify your machines to be operated at 100 per cent power factor, and you have got your system economized for load all the way up and down. Then, if you can load your machines at their proper load, you can generate at the maximum economy.

Next is the problem which affects the distribution of the energy to the consumer. Here again trouble comes in from the power companies' point of view. What is the character of that power?

If there are very rapid fluctuations in load, it requires certain methods of handling, or if it is a bulk power, such as five or six thousand kilowatts, it may be divided and you have no unbalanced condition to treat at all.

On the other hand, if you are installing balancer capacity, you put in balancer capacity only for the average unbalance of your system. As your single-phase loads grow the balancer capacity is not increased, that stays the same; so that you do not have to add either expensive alterations to your generators by making them larger, and adding dampers to them. You have your generators as efficient as they can be made. You only correct for the average condition. The more consumers you get the better off you are.

I would not worry the least bit about any furnace that I have heard mentioned today, because we are taking care of 20,000-kw. single-phase swings without any trouble at all, so that even with a very small power factor I would certainly not advise— I would not recommend the introduction of a motor-generator set, because the next customer who comes along has got to have another generator set; you cannot balance them very well, and you are adding to your investment cost. As I said before, what we are really aiming at is to keep our investment cost as low as possible.

Another question was asked with reference to the balancing of the fields.

I said the function of the booster was to balance the voltage.

There are two functions of the machine. One is to balance power, and the other is to balance voltage; and the purpose of the two fields is to compensate all of the three phases for any unbalanced condition of any of them.

Philip Torchio: I think the only direct question was raised by Mr. Summerhayes regarding the reason why we did not supply the railway load from our system bus.

We did not do it because we had to divide, in due proportion, the loads between our plant and the other station of the railroad company. If we had run our 200,000-kw. bus in parallel with the railroad, we would have taken all the heavy swings and introduced complications in the operation of the customer's station, which, after investigation of existing experience, we considered undesirable.

Mr. Summerhayes also asked the question of how a small company, having 1000 or 1500-kw. load, should take care of a prospective customer having a 2000-kw. single-phase load.

Such a company with a small installation of 2000 or 3000 kw. cannot handle 2000-kw. additional load without additional generating units; and here is the place to install generators with single-phase characteristics. The balancer or the motor-generator set is all right, if we can do the service with the existing equipment, but if we must install new generating apparatus, don't let us put ourselves in the same position that we are in now, that when a new customer comes along that wants 1000 or 2000-kw. single-phase we must again go to the manufacturers and put their engineers to their wits' ends to find out what they can do to rectify this load for us. Put capacity enough in the generators to take care of a liberal unbalanced load regardless of whether you will also use a balancer or not.

I do not think either, that Mr. Eglin is right when he says that generators should be designed for 100-per cent power factor. A commercial load generator should be designed for power factors lower than unity, at least eighty or eighty-five. We put, in 201st Street, the largest generator we could put on a 15,000-kw. turbine. The manufacturers said originally that they could make it 16, then refigured and went up to 19. We wanted 20, but 19 was the limit that the tensile strength of the material would allow, and we got a 19,000-kw. generator for a 15,000-kw. turbine, which runs at the most economical efficiency at 13,000 or 14,000 kw.; we lose some in slightly lower efficiency in having a larger generator, but we have the use of the full capacity of the unit at all practical conditions of power factor and unbalanced loads, which is more important.

In answering Mr. Rushmore's question—"What is the largest single-phase load we carry?"—The United Company's load is mainly single phase. I think the largest load of one district is at least 7000 or 8000 kw. We have three such single-phase loads, and we have operated them for years, at least ten years. Why should we have special apparatus in our stations to take care of some unbalanced loads, which will add to the cost of the equipment and station operation?

Regarding the handling of single-phase customers, this was pointed out by Mr. Buck. If a customer comes along and says he wants a furnace load of 6000 kw. and we know that he has three or four or five furnaces, we tell him that we will not furnish the service unless he distributes those three or four or five loads on different phases. That is done in different plants with large welding loads and furnace work—there is no difficulty about it; it is a logical, sensible way of solving the problem.

N. W. Storer: I have waited in vain for a reply to the question which I asked as to what this single-phase power costs?

If a power company can produce it—and it has been proven conclusively that they can supply the single-phase load—how much more is it going to cost?

Why should not they furnish single-phase power if the customer is to pay for it?

Farley Osgood: I would like to ask Mr. Eglin to tell us why he prefers purchasing machines at 100-per cent power factor, as against what you can conceive to be the probable average power factor per cent of his system as a whole, which is the practise at present with some companies?

C. F. Harding (communicated after adjournment): For many years we have been familiar with the advantages of a large diversity of load and a high load factor upon a power station furnishing either railway or lighting and power service. The very effective results obtained during the last few years by the Commonwealth Edison Company in Chicago by the consolidation of these three types of loads upon a single generating system, have made us realize that this same principle of great diversity of load and high load factor may well be extended beyond the individual loads to entire railway and lighting systems.

As an example I wish to emphasize the figures recently presented by an official of this corporation which indicate that the addition of a double peaked railway load, with an hourly maximum demand of 204,000 kw., to a light and power load with a single peak of 156,000 kw., raised the daily load factor from 52.5 per cent to 59.3 per cent. This also resulted in a saving in reserve capacity of 21,000 kw. of equipment over that which would have been required with the loads furnished from separate systems. If the estimated load which will be required by the electrification of the steam railroads entering Chicago be added as well, the load factor for a typical October day would reach 62 per cent.

Is it not possible and desirable therefore, to carry this line of reasoning a step further and secure as much single-phase load and as great a diversity of such loads as possible, provided the consumers demand cannot be met with a polyphase service? With the increase in single-phase traction, furnace loads and other single-phase power demands, not only will the difficulties in balancing a three-phase system with a variety of single-phase loads be lessened, but the load factor of the system will be simultaneously increased as well. It should be kept in mind that practically all single-phase loads which may be secured for a single system are of long hour duration and that the addition of any such loads which make more of the reserve equipment available for greater periods of time, simply results in eliminating fixed charges upon superfluous equipment which would otherwise have to be borne by the consumer.

Such a saving with separate single-phase generators in the station would affect the steam equipment only. With the use of some system which permits single-phase load to be furnished satisfactorily from polyphase generators, the saving in fixed charges is made applicable to the electrical apparatus in the power station as well. Ultimately, if the single-phase load is sufficiently large and diversified, it may be balanced upon the three-phase busses of the substation, in which case the substation equipment and the transmission lines profit by the higher load factor. Thus it seems that the policy of balancing as many varied single-phase loads or portions of such loads as possible upon a single polyphase system, is of importance from the standpoint of saving in fixed charges as well, and that with many large systems the converter and balancer will be considered as more or less temporary expedients to balance the loads during the period of acquisition of a sufficient amount and variety of single-phase loads to permit a permanent balance of the phases by proper distribution of such loads upon the various busses of a three-phase system.

Presented at the 325th meeting of the American Institute of Electrical Engineers, Philadelphia, Pa., October 13, 1916.

SINGLE-PHASE POWER PRODUCTION

BY E. F. W. ALEXANDERSON AND G. H. HILL

ABSTRACT OF PAPER

The general tendency of the electric power supply industry is toward the centralization of power stations, embracing a variety of loads. In order to be consistent with this development it is highly desirable that power stations be standardized in essential features, so that they may combine their resources toward the ideal arrangement. The production of single-phase power should not interfere with this general scheme. Looked at from this standpoint, single-phase power can best be produced from polyphase systems. Means are suggested for producing single-phase power without interfering with the broad usefulness of the power station. The mode of operation and theory of phase converters is discussed with particular reference to its adaptability for permitting single-phase power to be derived from polyphase circuits.

IN VIEW of the universal use by power companies of polyphase generation and transmission of electric power for general purposes, the production and delivery of single-phase power must be considered as a special problem.

No power company would or could afford to install a single-phase plant unless its sole purpose was to furnish power to a load that requires single-phase power. In other words, it is settled that polyphase generation and transmission is most efficient, flexible and economical, and the problem presented to power companies when the demand for single-phase power appears is how this may best be produced or derived from their polyphase systems.

Indeed it may be well to extend the problem to cover those cases where such large amounts of single-phase power are required as to apparently justify a special power house and to inquire whether it might not be preferable in such a case to generate and transmit by polyphase and derive the single-phase when and where needed.

Probably the strongest argument for such a view is the practical wisdom in standardizing the electric systems of the country so that they may be tied together as occasion and opportunity permit with a minimum of elaborate and power-consuming transforming apparatus. This idea of consolidation and cooperation has recently been given serious attention by many of our ablest men who appreciate the great value of diversified loads and the greater economic efficiency to be obtained by covering the greatest field possible from a common source of electric power supply. It is prudent therefore to condition any conclusion that involves power production with the essential requirement that it be consistent with this general tendency.

The rapid growth of electric power systems makes this a most practical consideration. There are enough differences between electric transmission systems as they now exist without introducing still further complications.

Differences in voltages can not be avoided but to equalize this does not entail great loss of efficiency or undesirable features.

Differences in frequency are more serious and the process of decision upon the most desirable frequency for general use has resulted in adopting a variety of frequencies in different localities. As we now look upon 60 cycles as standard, the use of 50, 40, 30, 25 and possibly other frequencies can not but be regarded as unfortunate since practical considerations will sooner or later force the systems having odd frequencies to seek means to free themselves from the handicap they entail. There are many excellent systems and stations using 25-cycle power and the reasons for adopting 25 cycles were good and sufficient when they were established. Without, therefore, criticising the engineering of these plants, it may be stated that they could be duplicated today with 60-cycle apparatus for less than the original cost and with a distinct gain in general economic usefulness and value.

It seems a logical and highly practical conclusion that general policy should be opposed to the establishment to any considerable extent of power systems having peculiar or special features making them inadaptable to efficient connection with other systems in the vicinity.

Single-phase power may be obtained by:

1. Separate generating and distribution systems designed for single-phase load.

2. Polyphase generation and distribution of single phase load between the phases so that in effect the load becomes a polyphase load.

3. Generation and transmission as polyphase with motor-generator sets at substations.

4. Mixed single-phase and polyphase load furnished by the same distribution system in combination with methods for correcting the unbalancing effect of the single-phase load.

The first method comes under the head of special and abnormal development already discussed. It has, besides the disadvantages mentioned, the further disadvantage, as regards the generator, of increased size, weight and cost and lower efficiency as compared with polyphase generators. Single- phase generators have been built only for 25 cycles or lower and to a limited extent for special purposes. As compared with other ways of obtaining single-phase power this method seems to offer the least promise of general usefulness.

The second method has the advantage of the polyphase alternator. It is generally used for incandescent lighting distribution and for power and heating where the unit of energy capacity is small and adapted to division between the phases so as to result in very little, if any, unbalancing. It has been proposed and used to a limited extent for heavy single-phase loads, but the difficulty of preserving even an approximate balance between phases makes this method insufficient for large power requirements. It has the further disadvantage of requiring generators of the same frequency as the load demands.

Method No. 3 has the advantage of entire freedom as to generator and transmission and permits a single-phase load of any frequency or power factor to be drawn from any standard polyphase system without disturbing the balance or regulation. It provides means, moreover, of improving the power factor of the system by synchronous motors and from the power system standpoint is the most desirable of all methods when large unit amounts of single-phase power are demanded. It is the only method of producing low-frequency single-phase power from a 60-cycle system. The only objection that is made to this method is the cost of motor-generator sets and the cost of attendance.

The first cost of equipment, it is true, is greater than static transformers alone, but this is balanced to some degree by lower costs at the power station and in the transmission line, and is fully justified in a large power system since it makes it possible to combine the single-phase load with the general load and obtain the benefit of a higher load factor.

The cost of attendance is frequently made negligible by so locating the substations that the attendants may have other duties. The expense of attendance in any case is a small percentage of operating costs and can be entirely eliminated by introducing automatic devices to start and switch the motor and generator, such as are coming into successful use for direct-current synchronous converters, waterwheel generators and other rotating apparatus.

This disadvantage, moreover, largely disappears when, as usually happens, a system of single-phase generation is connected to other systems through motor-generator sets for interchange of power.

No. 4 is in general respects the same as No. 2 with the addition of a relatively new development known as the "phase converter" which preserves the balance of the system even when large blocks of single-phase power are taken from the system. Its use greatly extends the possibility of connecting single-phase loads directly to a polyphase system provided the frequency does not have to be changed.

The use of phase converters is relatively recent and perhaps not very well understood. This makes it of interest to discuss the method of balancing and the apparatus employed more in detail.

Theory of Phase Conversion

The earliest known form of phase conversion is splitting the phase by inductance and capacity. In this case the energy of one phase is stored for a fraction of a cycle and released again so as to make the same energy active in another phase. All methods of phase conversion, therefor, involve the storage of energy. Even the phase conversion of wattless currents necessarily involves storage of energy. The expression "wattless energy" is not such a contradiction as it has sometimes been claimed to be. When energy is wattless it means that the energy delivered during one portion of a half cycle is returned during the other portion of the same half cycle; therefore the average energy flow is zero. But at the same time, we must not forget that even if a current is completely wattless, there is a real energy flow in both directions. Thus if we wish to change the phase of the current, whether energy current or wattless current, we must provide means for storing the momentary energy flow for a time corresponding to the change of phase that is to be effected.

The method of storing energy in inductances and condensers is very convenient for high-frequency currents but has not up to the present found much practical application for low-frequency power current. There is, therefore, for phase conversion on a large scale, only one type of apparatus that can be considered, a rotating machine which stores the energy in the mechanical inertia of the rotor.

In order to arrive at an understanding of the physical functions of phase conversion with a rotating machine, several different points of view are possible, as sometimes one and sometimes another is more helpful in arriving at direct conclusions. The following three methods of looking at the problem may be helpful:

I—Phase Converter Considered as a Motor-Generator

The phase converter is built as a quarter-phase induction motor or synchronous motor with a squirrel cage; one phase is a motor phase and the other phase is a generator phase. The input of the motor phase is equal to the output from the generator phase, not only in the average value of the power flow but in the instantaneous value of energy flow which is delivered and returned during the same half cycle. The only difference between the energy flow in the two phase windings of the converter is that the momentary values of current, volts and energy is delayed ¼ cycle in one winding in relation to the other. The squirrel cage is the medium for the transfer of energy, and the mechanical mass of the rotor provides the energy storage. In order to make it possible to store the energy in the rotor, there must be corresponding changes of speed and therefore the rotor must go through a cycle of speed change during each half cycle of the alternating current flow. This speed change of the rotor is evidenced by the vibration which is a characteristic of any single-phase machine. The speed change of the rotor has, however, nothing to do with the electrical functions of the machine in performing as a phase converter. If we could couple the rotor to a flywheel of infinite weight so that the speed change would be zero, the converter would perform in the same way.

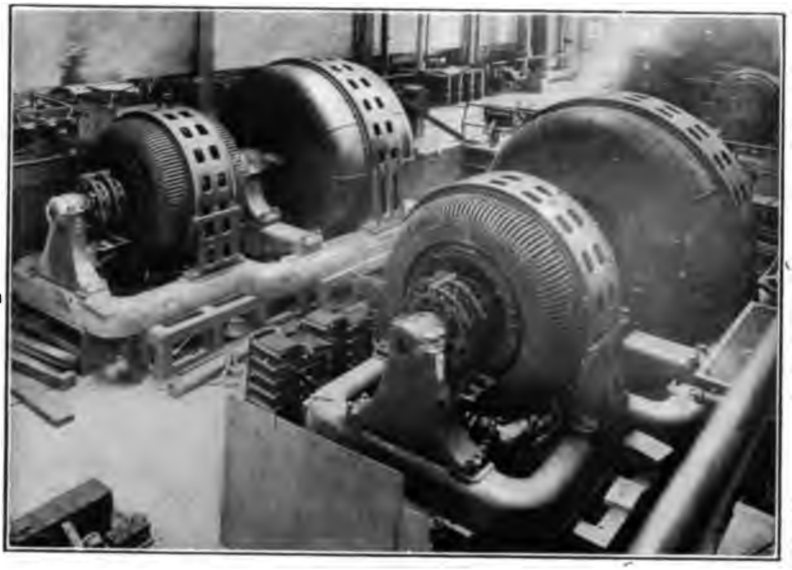
Having thus explained how it is conceivable that the phase converter operates as a motor generator, it remains to explain what means are provided for making it perform in this way; in other words, what causes the energy flow in the two phases to vary the same cycle of momentary values although delayed ¼ cycle in time. Various means can be provided for producing the desired energy flow and will lead to different types of phase converters. Broadly, it can be stated that whatever means are provided, the result of these means must be the desired flow of currents through the windings, and therefore the means must consist in providing the necessary electromotive forces to cause these currents to flow through the windings.

One method of providing these electromotive forces is to use an auxiliary generator which impresses the desired electromotive force on the windings. Instead of a generator any other convenient source of electromotive force may be used, such as a transformer or an induction regulator. Another method is to connect the windings of the converter with reference to the source of power and the load, in such a way that the electromotive forces are furnished automatically by the source of power.

The first method leads to the phase converter connected in shunt to the line and is the type that has been adopted in the phase balancer sets of the Philadelphia Electric Company; for the sake of brevity this type may be referred to as the shunt converter. The function of the shunt converter is to transfer energy from one phase to another in a polyphase system so as to neutralize the effect of single-phase load drawn from the same system in another place. The second method of producing the desired flow of current in the system leads to the series converter. In this type of converter the single-phase circuit is in series with one phase of the converter. The series converter, as applied for changing from single-phase power to polyphase power is described in a paper by one of the authors in 1911. This same arrangement is well adapted for change of polyphase to single-phase power and this method is in some cases preferable to the shunt converter. The function of the series converter is not to correct for a single-phase load that has been placed on a polyphase line but to change the single-phase load into a polyphase load before it is connected to the line.

II—The Phase Converter Considered as a Polyphase Generator

This second point of view is more artificial than the first but is more helpful in analyzing the function of the phase converter. For the purpose of such analyzing, a well-known mathematical artifice is made use of. A single-phase current can be considered as resolved into two polyphase components with opposite phase rotation. One of these polyphase components has the same phase rotation as a power system and constitutes



[ALEXANDERSON AND HILL]

FIG. 1—PHASE BALANCER SETS

a legitimate load on the power system. The other component, which has the opposite phase rotation, is the one that causes the unbalancing of voltage, heating of generators and motors connected to the system, etc. The function of the phase converter is to neutralize this component of the single-phase load which has opposite phase rotation. From these considerations, it becomes evident how the phase balancing can be accomplished. This function consists in providing a machine which feeds into the system a polyphase current which has opposite phase rotation to the system, and is equal and opposite to the component of the single-phase load we wish to neturalize. It is now evident how the phase balancer ought to be constructed. The converter should be a polyphase machine, not necessarily synchronous, but preferably so in order not to draw lagging current from the system, and means are to be provided for forcing a current to flow through the windings of the phase machine which has opposite phase rotation to the system. The currents of opposite phase rotation are to be regulated in magnitude and phase corresponding to the single-phase load. One convenient way of producing such adjustable polyphase currents is to provide a polyphase generator with its field controlled by suitable regulators. These considerations lead to the design of the shunt converter with direct connected balancer and regulators such as used by the Philadelphia Electric Company. The construction of these phase balancers is illustrated in Fig. 1. The sets consist of a main converter and an auxiliary balancing machine which is controlled by automatic regulators. The main converter is mechanically connected to a generator which is called a balancer. The function of this balancer is to circulate polyphase currents of the desired phase and magnitude in the windings of the converter. This auxiliary generator is small compared to the converter because its output is used only to overcome the losses and inductive drop in the windings of the main converter.

III—The Phase Converter Considered as a Transformer

This point of view is also more artificial than the first one but it is helpful in understanding and analyzing the functions of the series converter. The two stator windings of the phase converter are considered as the primary and secondary of a transformer. The squirrel-cage rotor is a medium for transferring the current from the primary to the secondary and the characteristics of the phase converter as a transformer differs from the ordinary transformer only by the fact that the time phase of the secondary is $\frac{1}{4}$ cycle from the time phase of the primary. This displacement of time phase is due to the time required for the squirrel cage to rotate through the angle corresponding to the location of the primary and secondary windings of the stator. The function of the series converter is easiest explained in connection with a quarter-phase system, but it is obvious that it can be used in a three-phase system by the use of a Scott transformer connection. The object in the use of the converter is to distribute the single-phase load equally in the two phases of the quarter-phase system. If the problem were to distribute the single-phase load in two circuits of a single-phase system, it is easy to see how this could be done by the use of a series transformer. The single-phase load might be put directly in series with one circuit through the intermediate of a series transformer. If this transformer has a ratio of 1:1, the current would be equally distributed on the two circuits at all loads. The two phases of the quarter-phase system differ from the two circuits of the single-phase system for our present purpose only by the relative time phase. However, if the phase converter may be used as a transformer which changes the time phase of the current between its primary and its secondary to the desired degree, it can be used as a series transformer between the single-phase load circuit and one of the phases of the quarter-phase system in the same way and with the same characteristics as stated above with reference to the ordinary series transformer used to distribute the load on two circuits of the single-phase system. Carrying the analogy between the phase converter and the transformer still further, we can trace the source of the electromotive force required to force equal and opposite currents to flow in the primary and secondary windings. This electromotive force is derived directly from the primary circuit. To cause a current to flow through a winding requires a voltage and this voltage is evidenced by the impedance drop in the winding. From the theory of transformation, we have become in the habit of regarding the impedance of the primary and secondary windings of a transformer as a single impedance, which for the sake of convenience can be said to be located in either the secondary or primary windings. In either case we assume that a certain amount of the primary voltage is used up to overcome the impedance drop of the transformer windings. This impedance drop is evidenced by the voltage drop on the terminals of the secondary winding. The same considerations apply to the use of the converter as a series transformer. The ratio of current transformation is for all practical purposes constant at all loads at which the transformer can be used. The voltage drop on the secondary side is the sum of the impedance drop in the primary and secondary winding. In the case of the phase converter, the impedance drop includes the drop in the squirrel cage which is the transfer medium. However, we are also in the habit of measuring the impedance of the induction motor windings on the primary side and look upon the impedance in the stator and the rotor as concentrated in the stator winding. We therefore find that the impedance of a converter when considered as a transformer is the same as the stationary impedance of the same machine measured as an induction motor at standstill. From this analogue, we have a right to expect the following characteristics of the series converter and these conclusions are in entire agreement with practical measurements. The change of a single-phase load into polyphase load is automatic and results in a *perfect distribution of current in the two phases at all loads*. The voltage delivered to the single-phase circuit has a slight drop with increasing load and has the same characteristics with reference to current and power factor that would be obtained by placing an impedance in series with the single-phase circuit equal to the impedance of the windings of the converter.

Applications of Phase Converter

In regard to efficiency and size, the phase converter can be considered as being in the same class as the synchronous condenser. In fact it has substantially the same structure, the difference being that the squirrel cage which is usually employed in the synchronous condensers to counteract hunting becomes in the phase converter the main rotor winding, while the field winding of the synchronous condenser is reduced to a small winding sufficient to carry no-load excitation. Due to the similarity in structure the same machine can act as a synchronous condenser and phase converter at the same time if the windings are proportioned for this purpose. The fact that the machines can be designed so that they are useful as synchronous condensers and phase converters simultaneously is worth consideration in the application of the methods of phase conversion, as several methods of application are possible. In the first place, it is possible to place the phase converters either in the power house or at any desired place of the distribution system. Synchronous condensers may be needed on distribution systems for the sake of counteracting low power factor, and such synchronous condensers can, if desired, be designed so that they can in addition be used as phase balancers, in order to make it possible to draw single-phase load from the same system. If, on the other hand, the main load is synchronous converters with unity or leading power factor it may be more practical to locate the phase balancers in the power stations. The single-phase load is usually of low power factor and the lagging current of the single-phase system may be furnished either to the single-phase distribution system by single-phase synchronous condensers or may be furnished in the power house by polyphase machinery after the whole kilovolt-amperes of the single-phase load has been converted to polyphase. In the latter case, the phase converter can be used for power factor correction as well as phase conversion, but in that case it must be large enough to convert the whole single-phase-kilovolt amperes at a low power factor and then furnish polyphase current to correct for this power factor; whereas in the other case where the single-phase power factor is corrected for by synchronous condensers the phase converter needs to convert only the power component of the single-phase load. The choice between these methods of conversion will depend upon local conditions of expediency.

The shunt converter is of particular value in those cases when it is expected that single-phase load may be drawn from different phases of a polyphase system. In such cases unbalancing of the single-phase load will be partly neutralized and it will be necessary to convert only the difference between the single-phase loads. There are, on the other hand, cases where the series phase converter can be used to best advantage. Those are cases when it is desired to convert the single-phase load at the point where it is connected to the polyphase system. The series converter has in that case the advantage of simplicity, as the arrangement is automatic and no auxiliary generator or voltage regulator is needed. In cases where a single electric welding machine or arc furnace is to be fed from a polyphase system, the series converter should be recommended. If such an installation has been made with a series converter in order to insure the lowest first cost and it should be desired to add other furnaces to the other phases, the same converter might be used as a shunt converter without any increase of converter capacity but with the addition of suitable regulating devices.

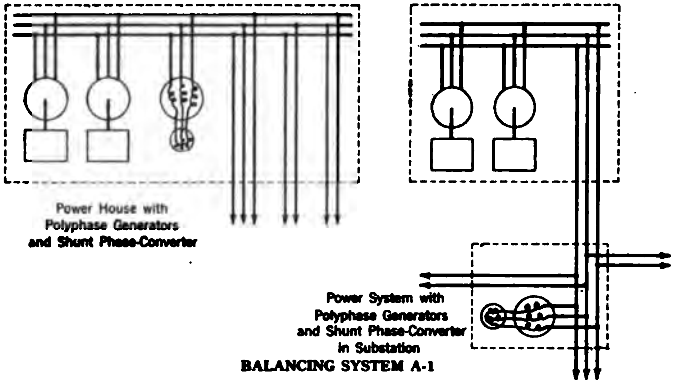
It has been pointed out that a synchronous condenser has a structure suitable for phase conversion. The same is the case with an induction motor or a single-phase turbo-generator, in fact any polyphase machine with a squirrel cage. Such machines are always connected in shunt to the line and would, therefore, be available as shunt converters wherever desired. If, for instance, a power house is built primarily for furnishing single-phase power from single-phase generators. but it is desired to furnish a certain amount of polyphase power in addition, the objection arises that the polyphase voltage is unbalanced in proportion to the single-phase load. In such a case it might be expedient to use the squirrel cage of the turbo-generator as a converter medium by adding suitable regulating devices. The interchange of current between the phases is then already determined by the load conditions, but the electromotive forces necessary to cause this interchange of current appear in the unbalancing of the line voltage. This unbalancing of voltages can be treated with the same method of analysis as given in the preceding for the unbalancing of current. The unbalancing electromotive forces are resolved into their components and the correcting electromotive force may be furnished by a generator driven either from the turbine shafts or by a synchronous motor. This generator has the same character and functions as the auxiliary balancing generator in the phase-converter set. A power house for mixed single-phase and polyphase load equipped in this way can be operated in multiple with other power houses using standard polyphase generators.

The methods that may be employed in order to equip a power system so that it can take on mixed single-phase and polyphase load can be classified in the following groups:

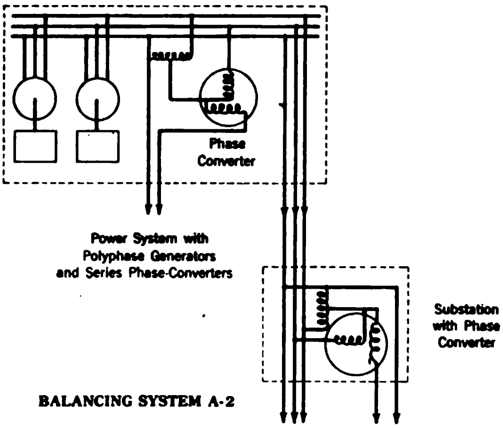
A. The use of standard polyphase generators and phase converters for correcting the unbalanced load. The phase converters may be placed either in the power station or substations and may be

1. shunt converters, or
2. series converters.

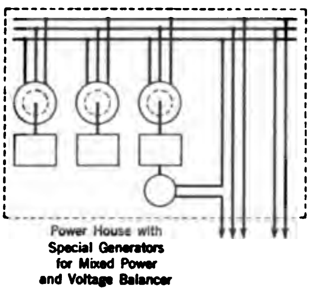
B. The use of special generators with squirrel-cage windings, adapted for mixed single-phase and polyphase load, and an equipment of automatic apparatus to prevent the unbalancing of voltage that the single-phase load tends to produce.



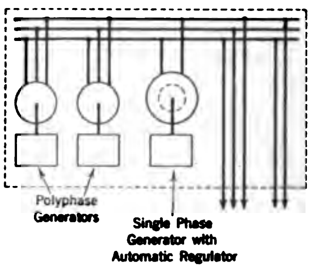
BALANCING SYSTEM A-1



BALANCING SYSTEM A-2



BALANCING SYSTEM B



BALANCING SYSTEM C

C. The use of standard polyphase generators and special single-phase generators connected to the same bus bars with automatic means for regulating the governors and fields of the single-phase generators so that they will absorb the entire unbalancing of the current.

The choice between these three methods of balancing a power system with mixed load will depend upon local conditions and general expedience. All three methods have the advantage of avoiding duplication of the transformation and distribution system. The first method involving the use of the phase converter introduces the least change in standard polyphase power systems and is adapted for the cases where the polyphase load is predominant. The second method is adapted for cases where the single-phase load is predominant, and has the merit of making all of the generating units available for both single and polyphase power as the system may demand. It is thus adaptable to growth and changes in the system, to preservation of good load factor and interconnection with other power systems. The third method does not offer any particular advantages over the two others but is mentioned for the sake of completeness. Its use might be considered in cases where single-phase and polyphase generators are already in use in the same power house and it is desired to use the polyphase distribution system for taking on single-phase load. The efficiency of all three methods may be said as a whole to be on a par. In specific cases some slight advantage may be figured out for each of the systems, but the determining factors will not be so much inherent efficiency of the electrical apparatus as the difference in load factors and the influence of load factors on steam economy.

For the sake of an easy comparison of the different methods proposed, a tabulated set of diagrams are given showing the essential features of each system.

Presented at the 325th meeting of the American Institute of Electrical Engineers, Philadelphia, Pa., October 13, 1916.

SINGLE-PHASE POWER SERVICE FROM CENTRAL STATIONS

BY R. E. GILMAN AND C. LE G. FORTESCUE

ABSTRACT OF PAPER

The purpose of the paper is to outline several methods by which single-phase power may be supplied from a polyphase system and to discuss their advantages and disadvantages.

The unbalance in voltage when single-phase power is supplied direct from a polyphase circuit is explained. The law of distribution of load in the polyphase system is deduced, and the limitations of this method of supplying single-phase power are discussed.

Single-phase generation is one solution of the problem, motor or steam drive may be used depending on the size of unit required. An outline of the theory of the single-phase generator is given from different points of view.

The essential requirements for phase balancing are deduced from which an outline of the theory of phase balancing is developed. Attention is called to the requirements of the control apparatus. The behavior of the balancer under short circuit is given consideration.

The merits of single-phase generation and phase balancing in the case of a single-phase load from one phase are discussed, with the conclusion that there is little difference in cost between the two schemes and there is much to be said in favor of single-phase generation for such a case.

INTRODUCTION

IT IS the purpose of this paper to outline several methods by which a power company may supply single-phase power, to indicate under what conditions each method may be considered as the most suitable, and to explain, from more than one viewpoint, some of the features of the design and theory of the apparatus required.

Central stations with polyphase equipment are often called upon to supply single-phase loads in small quantities. In general, this is attended with no difficulty, as the individual loads are ordinarily small and a combination of a large number of small loads ordinarily results in a fairly balanced total load. Under certain circumstances, however, even with relatively small single-phase loads, it would be desirable to balance up individual feeders if it were possible to obtain the necessary apparatus.

When, however, the individual single-phase loads become relatively large, compared with the total capacity of the station, both the voltage and current unbalance of the system resulting, may cause serious inconvenience and it becomes necessary to provide special means for handling these loads.

It is proposed to consider the problem under the following heads.

1. Single-phase loads supplied direct from the polyphase system.

2. Single-phase loads supplied from separate single-phase generators.

3. Single-phase loads supplied from polyphase system direct, but the balance of the system maintained by means of auxiliary apparatus.

I—Single-Phase Loads Supplied Direct from the Polyphase System

When a single-phase load is supplied direct from any polyphase generator, the effect of this load is to produce an unbalance in the terminal voltage of the machine. The voltage of any phase of a generator when carrying load is the resultant of the induced voltage and the e.m.f. necessary to force the current against the impedance of the phase winding. It is evident, therefore, that if equal currents of the same displacement are supplied by all phases, in other words, balanced load is delivered by the machine, that the terminal voltage diagram is similar to the no-load voltage diagram, but that all e.m.fs. are rotated through the same angle; balanced voltages are therefore maintained. If, however, a single-phase load is applied to the machine (for example in the case of a three-phase generator), the terminal voltages of two legs only are affected by the load current and the resultant triangle of terminal voltages is distorted from an equilateral or balanced triangle. See Figs. 1 and 2.

The division of an unbalanced load between the various machines connected to a polyphase system may be explained as follows: The distortion of the e.m.f. diagram must be the same for all generators connected to common bus bars and for all feeders leaving these bus bars, therefore, the magnitude of the impedance drop in the machines is identical for all units. In other words, the unbalance in load distributes itself between all machines connected to the system inversely in proportion to the impedance of the machine plus the impedance of the line circuit up to the point of application of the unbalanced load.

The magnitude of the voltage unbalancing in any system will depend, therefore, upon the relative amount of balanced load as compared with the unbalanced portion. In particular, symmetrical polyphase machinery, such as synchronous motors, synchronous converters or induction motors, will have a pronounced balancing effect on the system independent of the amount of load carried by them.

In addition to the voltage unbalance, single-phase loads on polyphase systems may produce undesirable temperatures in certain portions of the polyphase apparatus unless such apparatus is specially designed to carry unbalanced loads. A full explana-

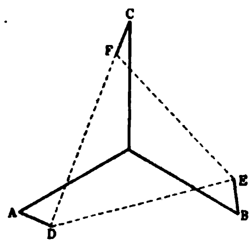


FIG. 1.—CHANGE IN VOLTAGE TRIANGLE DUE TO BALANCED LOAD

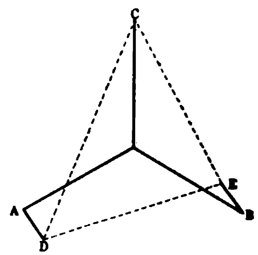


FIG 2.—CHANGE IN VOLTAGE TRIANGLE DUE TO SINGLE-PHASE LOAD

tion of this phenomenon will be given under the discussion on single-phase generators and phase balancing apparatus.

When the unbalance in voltage, or the heating of polyphase machines become excessive to such an extent that the service is in danger, some other means must be considered for supplying the unbalanced loads. The two means, which at once suggest themselves, are the use of separate single-phase generators, or the use of auxiliary apparatus to restore the balance.

In considering these two subjects, two general methods of analysis present themselves. The polyphase generator may be considered as a combination of single-phase generators, or the single-phase generator may be considered as a special case of loading of the polyphase generator. The problem will be presented from both points of view in the following discussion of the action of the single-phase generator and the general problem of phase balancing.

II—Single-Phase Loads Supplied from Separate Single-Phase Generators

If the single-phase load supplied, is of a different frequency from that of the polyphase system, it is obvious that a single-phase generator is the only logical solution. This generator may be driven either by steam direct, or by a motor connected to the polyphase system. If the frequency of the single-phase load is the same as that of the polyphase system, and it is decided to generate this load as single-phase power, the generators may be driven by motor, if the load is a small percentage of the total station capacity; or they may be steam driven, if the generators are of sufficient output to warrant it. Choice of the drive is largely one of dollars and cents, to be determined by the cost of the plant and the economy of operation. The main advantage in the use of steam drive is that the single-phase load of the station is entirely independent of the main system. The cost of power may be higher for the single-phase plant than for the main system, the difference depending upon the relative size of the units in the two systems, and upon whether steam drive or motor drive be used.

The only piece of apparatus requiring any explanation is the single-phase generator itself. This machine, as ordinarily built, is essentially a three-phase generator, except that the rotor is provided with a damper or a squirrel-cage winding in the faces of the field poles. The general construction and appearance of such dampers is well known, as their use is quite common in connection with different types of synchronous apparatus. In a self-starting synchronous motor, dampers are employed to increase the torque per ampere at starting, and in synchronous converters to prevent phase swinging or hunting from becoming excessive, while in single-phase machines dampers provide a low resistance, a low reactance path for currents induced in the rotor to compensate for the pulsating armature reaction.

The first requisite of any constant-potential machine is that the m.m.f. of the load circuit must not change the main flux of the machine, so long as the load is constant. In single-phase generators, therefore, where the m.m.f. of the load circuit is pulsating, that is, variable in magnitude from one instant to the next, and in position, with respect to the exciting circuit, also from one instant to the next, it is obvious that some other m.m.f. exists of such value at all instants, as to produce, in combination with the load reaction, a m.m.f. of constant value and fixed in position with respect to the main poles. This m.m.f. is supplied by currents which are induced in the damper winding.

A complete discussion going into the calculation of these currents is not warranted in this paper, but it may not be out of place to give an illustration of the underlying principle based upon the well known mathematical theorem that two vectors of equal value, rotating in opposite direction at equal angular

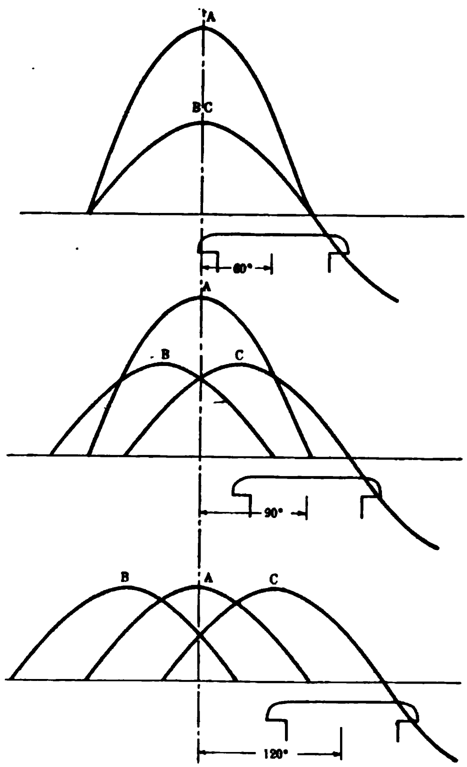


FIG. 3.—A = M.M.F. DISTRIBUTION DUE TO LOAD CURRENT.
B, C = VECTOR COMPONENTS OF A OF OPPOSITE ROTATION.

velocity, produce a sine wave. The diagrams shown in Fig. 3 are drawn under the assumption that the m.m.f. distribution of the armature winding is a sine wave. A little consideration will show that if these damper currents are not of sufficient magnitude to completely neutralize the pulsating component of the armature, the main flux must pulsate at double frequency. Also, that if the resistance to the flow of these currents is high , excessive losses may occur in the pole faces of the machine. This latter phenomenon explains the temperature rise which occurs in polyphase machines without dampers when carrying unbalanced loads.

There are some advantages in considering the single-phase generator from the point of view of a polyphase machine having an unbalanced load. It will be necessary, first of all, to accept the following theorem, the mathematical proof of which is given in the appendix and a graphical proof in the portion of this paper devoted to phase balancing.

Any unbalanced three-phase system of currents or e.m.f's, the sum of whose instantaneous values is zero, may be resolved into two component balanced polyphase systems, one of which has the same phase rotation as the unbalanced system and the other has opposite phase rotation.

The single-phase load may be considered as an unbalanced three-phase load having the following values.

$$I_1 = 0$$
$$I_2 = I$$
$$I_3 = -I$$

I_1, I_2 and I_3 being the vector values of the line currents of the three-phase system, and I being the vector value of the single-phase load current. This system of currents may be resolved as shown in vector diagram Fig. 9, into two balanced three-phase systems of currents of equal amplitude, one of which has the same phase rotation as the generator and the other has opposite phase rotation.

The three-phase component of normal phase rotation sets up a synchronous rotating m.m.f. in the main winding opposite to the direction of rotation of the main winding relative to the damper winding and which is, therefore, stationary relative to the latter. On the other hand, the counter-phase rotational component sets up a synchronous rotating m.m.f. which has the same direction of rotation as that of the main winding relative to the damper windings, and, therefore, the field set up by it cuts the latter at double synchronous speed, and induces in them double frequency polyphase currents, which produce a rotating counter m.m.f. approximate in value to the m.m.f. set up by the counter-phase rotational component of current in the main winding; the degree of approximation being proportionate to the closeness of magnetic coupling between the two windings. If it were possible to make the magnetic coupling perfect, and if the damper resistance were zero, no magnetic flux would be set up by the counter-phase rotational component and, therefore, the unbalancing in the terminal e.m.f. would be due only to the $I R$ drop in the main windings.

When the dampers are perfect, the exciting field winding and the pole faces will have no currents induced in them, but since it is not possible to obtain absolute perfection in this respect, a minute amount of double-frequency current will be set up in the pole faces and exciting circuit. In machines without dampers such as are commonly used for polyphase systems, these circuits, since they are not symmetrical polyphase circuits, will react on the main windings in an undesirable manner, when the machines are carrying unbalanced loads. For example, a counter-phase rotational m.m.f. induces in the field winding a double-frequency single-phase current, the m.m.f. set up by which in the main field windings, may be resolved into those due to two equivalent balanced three-phase systems of currents, one of which reacts so as to reduce the resultant m.m.f. while the other sets up a rotating m.m.f. of double synchronous speed in the opposite direction to that of the field relative to the main windings. The latter, therefore, induces triple-frequency balanced three-phase currents in the main windings, of the same phase rotation as the fundamental. These currents in turn react on the exciting circuit to set up quadruple-frequency currents, which in turn will react on the main windings to produce three-phase quintuple-frequency currents, and so on. The result is a complete train of three-phase odd harmonics of the same phase rotation as the fundamental and of diminishing amplitude in the e.m.f. of the main winding of the machine. One particular set of these odd harmonics, namely the multiples of three, because they are in three-phase relation in a three-phase system, will produce unequal wave forms on the three phases.

From the foregoing analysis of a single-phase generator, it appears that the single-phase impedance is made up of two elements, namely, the effective impedance of the generator considered as a polyphase machine to the symmetrical three-phase positive rotational component of the load, and its effective impedance to the negative rotational component of the load. The former is the impedance of the machine to a symmetrical polyphase current of positive phase rotation (the positive rotation being assumed to be that of the generator), when the machine is running in the normal direction at synchronous speed *with zero excitation*. The latter is the impedance of the machine to a symmetrical polyphase current of negative phase rotation when the machine is running in the normal direction at synchronous speed *with zero excitation*. The former of these quantities is dependent, in some degree, upon the saturation of the magnetic circuit, but corrections can be made from the no-load saturation curves of a machine for any desired degree of approximation. The latter value is only slightly affected by saturation, especially where the damper design is effective.

The single-phase impedance is the sum of the two impedances between neutral point and terminals, obtained in the manner described in the last paragraph, combined as complex quantities.

The effect of the dampers on short circuit is not to increase the transient value, but to sustain it. Therefore, the severity of a short circuit on a machine provided with dampers is not increased, from the magnetic standpoint, but the action continues for a longer period.

It will be obvious from the preceding discussion that the single-phase generator may also be used as a polyphase generator, if so designed, and will be of superior type to the standard polyphase machine, especially where the polyphase load is liable to be unbalanced. When installing single-phase steam-driven generators, the possibility of using them as auxiliaries for the polyphase system may be worthy of consideration. This would be particularly the case if the peaks of the single-phase and polyphase systems occur at different periods.

III—Single-Phase Loads Supplied from Polyphase System Direct, but the Balance of the System Maintained by Means of Auxiliary Apparatus

It has already been shown that any unbalanced single-phase loads will be distributed among the various machines connected to the system in inverse ratio to the impedance of the machine and the circuit up to the point of unbalance. From this consideration it is apparent that if a machine of zero impedance were connected to the system, all of the unbalanced load would be assumed by this unit. Therefore, to produce a balancer, it is only necessary to neutralize the impedance drop due to the unbalanced load. It is possible to produce the equivalent of zero impedance by introducing one or more single-phase boosters supplying a voltage of the proper magnitude and phase position so that the distorted triangle of voltages will be restored to a balanced or equilateral triangle.

It is evident that if a motor, having balanced symmetrical counter e.m.f., is connected to a balanced three-phase system it will absorb balanced load from the system. If all unbalanced loads were isolated and carried by one generator, it is obvious, as explained before, that the voltage of this generator would become unbalanced. For example, see Fig. 4. The problem now is how to connect this unit to the balanced system, without permitting any of the unbalanced load to be carried from the main generator. It is evident that by adjusting the excitation of this generator, so that the terminal e.m.f. of any phase, for example *A B*, is equal to that of the polyphase system, and if, in series with the terminal *C* a single-phase booster be connected giving an e.m.f. equal to *C D* and of the direction shown in the

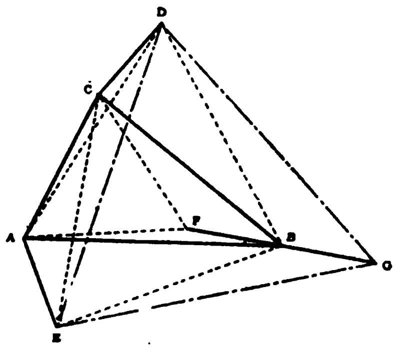


FIG. 4

figure, a balanced voltage triangle can be produced equal to that of the main system and, if this machine be paralleled with the main system, no redistribution of load will occur. If this generator and booster were driven from the same shaft, it would be possible to remove the driving power and the combined unit would act as a motor-generator taking balanced polyphase power from the system and delivering single-phase energy as a generator. A balancer has, therefore, been produced which will function properly so long as the unbalanced load remains fixed in magnitude and phase. If the phase of the single-phase load should change, it is necessary to change the phase of the booster with respect to the balancer and if the magnitude of the load should change it will be necessary to change the amount of booster in proportion. In the diagram shown, the resultant single-phase load is carried across terminals AC, and it is readily seen that if the load should be transferred to terminals AB, or BC the booster would have to be shifted in direction 120 deg. and 240 deg. respectively.

It is also possible to start from any other side of the triangle and by constructing equilateral triangles with these sides as a base, two other boosts are obtained, which can also produce the necessary balance.

It is evident, therefore, that in place of any one of these three boosts, such for example as CD, two boosts of equal voltage and 180 deg. phase displacement can be used if these boosters are connected to points A and B of the triangle. See Fig. 5. Or three boosters can be used, one connected to each corner of the original triangle. From Fig. 4, it will be seen that triangles

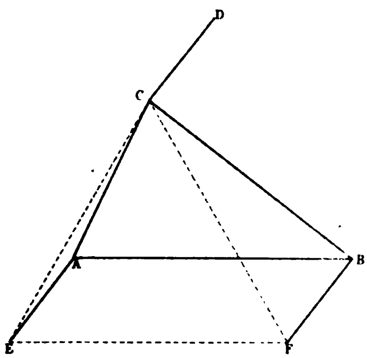


FIG. 5.

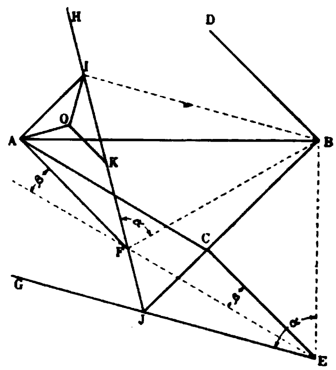


FIG. 6.

CDB and AEB are similar and equal and since by construction the sides CB and EB are 60 deg. apart, the sides CD and AE are 60 deg. apart and the e.m.fs. CD, AE and FB are 120 deg. apart and all equal in magnitude. If any of these values be reversed, it is readily shown that all three boosts can be employed to produce a balanced triangle. It would then be possible to combine all three booster windings on a single armature, which would be wound exactly like a three-phase machine except that the phase displacement of the terminal voltages would be 60 deg. in place of 120 deg. See triangle DEG, Fig. 4.

If starting out with the triangle ABC, an equilateral triangle be constructed with AC as a base, the boost BD can be replaced by two boosts AF and CE, and the equivalent equilateral triangle BEF will be obtained. If from point E a line EG be drawn at 30 deg. to the line CE, and from point F the line FH be drawn at 30 deg., it is apparent from the figure that with B as an apex a series of equilateral triangles can be formed by measuring equal distances from points E and F respectively along the lines GE and FH.

One case, which is of particular interest, is when the two boosts become parallel as shown in Fig. 6. In this case the boosts are at right angles to the line DB and this at once suggests the possibility of replacing them by a balanced three-phase system as indicated by the triangle AIK. It has been shown by the construction that triangle BIJ is equilateral and it is self evident that if IO, AO and KO be combined successively with IB, IJ and JB that an equilateral triangle would be obtained, as shown

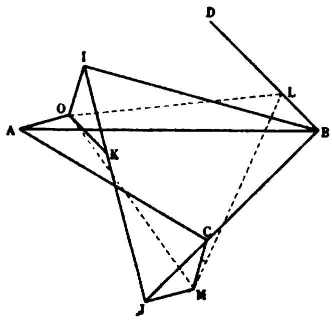


FIG. 7.

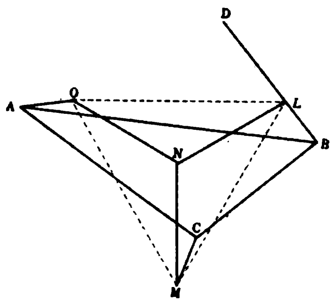


FIG. 8.

by OLM, Fig. 7. Also, the construction shows that AO, CM and LB drawn from points A, B and C produce the same triangle.

It is to be noted that AO, CM and LB are all respectively equal to one-third of the length BD. Also that these three boosts form a balanced three-phase system, and combine with AB, BC and CA to produce an equilateral triangle with opposite phase rotations.

It has been shown graphically, step by step, how any unbalanced triangle of voltages can be forced to a balanced triangle by various combinations of single-phase boosters using one, two or three boosters to accomplish this purpose. The solution shown in Fig. 7, is the most general for the three-phase system, and can be stated as follows: Any unbalanced triangle of voltages in a three-phase system can be replaced by two balanced systems of the proper magnitude and combined at the correct phase angle. In order to simplify matters, the graphic demonstration of this fact has been confined to the case of the three-phase system. It is shown, however, in the appendix to this paper, that the above solution of unbalance is perfectly general.

Given an unbalanced triangle, as shown in Fig. 8, the graphic solution is indicated.

In an extensive polyphase system, it frequently happens that while the aggregate single-phase loads produce fairly balanced polyphase load at the central station bus bars, the voltage at the ends of individual feeders may be considerably unbalanced. It is proved in the appendix that an unbalanced polyphase e.m.f. can be resolved into two balanced polyphase e.m.fs., one of which is of opposite phase rotation to that of the system. If, therefore, at a distributing point, a polyphase booster be connected in series, in the feeder lines, with phases in opposite rotation to that of the system, and if provision be made for changing the phase position and magnitude of the booster e.m.f., the unbalanced e.m.fs. at this point may be boosted into a balanced system. Fig. 10 in the appendix, shows graphically how to obtain the booster e.m.f. required to balance up a distorted system.

Means must be provided to control the voltage and phase angle of the booster according to the balancing requirements. This may be accomplished by two specially arranged regulators, the arrangement of which will depend upon the methods used to adjust phase and voltage in the booster.

Where both current and voltage are seriously unbalanced, the auxiliary apparatus must be such as to supply the elements necessary to produce balance in both voltage and current. It has already been pointed out that when an unbalanced load is supplied from a polyphase system, all the polyphase rotating machinery connected to the system tend to keep the voltages in balance and supply current in such a manner as to approach a condition of balance at the bus bars. The particular element of an unbalanced load that must be supplied in order to maintain a balanced load at the bus bars, is the counter-phase rotational symmetrical polyphase component of the load.

The impedance of a dynamo electric machine to counter-phase rotational symmetrical polyphase currents may be made extremely low by the addition of carefully designed polyphase dampers or squirrel-cage windings. If, in addition, auxiliary means be provided, externally or internally, to assist the natural action of the machine as a balancer, its admittance to the counter-phase rotational currents may be made infinite, so that the terminal e.m.f. of the machine will be absolutely balanced no matter how much counter-rotational current it may be called upon to supply.

The ability of an unassisted dynamo electric machine to act as a balancer is measured by its impedance to the counter-phase rotational component of the unbalanced load. The action of such a machine, when thrown on to an unbalanced system, consists in supplying such an amount of this counter-phase rotational component as will be necessary to pull the system and the machine into the same degree of unbalance. The voltage balance of the system is thereby improved at the expense of the voltage balance of the machine. The voltages that cause unbalance at the machine terminals are the impedance drops due to the counter-phase rotational current supplied by the machine, and are, therefore, counter-phase rotational and symmetrical. One way, therefore, for assisting the machine to maintain a balance, is to supply an equal and opposite counter-phase rotational e.m.f. in series with the windings by means of a booster, and this will render the effective impedance of the machine to these currents zero.

Since with varying degrees and phases of unbalance the impedance e.m.f. will vary in degree and phase position, the external source of e.m.f. must be provided with similar adjustment in voltage and phase position, and the apparatus provided to control these adjustments must respond to the variations of unbalance in the proper degree. The means of adjustment for an auxiliary machine connected rigidly to the main machine may consist of two field windings in quadrature relation, connected to separate exciters. This will permit of adjustment both in magnitude and phase position of the auxiliary machine in respect to the main machine.

The control of the adjustment of the auxiliary machine, with various degrees and phases of unbalancing, is not a simple problem, and until it has been satisfactorily solved, a perfect phase balancer cannot be considered as an accomplished fact. The essential requirements of the regulating apparatus are:

1. That it be extremely sensitive to voltage differences.

2. That it be capable of adjustment so that there will be no hunting between the control elements.

Whether these conditions have been obtained in any installation of balancers, up to the present time, is open to question.

Since a single-phase e.m.f. may be resolved into two balanced polyphase e.m.fs. of opposite phase rotation, perfect balance may be obtained by one single-phase booster in connection with the main machine. One component of this single-phase voltage must be the counter-phase rotational component required to balance up the terminal voltages of the main machine. The other component, which is of the same phase as the system, is provided for by the excitation of the main machine. The single-phase machine may be arranged so that its middle point is connected to the neutral of all but two of the windings of the main machine, its terminal being connected to the ends of the two remaining windings of the main machine, which would otherwise be connected to the common point, and it should be mounted on the same shaft as the main machine and be provided with means for changing voltage and phase with respect thereto.

The obvious defect of such a system lies in the difficulty of control, since with changing phase of unbalancing, the excitation of the main machine must be changed as well as that of the auxiliary single-phase booster.

A modified form of the same scheme would require a number of single-phase machines of the same phase, connected between the neutral point and each phase of the main machine, the complete set of machines being capable of simultaneous phase shifting, and each machine separately having full voltage control.

As a corollary to the above, it may be stated that any system of unbalanced polyphase e.m.fs. may be used as an auxiliary means of producing perfect phase balancing.

While some of the schemes outlined above may, with restricted phases of unbalancing, offer a satisfactory solution, the use of a polyphase main machine combined with a polyphase auxiliary machine is the simplest solution for the problem of general balancing and all practical balancers will be based upon this feature.

A convenient way of regarding the phase balancer is to consider it as a motor taking power symmetrically from the polyphase system and delivering it to the same system as single-phase current. The motor and generator actions tend to counteract one another in any polyphase machine provided with dampers and when the auxiliary booster is added, the annulment is complete after the auxiliary has become adjusted.

The action of a balancer under short-circuit condition will, therefore, depend on the range of excitation of the auxiliary. For the initial condition, until the auxiliary has had time to adjust itself, the main machine will feed into the short circuit in much the same manner as any other synchronous machine provided with dampers. If the auxiliary had a range sufficient to give complete balance under short circuit, the full polyphase capacity of the system would be concentrated in the short circuit and the phase balancer would necessarily carry a counterphase rotational load of equal value. In other words, the current delivered by a perfect balancer under short-circuit condition, is limited only by the current that the system on which it is operating, can deliver to a symmetrical short circuit.

Practically the short-circuit conditions are not so bad as indicated in the above paragraphs, because the limitation in voltage of the auxiliary machine permits of perfect balancing only up to a certain point. The short-circuit stresses in the balancer will nevertheless be much more severe than such as would be obtained in a generator or synchronous condenser of the same size operating on the system.

Conclusion

Where the unbalanced load fluctuates between the different phases and is of sufficient magnitude to cause trouble, a phase balancer is clearly the proper solution of the problem.

When a single-phase load on one phase is to be supplied, the problem becomes one of relative economy and reliability in service of the balancer, as compared with the single-phase generator. The main machine of the balancer set must have the same polyphase output as the alternative single-phase machine, and must also be provided with dampers of equal rating; but it must also be capable of withstanding the more severe short-circuit conditions due to its balancing action. In the balancer there is very little torque on the shaft and, therefore, the mechanical design may be cheapened and the operating speed increased. It is doubtful, however, if the main machine of the balancer set can be made much cheaper than a single-phase machine of the same output.

The auxiliary machine will be necessarily costly on account of the double set of poles and the wide range of excitation required. Its exciters must be relatively large in capacity so as to provide rapid change in excitation from full positive to full negative. In addition there will be the control system, which is complicated and costly. It is questionable whether this portion of the balancer set can be made for much less cost than the motor required for the equivalent single-phase machine.

From an operating standpoint, there is much to be said in favor of single-phase generation. In the first place, it is isolated to a large extent, or, if steam driven, completely, from the main polyphase system. This is of distinct advantage if the single-phase load is subject to frequent and violent interruptions. In the second place, the short-circuit condition resulting from the use of the single-phase machine will be, in general, much less severe and, therefore, less apt to cause trouble and prolonged interruptions in service, than when a balancer is used.

From the point of view of economy of operation, there is little to be said in favor of one over the other; the balance is probably in favor of the phase balancer when compared with the motor-generator set, and in favor of the generator when it is steam driven.

APPENDIX

An unbalanced three-phase system, in which the sum of the instantaneous values of the elements is zero, can be resolved into two balanced systems of positive and negative phase rotation.

In a three-phase system let the positive and negative phase rotational systems be,—

$$E_1 = E_1 \qquad E_1' = E_1'$$
$$E_2 = \omega E_1 \qquad E_2' = \omega^2 E_1'$$
$$E_3 = \omega^2 E_1 \qquad E_3' = \omega E_1'$$

Where ω is one of the imaginary cube roots of unity. Then if Ea, Eb and Ec be the unbalanced e.m.f. such that,—

$$Ea = E_1 + E_1'$$
$$Eb = E_2 + E_2'$$
$$Ec = E_3 + E_3'$$

With the condition, $Ea + Eb + Ec = 0$, this set of equations is determinate and the symmetrical solutions for the balanced components are as follows,—

$$E_1 = \frac{Ea + \omega^2 Eb + \omega Ec}{3}, \qquad E_2 = \frac{Eb + \omega^2 Ec + \omega Ea}{3}$$

$$E_3 = \frac{Ec + \omega^2 Ec + \omega Eb}{3}$$

$$E_1' = \frac{Ea + \omega Eb + \omega^2 Ec}{3}, \qquad E_2' = \frac{Eb + \omega Ec + \omega^2 Ea}{3}$$

$$E_3' = \frac{Ec + \omega Ea + \omega^2 Eb}{3}$$

Applying these to a single-phase load on a three-phase system, if I_1 be the value of the current.

$$I_a = 0$$
$$I_b = I_0$$
$$I_c = -I_0$$

and, therefore,

$$I_1 = -j\,\frac{I_0}{\sqrt{3}},\; I_2 = \frac{3 + j\sqrt{3}}{6} I_0,\; I_3 = -\,\frac{3 - j\sqrt{3}}{6}\, I_0$$

$$I_1' = +j\,\frac{I_0}{\sqrt{3}},\; I_2' = \frac{3 - j\sqrt{3}}{6}\,,\; I_3' = -\,\frac{3 + j\sqrt{3}}{6}\, I_0$$

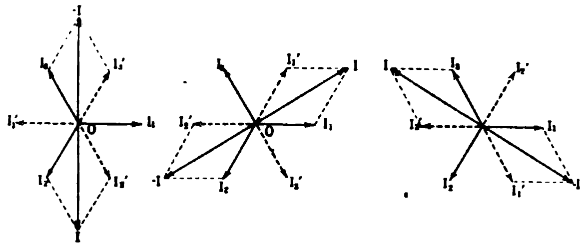


FIG. 9.—SINGLE-PHASE LOAD ON PHASES *A*, *B* AND *C* RESPECTIVELY RESOLVED INTO TWO BALANCED THREE-PHASE COMPONENTS OF POSITIVE AND NEGATIVE PHASE ROTATION.

Fig. 9 shows in a vector diagram the positive and negative phase rotational components of a single-phase load of equal magnitude and power factor on each phase of a three-phase system. The component of the same phase rotation as the system remains constant, while the counter-phase rotational component changes in phase through 120 deg. with each change in load position.

The formulas given above, may be interpreted as follows:

The negative phase rotational system is the mean of the three symmetrical systems obtained by taking each of the e.m.fs. E_a, E_b and E_c of the original system and considering it as a member of a balanced system. This results in the three systems:

$$\left.\begin{array}{l} E_a \;\;= E_a \\ E_{b1} = \omega^2 E_a \\ E_c \;\;= \omega E_a \end{array}\right\} \qquad (1)$$

$$\left.\begin{array}{l} E_b \;\;= E_b \\ E_{c2} = \omega^2 E_b \\ E_{a1} = \omega E_b \end{array}\right\} \qquad (2)$$

$$\left.\begin{array}{l} E_c \;\;= E_c \\ E_{a2} = \omega^2 E_c \\ E_{b2} = \omega E_c \end{array}\right\} \qquad (3)$$

from which the negative phase rotational component is obtained by taking the mean of the three quantities in the three groups having the same sub-letter.

Similarly the positive phase rotational component is obtained by taking the mean of three symmetrical systems of positive rotation, formed from the elements E_a, E_b and E_c of the unbalanced systems. These are as follows:

$$\left.\begin{array}{l} E_a \;\;= E_a \\ E_{b3} = \omega E_a \\ E_{c3} = \omega^2 E_a \end{array}\right\} \qquad (4)$$

$$\left.\begin{array}{l} E_b \;\;= E_b \\ E_{c4} = \omega E_b \\ E_{a3} = \omega^2 E_b \end{array}\right\} \qquad (5)$$

$$\left.\begin{array}{l} E_c \;\;= E_c \\ E_{a3} = \omega E_c \\ E_{b4} = \omega^2 E_c \end{array}\right\} \qquad (6)$$

Then, as before, each element of the component of positive phase rotation is obtained by taking out of each group the elements having the same sub-letter and finding their mean value.

Fig. 10 illustrates the graphical construction required to carry out the operations indicated above. The triangle A, B and C represents the unbalanced polyphase system which may also be represented by the vectors $O A$, $O B$ and $O C$ drawn from the centroid O of the triangle A, B and C. Two circles are described with O as center, namely $A\ C_1 C_3$ having $O A$ as radius, and $B\ C_2 C_4$ having $O B$ as radius. In the circle $A\ C_1 C_3$, $O C$ is taken 120 deg. in advance of $O A$ and, therefore, corresponds to $O C$ in the symmetrical system based on OA, having negative phase rotation. In the circle $B\ C_2\ C_4$, $O\ C_2$ lags 120 deg. behind OB and, therefore, corresponds to the vector OC in the symmetrical system of negative phase rotation based on OB. The corresponding vector $O3$ of the symmetrical negative phase rotational component is the mean between the vectors OC, OC_1 and OC_2 and is obtained by drawing a line from O to the centroid of the triangle $O\ C_1\ C_3$ that is $O3$. By describing a circle with radius $O3$ and center O, and taking points *1* and *2* respectively 120 deg. and 240 deg. lagging behind 3, the complete symmetrical negative phase rotational component 1, 2, and 3 is obtained.

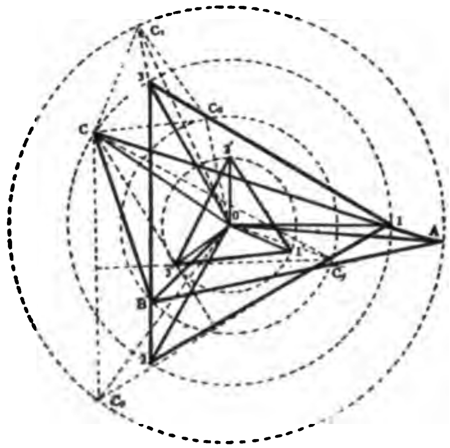


FIG. 10.—UNBALANCED THREE-PHASE SYSTEM RESOLVED GRAPHICALLY INTO TWO BALANCED SYSTEMS OF POSITIVE AND NEGATIVE PHASE ROTATION.

The positive phase rotational component is obtained in a similar manner, $O\ C_3$ and $O\ C_4$ having their vectors corresponding to $O\ C$ in symmetrical positive phase rotational systems based on OA and OB respectively. The vector $O3'$ of the positive phase rotational system corresponding to $O3'$ in the negative phase rotational system is the mean of the vector OC, OC_3 and OC_4 and is obtained by drawing a line from O to $O3'$, where $O3'$ is the centroid of the triangle $C\ C_3\ C_4$. The triangle representing the symmetrical positive phase rotational component is obtained by drawing the circle 1 2 3 with O as center and $O3'$ as radius, the points 1 and 2 being taken respectively 120 deg. and 240 deg. in advance of 3.

demonstration of this fact has been confined to the case of the three-phase system. It is shown, however, in the appendix to this paper, that the above solution of unbalance is perfectly general.

Given an unbalanced triangle, as shown in Fig. 8, the graphic solution is indicated.

In an extensive polyphase system, it frequently happens that while the aggregate single-phase loads produce fairly balanced polyphase load at the central station bus bars, the voltage at the ends of individual feeders may be considerably unbalanced. It is proved in the appendix that an unbalanced polyphase e.m.f. can be resolved into two balanced polyphase e.m.fs., one of which is of opposite phase rotation to that of the system. If, therefore, at a distributing point, a polyphase booster be connected in series, in the feeder lines, with phases in opposite rotation to that of the system, and if provision be made for changing the phase position and magnitude of the booster e.m.f., the unbalanced e.m.fs. at this point may be boosted into a balanced system. Fig. 10 in the appendix, shows graphically how to obtain the booster e.m.f. required to balance up a distorted system.

Means must be provided to control the voltage and phase angle of the booster according to the balancing requirements. This may be accomplished by two specially arranged regulators, the arrangement of which will depend upon the methods used to adjust phase and voltage in the booster.

Where both current and voltage are seriously unbalanced, the auxiliary apparatus must be such as to supply the elements necessary to produce balance in both voltage and current. It has already been pointed out that when an unbalanced load is supplied from a polyphase system, all the polyphase rotating machinery connected to the system tend to keep the voltages in balance and supply current in such a manner as to approach a condition of balance at the bus bars. The particular element of an unbalanced load that must be supplied in order to maintain a balanced load at the bus bars, is the counter-phase rotational symmetrical polyphase component of the load.

The impedance of a dynamo electric machine to counter-phase rotational symmetrical polyphase currents may be made extremely low by the addition of carefully designed polyphase dampers or squirrel-cage windings. If, in addition, auxiliary means be provided, externally or internally, to assist the natural action of the machine as a balancer, its admittance to the counter-phase rotational currents may be made infinite, so that the terminal e.m.f. of the machine will be absolutely balanced no matter how much counter-rotational current it may be called upon to supply.

The ability of an unassisted dynamo electric machine to act as a balancer is measured by its impedance to the counter-phase rotational component of the unbalanced load. The action of such a machine, when thrown on to an unbalanced system, consists in supplying such an amount of this counter-phase rotational component as will be necessary to pull the system and the machine into the same degree of unbalance. The voltage balance of the system is thereby improved at the expense of the voltage balance of the machine. The voltages that cause unbalance at the machine terminals are the impedance drops due to the counter-phase rotational current supplied by the machine, and are, therefore, counter-phase rotational and symmetrical. One way, therefore, for assisting the machine to maintain a balance, is to supply an equal and opposite counter-phase rotational e.m.f. in series with the windings by means of a booster, and this will render the effective impedance of the machine to these currents zero.

Since with varying degrees and phases of unbalance the impedance e.m.f. will vary in degree and phase position, the external source of e.m.f. must be provided with similar adjustment in voltage and phase position, and the apparatus provided to control these adjustments must respond to the variations of unbalance in the proper degree. The means of adjustment for an auxiliary machine connected rigidly to the main machine may consist of two field windings in quadrature relation, connected to separate exciters. This will permit of adjustment both in magnitude and phase position of the auxiliary machine in respect to the main machine.

The control of the adjustment of the auxiliary machine, with various degrees and phases of unbalancing, is not a simple problem, and until it has been satisfactorily solved, a perfect phase balancer cannot be considered as an accomplished fact. The essential requirements of the regulating apparatus are:

1. That it be extremely sensitive to voltage differences.

2. That it be capable of adjustment so that there will be no hunting between the control elements.

Whether these conditions have been obtained in any installation of balancers, up to the present time, is open to question.

Since a single-phase e.m.f. may be resolved into two balanced polyphase e.m.fs. of opposite phase rotation, perfect balance may be obtained by one single-phase booster in connection with the main machine. One component of this single-phase voltage must be the counter-phase rotational component required to balance up the terminal voltages of the main machine. The other component, which is of the same phase as the system, is provided for by the excitation of the main machine. The single-phase machine may be arranged so that its middle point is connected to the neutral of all but two of the windings of the main machine, its terminal being connected to the ends of the two remaining windings of the main machine, which would otherwise be connected to the common point, and it should be mounted on the same shaft as the main machine and be provided with means for changing voltage and phase with respect thereto.

The obvious defect of such a system lies in the difficulty of control, since with changing phase of unbalancing, the excitation of the main machine must be changed as well as that of the auxiliary single-phase booster.

A modified form of the same scheme would require a number of single-phase machines of the same phase, connected between the neutral point and each phase of the main machine, the complete set of machines being capable of simultaneous phase shifting, and each machine separately having full voltage control.

As a corollary to the above, it may be stated that any system of unbalanced polyphase e.m.fs. may be used as an auxiliary means of producing perfect phase balancing.

While some of the schemes outlined above may, with restricted phases of unbalancing, offer a satisfactory solution, the use of a polyphase main machine combined with a polyphase auxiliary machine is the simplest solution for the problem of general balancing and all practical balancers will be based upon this feature.

A convenient way of regarding the phase balancer is to consider it as a motor taking power symmetrically from the polyphase system and delivering it to the same system as single phase current. The motor and generator actions tend to counteract one another in any polyphase machine provided with dampers and when the auxiliary booster is added, the annulment is complete after the auxiliary has become adjusted.

The action of a balancer under short-circuit condition will, therefore, depend on the range of excitation of the auxiliary. For the initial condition, until the auxiliary has had time to adjust itself, the main machine will feed into the short circuit in much the same manner as any other synchronous machine provided with dampers. If the auxiliary had a range sufficient to give complete balance under short circuit, the full polyphase capacity of the system would be concentrated in the short circuit and the phase balancer would necessarily carry a counter-phase rotational load of equal value. In other words, the current delivered by a perfect balancer under short-circuit condition, is limited only by the current that the system on which it is operating, can deliver to a symmetrical short circuit.

Practically the short-circuit conditions are not so bad as indicated in the above paragraphs, because the limitation in voltage of the auxiliary machine permits of perfect balancing only up to a certain point. The short-circuit stresses in the balancer will nevertheless be much more severe than such as would be obtained in a generator or synchronous condenser of the same size operating on the system.

Conclusion

Where the unbalanced load fluctuates between the different phases and is of sufficient magnitude to cause trouble, a phase balancer is clearly the proper solution of the problem.

When a single-phase load on one phase is to be supplied, the problem becomes one of relative economy and reliability in service of the balancer, as compared with the single-phase generator. The main machine of the balancer set must have the same polyphase output as the alternative single-phase machine, and must also be provided with dampers of equal rating; but it must also be capable of withstanding the more severe short-circuit conditions due to its balancing action. In the balancer there is very little torque on the shaft and, therefore, the mechanical design may be cheapened and the operating speed increased. It is doubtful, however, if the main machine of the balancer set can be made much cheaper than a single-phase machine of the same output.

The auxiliary machine will be necessarily costly on account of the double set of poles and the wide range of excitation required. Its exciters must be relatively large in capacity so as to provide rapid change in excitation from full positive to full negative. In addition there will be the control system, which is complicated and costly. It is questionable whether this portion of the balancer set can be made for much less cost than the motor required for the equivalent single-phase machine.

Explanation of the Action of the Phase Converter

In order to balance the single-phase load and distribute it equally on the three phases of the generator, the three currents of the generator must be made equal and each current will be 1 divided by 1.73 or 58 per cent of the single-phase load current. Designating the single-phase load currents as A and B (see Fig. 1) the current A is composed of two components. A_1 coming from the generator equal to 58 per cent of A and 30 deg. out

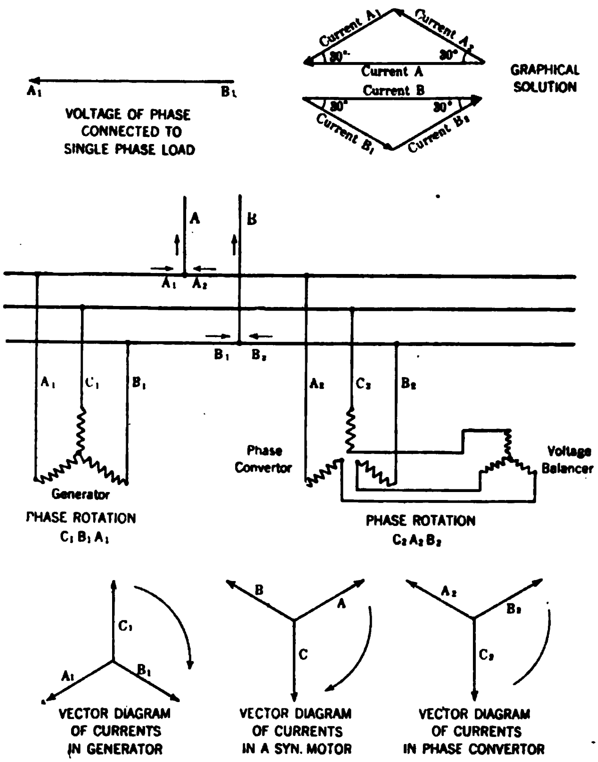


Fig. 1—Current Relations in Phase Converter

of phase with A, is the known component. By graphical solution (see Fig. 1) the other component of current A, which we will designate as A_2, coming from the phase converter is equal to A_1, 30 degrees out of phase with A and 60 degrees out of phase with A_1 In other words, A is composed of two components combined at 60 degrees phase angle.

On the other leg of the single-phase load we will designate the current as B. At any given moment when A is the outgoing current, B is the incoming current. B is equal to A and they are 180 degrees apart. In a manner similar to the above we find that

B is composed of two components each 58 per cent of B and 30 degrees from B in phase relation, B_1 coming from the generator being 60 degrees from B_2 which comes from the phase converter.

Completing the vector diagram of currents on the generator since the currents are balanced and 120 degrees apart, we find that the third phase of generator current is C_1, as shown in Fig. 1. This same current C_1 flows into the phase converter, but since the generator current is an outgoing current and in phase with the voltage (at 100 per cent power factor) and the current C_2 flowing into the phase converter is a synchronous-motor current, C_2 when represented on a vector diagram will be 180 degrees from C_1 and at 100 per cent power factor would be 180 degrees from the bus voltage like any other synchronous-motor current.

By combining the three vector currents, A_2, B_2 and C_2 we obtain the vector diagram of currents in the phase converter and find that these currents in order to balance a given single-phase load are equal to the currents in the generator. The current C_2, like any synchronous motor current is 180 degrees out of phase with the generator current, but the currents A_2 and B_2 are only 60 degrees out of phase with A_1 and B_1 and on the vector diagram it is seen that the phase rotation is in opposite direction to that of the generator, whereas in the vector diagram for a synchronous motor the currents are all 180 deg. out of phase with the generator currents and the phase rotation is the same as for the generator. In the phase converter the voltage of the large machine is in the same phase rotation as the generator voltage but on account of the voltage distortion produced by the voltage balancer the currents in the phase converter are in opposite phase rotation to those in the generator.

The unbalancing of currents in the generator produced by single-phase load is accompanied by a distortion of the voltage triangle and in order to bring the currents in the generator back into balance we must produce internal voltages in the windings of the phase converters of such magnitude and phase relations as will produce the currents necessary to combine with the balanced generator currents to supply the single-phase load currents. Since the currents in the phase converter to accomplish this balancing must be in opposite phase rotation to those in the generator, while the main counter e.m.f. produced in the phase converter is in phase with the generator voltage, the currents in opposite phase rotation to the generator currents are produced by introducing in the Y connection of the phase converter a smaller three-phase machine mounted on the same shaft and driven by the phase converter. This machine is designated as the voltage balancer and is so connected as to have opposite phase rotation to the phase converter.

The revolving field of this machine is not a definite pole construction but consists of a laminated structure containing slots in which there are two field windings at right angles to each other in space (see Fig. 2).

By exciting field winding 1 in a positive direction a three-phase current is generated of opposite phase rotation to that in the converter, but in a certain phase relation to it depending on the relative positions of the stators.

The stator of the voltage balancer is mounted in a cradle so that it can be fixed in different angular positions with respect to the position of the stator of the phase converter.

By exciting the field 2 only, three-phase currents will be produced with a phase relation of 90 deg. to those produced by field 1 only. Fields 1 and 2 may be reversed thus producing phase relations 180 deg. from the two former positions and by exciting 1 and 2 at the same time and to the same magnitude the intermediate forty-five degree positions are produced. By exciting 1 and 2 at the same time, but with different magnitudes, the voltage of the balancer may be made to assume any desired phase relation with respect to that of the converter.

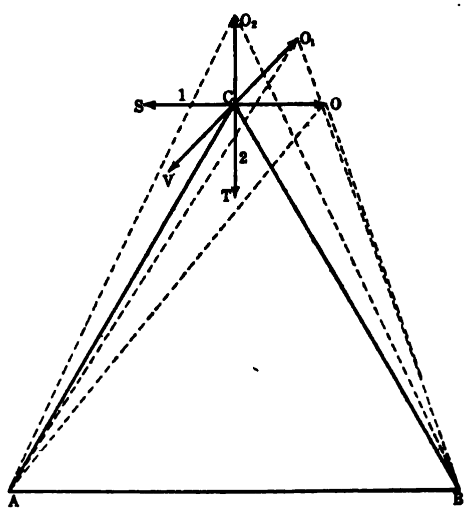


FIG. 2—VOLTAGE RELATIONS IN VOLTAGE BALANCER AND PHASE CONVERTER

Referring to Fig. 2 the delta *A*, *B*, *C* represents balanced voltage on the generator.

When single-phase load is taken off the phase *AB* the voltage triangle will be distorted. If the single-phase load is of 100 per cent power factor the point *C* moves in the direction of *CO* and the voltage triangle becomes *AOB*. If the load is at 70 per cent power factor (45 deg. lag.) the point *C* moves in the direction of CO_1 and the voltage triangle becomes AO_1B. If the single-phase load were of zero power factor point *C* would move in the direction of CO_2 and the voltage triangle becomes AO_2B.

By properly combining the direction and magnitude of the fields in the voltage balancer we can produce a voltage distortion opposite to that produced by the single-phase load and this will cause currents to flow which will balance the single-phase load in the generator. It is possible, for instance, to set field 1 so that when used alone it will produce a voltage distortion *CS* opposite in direction to *CO* and field 2 so that when used alone it would produce a voltage distortion *CT* opposite in direction to CO_2, the combination of these two fields would obviously produce a voltage distortion *CV* opposite to CO_1. Thus field 1 would compensate for single-phase load at 100 per cent power factor and bring the voltage triangle back to normal, field 2 would compensate for single-phase load at zero power factor and a combination of the two fields in equal magnitude would compensate for single-phase load at 70 deg. power factor or 45 deg. lag when this load is applied on phase *AB*. For any other power factor the two fields could be used in different proportions.

It is assumed in the above case that the voltage of the phase *AB* is controlled and held constant by the generator regulator, so that, the single-phase load does not affect the voltage *AB*.

It will be noted that when unity power-factor single-phase load is thrown on and the voltage triangle tends to assume the shape *AOB*, that the voltage *AC* is increased and the voltage *BC* is decreased. For lower power factors both voltages may be increased. Therefore, if a voltage regulator is connected across phase *AC* and made to regulate field 1 and another regulator is connected across phase *BC* and made to regulate field 2, these regulators will so control the fields as to maintain the voltages *AC* and *BC* constant and in so doing currents of the proper phase relation and magnitude to balance the single-phase load are produced in the windings of the phase converter, these currents being made to flow by the internal voltages generated in the voltage balancer, which overcomes the impedance in the windings of the phase converter.

When the single-phase load is thrown on phases *AC* or *BC* the voltage triangle is again distorted, point *C* moving in a different direction but regulators which are arranged to reverse the fields when necessary will so control the fields as to deliver the proper balancing currents no matter what direction the point *C* tends to move.

In the main machine or phase converter an action goes on in the squirrel-cage winding which may be explained as storage of power from the phase *C* and delivery to the phases *A* and *B*.

In actual practise the currents flowing to the converter will be slightly unbalanced on account of the losses in the machine, but the generator currents will be balanced.

R. E. Gilman: It is the single-phase load, superimposed on a polyphase system which causes voltage unbalance.

It must remembered that all the machines on the system are in parallel and consequently the voltage unbalance is common to all. This distortion is due to unequal impedance drops in the various phases of any machine. These drops are necessarily the same in corresponding phases of all machines. That is the phase and magnitude are equal for corresponding phases. The currents therefore are inversely in proportion to the impedance of the machine. To force any machine to assume all the unbalanced load, all that is necessary is to reduce the equivalent impedance of that machine to zero. This can be done by introducing one or more voltages of the proper phase and magnitude to neutralize the inherent impedance drop of the machine.

The shunt phase balance as described is a particular solution of the problem based on introducing a voltage in series with each phase of the machine which is to assume the unbalanced load. These boosting voltages are all equal and make up a polyphase system with opposite phase rotation to that of the main unit.

W. C. L. Eglin: At a Chicago meeting some years ago Dr. Steinmetz presented a paper on "The Reliability of Power Company Service" and pointed out very clearly that the standard for reliability of service was the simple d-c. distribution, and that with the increasing general use of alternating current we had to go back to the simple standards laid down by Mr. Edison for satisfactory general power distribution.

He also pointed out very clearly that if the proper study of the power companies' requirements, and the consumers' requirements was made, there was no reason why a-c. systems could not follow along the lines laid down by Mr. Edison and be equally as reliable. The particular feature emphasized was the proper use of reactances.

As has been brought out by Mr. Gilman, the main difficulties are in producing a satisfactory phase converter or phase balancer. All that he says is true, and all of these difficulties have been overcome by Mr. Alexanderson and his assistants.

Whatever phase the unbalance comes on, it is automatically taken care of. The dangers of a heavy short circuit have been taken care of in the two ways; first, by the limiting of the reactances on the feeders; and second, by the limitations put on the regulators; so that there is a limiting load which can come on the phase balancer.

In this work there is one other feature to be considered and that is the correction for power factor. As has been pointed out, very serious losses are involved in the transmission system with a low power factor.

With large loads it is essential in my judgment that they must only be considered on the basis of unity power factor. All of the problems then, including the balancing problem are infinitely easier. The corrections for power factor should be part of the equipment.

I think Mr. Reist has very clearly shown that in the large size generators the complications in building are bad enough now without adding to the size, to take care of something that can be taken care of in a different way.

I was asked to state something on what it costs to produce single-phase power.

It is very difficult to answer that exactly. We determined first that we would work for the power house to be the most economical that could be built. That necessitated that we fix some standard of power factor. From our studies of the results of correcting poor power factors, we were convinced that we should put in sufficient synchronous apparatus to obtain unity power factor.

In a power station the load is not fixed, it is constantly growing from year to year, and an inductive load added varies with the different character of customer's loads, so that you cannot say that your power factor will be 80, 90 or 95; it may be that one year, and greater or less the next year.

That made us desire at first that the generator be designed for unity power factor, and that it have no dampers for the reason that dampers add, as has been explained, first to the size of the machine, and secondly to its first cost. We would take care of the unbalancing of load in some other way.

All of the methods that were described here were carefully discussed and analyzed, as far as our conditions were concerned, and we determined on the phase balancer. Naturally there were skeptics, some fears as to what we could accomplish, especially as we were depending largely on automatic devices to overcome some of the difficulties.

A number of people have seen this machine in operation, and it has fulfilled every condition that has been expected of it; in fact, I think it works a little better than most of us expected.

I was asked also what was the biggest single-phase load that we would have to carry.

The principal single-phase load, in fact the entire single-phase load that we have today, is for electric railroad operation.

We endeavored naturally to have the various sections of this single-phase load distributed over the three phases of our bus bars, and our contracts provide for the sale of three-phase power. That is very difficult, especially in the starting of a system; The railroad starts with one division which can be put on one phase, another division may be put on the second phase, and a third division may be put on the third phase; so that we get a certain amount of fixed balance under these conditions.

The operation of a railroad, however, or any other load, even 5000-kw. electric furnaces, is not continuous; it may be shut down. You may have three 5000-kw. furnaces, and if one is shut down, you have a condition of unbalance, so that the phase balancer size has to be the size of the largest single-phase load that you may have to supply. That, in this case is the heaviest division of the railroad, to which we have supplied I think about 30,000 kv-a. The phase balancer, of course, as has been pointed out before, does not have to carry all of that unbalanced load because of the other synchronous apparatus that is on the bus-bar system, all of which tends to balance the load.

This load is corrected for very nearly unity power factor, and the synchronous condensers are installed in a sub-station about midway of the electrification, so as to get the real advantage of the correction of the power factor, reducing the line losses and maintaining the uniform voltage on the lines. The synchronous condenser in this case has a double purpose.

There is another point that has come up, and that is a question of frequency. There have never been any real standards of frequency established. I do not think any two standards can ever be called a standard. We have had the so-called 25-cycle and 60-cycle systems. I should very much like to see the Institute, through its Standards Committee, take up and solve for the industry at large, the question of the American standard frequency; and I think that will do more to help the development in every way, both in the use and sale of power and apparatus, than probably anything else that the Institute can do.

B. A. Behrend: Mr. Eglin suggested the standardization of frequency. Now, let us understand the fundamental reasons which underlie the difficulties in the generation of single-phase current. They are due to the turbo-generator which has completely superseded the multipolar reciprocating generating units of ten or fifteen years ago.

It is very easy to design an electric generator of say 25,000-kw. capacity or even 50,000-kw. capacity, provided it is a multipolar unit, as a single-phase generating unit.

It is not possible at the present state of the art to make a single-phase generating unit for a capacity in excess of say 15,000-kw. and I should prefer to limit the capacity of the single-phase unit to 15,000 kv-a. considering the nature of the load, which of course is a railway load of a low power factor.

C. A. Adams: How many poles?

B. A. Behrend: I refer to two-pole units. Now then, where does the question of frequency enter into our problem? It is at the present state of the art not possible to design single-phase motors, and therefore locomotives, for 60-cycles, which frequency Mr. Eglin doubtless had in mind, when he made his suggestion for the standardization of the frequency. In this world unfortunately conditions are not as we want them to be, and we have to recognize the facts as they are.

Two-pole single-phase generators are difficult machines to design, as Mr. Reist has pointed out, and as is so well known to us.

Mr. Eglin has stated that it is necessary in modern power plants to use a certain amount of reactance in the generators and feeders, and it may be added that the increase of the internal reactance of the generators has increased the difficulty of designing the damping circuits on the revolving elements of the turbo-generators, as the dampers have to be in proportion to the strength of the armature. Turbo-rotors travel at a circumferential speed of approximately four miles a minute; at which speed the centrifugal forces developed are terrific. The conducting materials at the present state of the art have no considerable mechanical strength. In a device which we have developed they have to be hammered and peened into the chrome nickel steel end rings in a somewhat complicated manner, in order to hold them in place, and prevent them from shifting and bending.

There is also great difficulty in obtaining and securing satisfactory contact between the axial copper conductors and the circumferential conductors.

Therefore, it may be stated that the capacity of single-phase generators is limited; and the engineers who have an opportunity to specify the unit capacity of such generators should be very careful indeed not to demand of the manufacturer too large a unit as it involves frequent repairs, and imperils reliability of service.

This is the fundamental reason for the question that has been considered in the sessions today, Mr. Alexanderson having given us a means of utilizing the existing 25-cycle three-phase power plants for the generation of the single-phase currents, so far as this 25-cycle single-phase current is going to be used in the operation of our great railway systems.

Now then, in the case of 60-cycle power plants, we are confronted with an additional difficulty, viz., the difficulty of transforming from 60 to 25 cycles; which must be done by motor-generator sets. Therefore, in this case Mr. Alexanderson's invention can be dispensed with.

The question of power factor is one of great importance, and I agree with Mr. Eglin that it is desirable that every one of us should give it a little more attention; but by giving it a little more attention we do not raise the power factor.

The peculiar conditions of railway operation, the peculiar nature of the single-phase railway system, combine to make the power-factor problem a very formidable one, with a low load factor, if a power plant is devoted exclusively to the generation of single-phase electric currents.

These are difficulties which a year or so ago made me remark, that, when Mr. Wynne discussed the electrification of the Norfolk & Western railway system, it was the "least unsatisfactory solution" of an intensely difficult problem for which remark my friend, Prof. Scott, took me to task and was very hard on me. I am afraid, however, my statement must stand, since, unless we realize that we are solving these problems temporarily in the least unsatisfactory manner, solutions good enough to hold their own but no better, we shall not advance.

D. W. Roper: I disagree with Messrs. Gilman and Fortescue, as to the latter part of their conclusions, which favors steam-driven single-phase generators.

To take the case in Philadelphia, for example, where they have a load of say 25,000 kv-a., and with the figures given by the previous speaker, it would require at least two single-phase generators to carry that load.

The exigencies of central station operation require that some reserve should be kept for the generating apparatus, and that would mean the installation of three machines, any two of which may carry the load.

I think central station men will also agree that idle generating capacity on the peak of the load is undesirable.

It would therefore appear that if the short-circuit conditions are of any serious moment in determining the design of your plant, that those conditions should be met by reactors, or other similar protective devices, rather than by any scheme which contemplates idle generating capacity on the peak of the load.

G. H. Hill: The first generated current ever produced was a single-phase current, and it seems curious that at this time there is need of such a considerable amount of discussion, to make clear how that first single-phase current can best be produced for use commercially. I would like to emphasize the fact that this problem is a general one. We cannot confine ourselves to particular applications.

Mr. Torchio's solution none of us will criticise, because he has met his conditions in the way that fits the situations best; he has by inheritance a complex system, 25-cycle and 60-cycle, three-phase and single-phase, all of which had to be taken care of, but I feel sure that he would not duplicate his entire system if he had it to do over today. I think we must keep in mind the ideal in discussing this problem and make sure that we establish a reliable guide for industrial development.

I belive there is not much doubt in the minds of those who are acquainted with the situation over the whole country that the question of cycles is answering itself.

In the East where the power plants are oldest, we have numerous excellent 25-cycle systems, but in the West, which is the stronghold of transmission and water-power developments, 60 cycles is almost universal and you cannot convince our western friends that there can be anything but 60 cycles as the standard frequency. From the experience along this line an illustration may be drawn of the fallacy of trying to make compromises.

The old question as to what frequency should be used generally led a number of engineers to the opinion that a compromise on 40 cycles would be about right but no attempt was made to establish 40-cycle apparatus as standard. Failure to do so was inevitable because the compromise was not the best frequency for either lighting or power. The net result is a local section handicapped with a frequency that requires special apparatus.

The same idea applies to a large extent to the question we have here. Single-phase power is perfectly easy, in an engineering sense, to produce in a number of ways.

It can be a separate system, single-phase generators and transmission system independent of the other power system; but this does not meet the ideal conditions at all. We cannot advocate such duplication and separation of power loads as a solution of anything except perhaps some local situation.

You can produce single-phase power from polyphase generators by adapting these generators so that they will deliver an unbalanced load without overheating, and without seriously affecting the value of the polyphase power, but the result is a compromise which is not a solution because it will not be acceptable as best for either polyphase or single phase.

The effect of unbalancing a polyphase system is bound to be bad in one way or another and even if you attempt to balance the single-phase loads among the phases as pointed out by a number of speakers, the asynchronous application of these loads is bound to occur and there must be a regulating device to correct the resulting unbalancing. Such an arrangement is a poor compromise because it handicaps the polyphase in first cost and complication, and restricts the use and convenience of the single phase. It would be a handicap in the development of the art because you could not be free to choose the most economical system. It does not lend itself to either old systems or extensions of systems in a way that we ought to set down as an ideal.

What we want is a means for producing single phase, retaining the standard and best form of generator and transmission, without duplication, without segregation of load, without raising the cost and without affecting the value of the polyphase system for any purpose for which it is useful. Such a means is now suggested and the conclusion seems inevitable that it is the ideal, and one toward which we should look for the solution of the problem.

If there is involved a change in frequency it is necessary to use a motor generator. If the motor-generator sets are not perfect (as one speaker implies) they are certainly very practical and very successful and we do not know of any other way to change frequency than by two rotors, that is, in a commercial way for power purposes. I know no reason why motor generators should not be used to produce single-phase current of a low frequency from a polyphase system of a higher frequency.

While single-phase railways demand low frequency there will be a considerable amount of use of single-phase current of 60 cycles, for furnace work and heating work, especially in the West. For this, 60 cycles is absolutely satisfactory and a phase converter will supply the single-phase demand from a 60-cycle three-phase system, without unbalancing or affecting it adversely in any way.

Moreover it is particularly fortunate that we are able to take a single-phase load from a three-phase system in the way particularly suited to the character of the single-phase load.

If it is possible to approximately balance the single-phase load on the three-phase system and most convenient to use the transmission system as a bus line, then the shunt converter can be used to correct the unbalancing in the loads, so that the three-phase supply is not affected.

The series converter is particularly adapted to take three-phase power as an absolutely balanced load and supply a large single-phase load, where it is sufficiently great to warrant a special substation.

I cannot sympathize very much with the point of view that has been brought out, that there are a great many complicated reactions in this converter. I know that every polyphase circuit is awfully busy. If we try to follow out all the reactions, phase displacements and frequency distortions that are going on, the matter is very complex.

But I know that the converter accomplishes all these things, does keep in phase, does give the regulation desired, does draw balanced polyphase load, and does deliver single-phase load of good regulation. This has been pretty well demonstrated and I think that the manufacturing companies will be prepared to supply such apparatus under proper guarantees of successful operation to those that require it.

The phase converter is practical, flexible and efficient, and considering the needs of the whole system and the future development, I cannot see why it should not be accepted as the ideal solution of the problem.

Philip Torchio: I am very glad to hear of the completely successful operation of these balancers in the Philadelphia station. Personally I feel very much gratified that we can dispose of such apparatus in our requirements.

In discussing this matter, Mr. Hill has just now emphasized to some extent that there are two problems to take care of; one is the 60-cycle distribution and one is the 25-cycle railway load. They are entirely different services.

The single-phase loads from a 60-cycle system, used for welding machines, furnaces and services of that character, if they cannot absolutely be balanced among themselves, will necessarily require some balancer, such as Mr. Alexanderson has developed because the upsetting of the voltage balancing on the distribution system would be too severe to be tolerable.

I have no hesitation in advocating such a piece of apparatus in a 60-cycle system which must carry unbalanced single-phase loads. The arrangement is ideal. There is no question about that; I do not want to be understood that I take any exception to it.

My point is that, whenever a company operating a 25-cycle system has to supply single-phase railway loads, such company should for new equipment install generators having the single-phase characteristics. In our special New York conditions we had an additional object in selecting the plan described in my paper—that was to be able to operate in parallel with the other station of the railroad company, because, by running all the railroad system in parallel, we secured that very object which Mr. Eglin emphasized in his paper as derived by the diversity factor of the peak loads of an amplified system, evening up the resultant combined load. Railway loads are just of the character to require combining, and our perfect parallel operation and sharing of peaks with our customer's station has undoubtedly contributed to the satisfactory result of our service to the New Haven Company.

Coming to the economic features of our solution, involving generators with single-phase characteristics compared with an installation with balancers, if Mr. Doherty means that we are running at 123 per cent loss, compared with 85 with the balancers, I take issue with such a statement. I would only state that it is not a fact. It is very far from the fact.

There cannot be 45 per cent greater loss in our system than with the balancer. I believe that our losses are not any greater, and I believe that they are less, that our efficiency is better. We have a turbine specially designed and equipped with an additional set of nozzles controlled by a hand operated valve to give high economy at low loads.

That machine, without the special valve, would operate at higher average loads with practically the same efficiency as a standard machine operating at its most economical point. But in our actual operation we have something in the order of a fraction of a pound of steam per kw-hr. more consumption than we would have, operating at the most economical point; but that is all the difference, and that could not account for the difference between 85 and 123.

As far as the extra cost of this special machine is concerned, in comparison with a balancer installation, I do not like to see the comparison between 65 and 96. I don't know what is compared there.

If it is meant to say that our cost is in the relation of 96 to 65, I will say that the actual figure of extra costs of the single-phase generators, as estimated by the manufacturers, were $16,000 a machine, or $32,000 total; that was all the extra cost we paid, and we have been doing a satisfactory business for ourselves, and giving entirely satisfactory service to the customer.

As I stated, we discussed the balancer at the time, but then the balancer was not developed and was not ready to use.

If Mr. Alexanderson's balancer proves, and, as I have said before, I am happy to hear that it has proved, satisfactory, all we have to do is to spend that money buying the balancer and then we are better off than we were before; we utilize in its entirety all of our equipment; we have not lost one cent in any other respect except that we have paid the $16,000 extra per machine, and in the meantime we have had two years' service before the development happened.

In concluding, I would say that even this trivial extra cost of installing machines with single-phase characteristic would not be a loss; I don't know what the 5000-kw. balancer costs; probably we would need a larger machine for our load; the cost of one balancer would certainly be in the order of the $32,000 that we paid extra for our generators; if we did not have the single-phase characteristic machines, we would have had to buy at least two balancers, one for spare, whereas now one would be sufficient, because if it breaks down, our generators would carry the single-phase load, as they do now.

The saving that we make of an extra balancer, I think, must at least balance the extra cost we paid for the generators, and so we come out even.

To come back to my original proposition—and I am not talking derogatory to the balancer system in any way—but I really believe that central stations distributing commercial loads should put in generators capable of taking care of poor power factors, and unbalanced or single-phase loads.

I think it is a wise investment; it makes better and more durable machines, it enables the station to do a lot of things on emergency, and I think it is not going to be very costly.

R. E. Doherty: The comparison of loss of 85, in the case of the series converter, against 123 in the case of the single-phase turbo-generator, was this:

The phase converter is capable of delivering 5000 kw. continuously and 12,000 kw. for five minutes.

A single-phase turbo-generator, to deliver the same load, would have losses of 123 instead of 85.

The figure 85 represents the losses of the series converter, the one machine by itself operating at 5000 kw., 123 represents the losses in the single-phase turbo-generator when it is delivering 5000-kw. single phase, a ratio of 123 to 85.

The difference between 85 and 100 represents the losses in the auxiliary machine, which is known as the voltage balancer.

H. G. Reist: To be fair, should you not include the general losses?

C. A. Adams: The three-phase generator losses in the machine that supplies the series converter?

H. G. Reist: Yes, exactly.

R. E. Doherty: These figures are not intended to be a comparison of the losses from the steam to the single-phase load. It is intended only to give the losses in a single-phase turbo-generator when it is delivering the same load as a series converter.

H. G. Reist: Yes, but the series converter first goes through the generator, and has separate losses.

R. E. Doherty: Yes, indeed.

W. C. L. Eglin: I think Mr. Torchio has brought out very clearly his presentation of what the great future for all of that work is, *i.e.* in the future extensions, the enormous growth of power-house apparatus. The dollar saved in the generators is in a constantly increasing amount, that is, it will not be necessary in the future to equip all the generators with dampers, etc.

It is not only the added cost of the increased size of the generator, but there is positively a reduction in the efficiency; that is, the machine is not as efficient as if it was made without dampers.

Peter Junkersfeld: I would like to add a comment on this matter of power factor. I am referring now, not to these few large systems that have single-phase railway loads, but to the very much greater number of central stations over the country. I want to make sure that the proper place for synchronous condensors is not misunderstood.

There are a great many systems over the country where the peak comes at night, when the lighting is almost the entire load, and when the power factor is of the order of 95 or 100 per cent. They may have a day load whose power factor is as low as 60 or 70 per cent, but the volt-ampere day load may be less than at night when the power factor is high; therefore in those cases the limiting feature of the size of copper in the distribution system is created by the night load and not by the day load. In such a case the synchronous condenser has not yet found its place, but the day load is growing at a very much greater ratio than the night load and it is only a question of time when these companies will find a place for the synchronous condenser.

C. F. Scott: One of my points was that the best place to provide for power factor and single-phase generation, is in the generator itself, being the simplest and often the cheapest way; that the applications to be made here are those that apply to the largest power plants where we are reaching the limits of size, and where the size of the auxiliary apparatus is itself very large, but that these considerations might not apply at all to smaller plants.

In the matter of synchronous condensers for correction, I think the point brought out by Mr. Summerhayes illustrates that it is not universally applicable. Specific cases must be considered carefully.

H. C. Albright: I understood Mr. Torchio to say that with his three-phase generators especially built for single-phase loads, carrying heavy loads, the voltages varied as much as 12,200, 11,000 and 13,900 on the various phases.

I would like to ask him whether this voltage distortion is not a serious handicap, and an objection for generation in that manner, over the phase balancers?

Philip Torchio: If I understand the question, it applies to the joint system of the New Haven and our system: They are operated on single phase purely, and will not affect any other customers at the present time, and therefore the question of a balancer, I could not answer.

E. F. W. Alexanderson: I do not know whether I can answer that question. Of course it belongs to the New Haven system.

Philip Torchio: The question of balancing; if the balancer was used, there would not be any unbalanced voltage.

E. F. W. Alexanderson: Yes.

Philip Torchio: The answer is there.

E. F. W. Alexanderson: Mr. Fortescue and Mr. Gilman, in their paper, brought out some very appropriate questions in regard to the possibility of short circuits, etc.

Those problems were real problems. Since Mr. Eglin has expressed his satisfaction in the way those problems have been solved, we have already the answer to them.

C. L. Fortescue: The questions raised in connection with the regulation of the phase balancer are real problems that have to be met in the phase balancer. They are not raised for the sake of controversy.

I think there is a big future for the phase converter, but I also think that in certain cases heavy single-phase loads can be better handled separately, than from a polyphase system, especially when the load is very large, and particularly if in order to handle the load the power company has to purchase new material.

I think that the statement, that a single-phase machine is not so good a machine as a polyphase because it has dampers, is not correct.

I think that the correct statement is, that a single-phase machine is a superior type of polyphase machine because it has dampers.

The dampers in the machine enable it to carry quite a considerable amount of unbalanced load without undue heating while with a balanced load they have no effect on the efficiency of the machine. The small amount of loss in space due to the damper, I think is very well met by the improvement due to its ability to handle unbalanced loads.

Philip Torchio: When the machine is running three-phase balanced, is the efficiency of the unit lower than a machine without dampers?

C. L. Fortescue: When operating as a balanced polyphase machine at the same load as the same machine without dampers, the effciency of both would be the same. The dampers are inert under this condition.

Philip Torchio: How much?

C. L. Fortescue: Mr. Eglin says that the balancer is assisted in handling unbalanced loads by the synchronous machinery on a system.

When the balancer is operating this is not true, except in so far as synchronous machinery improves the power factor of the unbalanced load; otherwise, the only way in which the synchronous machinery on the system can help to balance the single-phase load is by the actual distortion produced thereby.

In other words, the distortion is inversely proportional to the admittance of the system to the balancing or counterphase rotational current in the circuit.

C. A. Adams: Insofar as the balancer can not perfectly balance, other apparatus would assist?

C. L. Fortescue: Of course, if the balancer is not doing its work perfectly, the rest of the apparatus will help it out.

I think a great number of the comments made by the various speakers on single-phase machines have been due to considering particular cases.

If consideration is given to the fact that large railway electrifications demand large amounts of single-phase power, it begins to be evident that the relative amount of single-phase power as compared with polyphase may be so large, that new apparatus is required and therefore it seems to me that careful consideration should be given to the merits of separate single-phase generation.

If the peak loads of the single-phase system do not occur at the same time as the peak loads on the polyphase system, it is possible to combine the two systems, so that, the single-phase generators can be used as polyphase generators at the time of the high demand on the polyphase system.

Without reflecting on the balancer phase converter, I wish to bring out the principal point that should be considered in its development.

If the load is constantly changing from one phase to the other, which is quite liable to occur—for example if two single-phase railway loads are being supplied, the load is variable and high sudden peaks occur—the peak on one phase may occur at an instant when the other phase is changing suddenly from peak value to very little load. The changes in these peaks are very rapid, and the regulating part of the balancer has to take account of the peaks very quickly.

It can readily be seen that a condition may occur where a balancer is at the maximum regulating condition for the peak on one phase and at the same time as that load is suddenly lost, the load on the other phase comes on, in which case the balancer may produce a greater unbalance for the instant than if it was not there.

In other words, it is important to have the regulating apparatus very sensitive, and very quick acting.

As to the question of the operation of the present balancer, it must be remembered that it is operating to balance a single-phase load on one phase only.

The question is, how will it operate when it has to balance a variable single-phase load on two phases, such as will occur when the Chestnut Hill electrification goes into effect—will it be able to follow the sudden changes of load from one phase to the other? Is it possible to make a regulator sufficiently sensitive to give perfect satisfaction?

Mr. Behrend makes the statement that it is absolutely impossible to build a single-phase two-pole turbo-generator above a certain capacity. I think he must have meant, that at the present time there was no known way of building such a machine. I remember talking to a man who said that at one time a number of years ago he required a 100-kw. transformer, and submitted the problem to the engineers of two manufacturing companies. The engineer of one of the manufacturing companies said he believed it was absolutely impossible to build a transformer of such a size, the heating could not be dissipated and the reactance would be so high that it would be impossible to get good regulation, but the other manufacturer said he would be willing to try it out, but the purchaser would have to assume the risk. The purchaser was a good enough sportsman to take the risk and the transformer was built. Now we are building 10,000-kw. units, so that what it seems impossible to do today, may in a few years be quite practicable.

R. E. Gilman: In respect to the relative size and cost of turbo-generators, the limitation of the turbo-generator, especially the two-pole machine, is largely a question of field design. Take, for example, a 25,000-kw. 100-per cent power factor, single-phase generator, two-pole, it would be built on exactly the same frame as a 14,000-kv-a., 70-per cent power factor, single-phase machine; and if the same frame were used for a polyphase generator at 70-per cent power factor the approximate output would be 17,500 kv-a.

As to the relative cost and performance of the machine with or without dampers, the efficiency for the same machine operated as a polyphase machine, at the same power factor, is the same. The cost would be increased due to the damper, possibly 5 to 8 per cent.

In comparing cost of single-phase equipment against polyphase generators or phase balancers we must bear in mind that the single-phase turbo-generator is a part of the main generating equipment and that the shunt or series converter is an addition. These same remarks hold in comparing the efficiency of the two systems.

Presented at the 326th meeting of the American Institute of Electrical Engineers, New York, November 10, 1916.

THE EFFECT OF RECENT DECISIONS ON THE WORK OF INVENTORY AND APPRAISAL

BY PHILANDER BETTS

ABSTRACT OF PAPER

In order that our inventories and appraisals shall be useful in determining all of the appropriate elements of value, they must be classified as to age, condition, use, and extent of use in each class of service.

DURING the past few years there has been much discussion on the proper basis for rates. This discussion has been quite confusing at times because of the entrance into it of those who were not familiar with all sides of the question. That is, engineers not familiar with the existing legal decisions have argued pro and con on the subjects of valuation and depreciation, and lawyers not familiar with development cost have based their arguments entirely on the decisions of the Courts.

If we are to have proper respect for our Courts, we must abide by their decisions and, if not satisfied, we must familiarize ourselves with all of the conditions leading to the Courts' decisions. Probably the earliest cases which begin the history of decisions concerning valuation are those of the Brunswick and Waterville, Maine, cases. We must bear in mind, however, that those were cases in which negotiations were in progress looking to the sale by water companies of their properties to the municipalities. In those cases the franchise rights had either expired or the municipalities had the right to take over the properties as well as the franchises, and thereafter operate them. In "purchase and sale" cases, clearly the matter to be determined is the *value* of the property, all things considered, including "going concern" values if any exist. After a study of many of the great rate cases, the writer has come to the conclusion that the confusion of mind has come from the fact that the early decisions were based upon "purchase and sale" cases and did not primarily have anything to do with cost in its broad sense.

Value not Cost

If we are, however, to do our work in conformity with the Courts' decisions, we must take as our primary basis for the consideration of rates, the value of the property and not necessarily the cost. Justice Harlan was wiser than he knew when, in the famous case of Smyth v. Ames, he said as follows:

We hold, however, that the basis of all calculations as to the reasonableness of rates * * * * * must be the fair value of the property being used by it for the convenience of the public. And in order to ascertain that value, the original cost of construction, the amount expended in permanent improvements, the amount and market value of its bonds and stock, the present as compared with the original cost of construction, the probable earning capacity of the property under particular rates prescribed by statute and the sum required to meet operating expenses, are all matters for consideration and are to be given such weight as may be just and right in each case. We do not say there *may not be other matters* to be regarded in estimating the value of the property. What the company is entitled to ask is a fair return upon the value of that which it employs for the public convenience. On the other hand, what the public is entitled to demand is that no more be exacted from it * * * * * than the services rendered by it are reasonably worth."

Reproduction Value v. Original Value

The general trend of recent decisions has been to make reproduction cost the sole or controlling basis of value for rate purposes. Some Courts plainly state that, in their opinion, actual cost, capitalization and other factors are to be considered only to the extent that they may throw light on the cost of reproduction or existing depreciation. In support of this principle, the opinions of the Supreme Court of the United States, indicate that it is the "present value" of the property that is to be determined; thus, in Smyth v. Ames, reference is made to "the fair value of the property being used * * * * * for the convenience of the public"; in San Diego Land and Town Company v. National City, it is "present value"; in the same case, on appeal to the Supreme Court, Justice Harlan refers to "reasonable value of the property at the time it is being used for the public"; this is quoted as settled law by Justice Holmes in 1903, and by Justice Peckham in 1909 in Wilcox v. Consolidated Gas Company. It is argued that this constant use of the present tense by the Supreme Court in referring to fair value for rate purposes must at once exclude actual cost or original cost from having any controlling influence in the determination of fair value. Under this interpretation present value must be based either on market value or reproduction cost, and as market value is not usually considered a fair or possible standard for rate purposes, reproduction cost is turned to as the only available standard. This line of argument would be more convincing were it not for the fact that in the leading case of Smyth v. Ames in which the present value principle is laid down, it is also distinctly stated that both original cost and reproduction cost shall be considered in determining a fair present value, and it is no indication that either of these factors should be given a controlling influence. This cannot be accepted as the settled rule of law as the whole subject of valuation is still in a developmental stage. The Supreme Court of the United States has wisely refrained from laying down a hard and fast rule which might have to be reversed when all of the factors of the problem shall have been more clearly discussed.

Value New v. Depreciated Value

In the so-called Idaho case, it has been determined by the Court that the value new of the property is the proper basis for computation of rates rather than a "present value" obtained by deducting the full estimated depreciation. This decision follows a number of commission decisions along the same general line and is best expressed in the words of the St. Louis Public Service Commission in the case of the Union Electric Light and Power Company of St. Louis, decided in 1911, "In depreciating, to arrive at the present value, the Commission does not consider it fair to make deductions for anything but the present physical condition and for items where it is plainly apparent that the property has become obsolete and inadequate."

Property Used and Useful

From the earliest cases down to the present time, the Courts have been unanimous in the determination that the basis for rates must be the value of the "property used and useful" and have not been very definite in further defining these terms. The Commissions have, however, in a number of cases, after determining the value of the entire property, made deductions for property considerably in excess of that required for the present * customers or those who might be taken on in the near

*San Diego Land & Town Co. v. National City.
Long Branch vs. Tintern Manor Water Co.
Mantua vs. New Jersey Gas Co.

future. This has sometimes occurred, and occurred recently in New Jersey, where companies have been too optimistic with regard to the development of the territory and have built plants far in excess of the actual needs. It also follows from this, that rates may not be based upon an inadequate plant but that the valuation to be determined will be that of a plant adequate in all respects for the customers now connected and including a reasonable reserve for customers who may be taken on in the near future, as well as reserve to guard against the ordinary break downs and interruptions in service.

Classification as to Use

The next decisions of interest affecting our work of inventory and appraisal are those of the Norfolk and Western Railroad Company v. Conley, et al, and the Northern Pacific Railroad v. the State of North Dakota. The effect of these decisions is to require different rates for classes of service where the costs are greatly different. The basis for differential rates is found in one of the earliest Supreme Court decisions in which it was held that "what the company was entitled to was a fair return upon the value of that which it devoted to the public use" but the Court went on to say that what the purchaser was entitled to was "service at no more than the worth to him." This decision practically confirmed the railroads in their existing practises of having different rates for different classes of service. With regard to electric lighting and power companies, it has been customary to classify customers in accordance with their requirements for service. This classification, however, was based on and adhered more or less closely to the cost for the respective classes of service.

Result

The result of the above mentioned decisions is that the inventories and the resulting appraisals must be classified in accordance with the use and the extent of the use. So far as the engineer is primarily concerned with cost, the inventory and appraisal will arrive at the same aggregate in any case, but the engineer is further concerned with the use and operation of the electrical property and it is the duty of the engineer to determine to what extent each class of property is required in the service of the public and to what extent it is required for the furnishing of the various classes of service. In preparing our inventory, therefore, such classifications must be made as will readily show the use to which the property is devoted. In the determination of rates it becomes especially important when it is recognized that charges for municipal street lighting have almost invariably been lower than the proper proportionate costs for this class of service, and where a company has been reasonably successful in carrying on its business it follows that the rates charged for other classes of service have been too high and the recent Court decisions* forbid the collecting from one class of customers any unreasonable portion of that which ought to be collected from other classes of customers, and further forbids the lowering of rates for reasons of public policy.

As to the calculations for depreciation, while the Idaho decision is to the general effect that full or theoretical depreciation should not be deducted in obtaining the fair value of the property, it cannot be said that this principle is at all well established, and it becomes necessary, in our inventory, to determine the accrued depreciation of each item, taking into account not only ordinary wear and tear, but obsolescence and inadequacy (which some authorities call functional depreciation). The writer has long been of the opinion that in order to square our valuations with the Court decisions, we must (1) obtain definite appraisals of the existing physical property, (2) ascertain the full theoretical depreciation, (3) make such deductions as are necessary because of property built unwisely or for anticipated increases in population which have not materialized or for classes of service which have not been taken on. In other words, our valuation must be determined by using our best present-day judgment as to the amount and classes of property required to serve the customers now connected and those which may be connected within a reasonable future period. This may even involve an addition for property not now in place, but which ought to be in place in order to assure continuity of service with the requirement that same be installed. In addition, however, to the value of the physical property, the writer desires to take refuge behind the words of Justice Harlan when he says, "We do not say that there may not be other matters to be regarded in estimating the value of the property." It is the writer's contention that in making the appraisal of the physical property, due allowance must be made for overhead charges. The writer's opinion on this phase of the matter has already been expressed in a written discussion which appeared at the San Francisco

*See Norfolk & Western & North Dakota cases cited above.

Convention of the Institute in 1915. In addition, however, there are allowances for various intangibles not properly included under the head of overhead charges. They are (1) cost of organization and obtaining the necessary charters and franchises, (2) deficits in operation in the early history of the project, (3) lack of profits in the later years and (4) the unearned depreciation which has accrued. It is the writer's further opinion that the aggregate of these elements ought to bear some favorable relation to the total value of the physical property, but it is the province of the engineer to investigate and determine the various items referred to with the exception, perhaps, of items concerning the cost of organization and obtaining the necessary charters and franchises. All other elements in determining the appraisal and valuation of a public utility property and in the determination of the deficits, lack of profits or otherwise, are matters solely within the province of the engineer.

The above items should be considered as making up the "cost of establishing the business." There has been much contention with reference to the necessity of including "going value" but here again we are confusing cases involving justice to the investor with "purchase and sale" cases. "Going value" is an element to be considered in "purchase and sale" cases and has no pertinency whatever in rate cases. The United States Supreme Court, in its recent decision regarding the Des Moines gas rates, decided that "going value" was to be considered in these cases, but based its estimates of "going value" on those elements which go to make up the "cost of establishing the business." In the determination of reasonable or fair rates, full consideration must be given to the sacrifice made by the investor. This will include, in addition to the investment in the physical property, early losses, lack of profits and unearned depreciation, the aggregate of which should be classified as the "cost of establishing the business."

CONCLUSIONS

1. Property must be inventoried in such detail as will lead to a determination of its value or cost within a very small percentage of absolute accuracy.

2. It must be classified as to its use and as to the degree of its use in the various classes of service.

3. The inventory must include full information as to age and present condition, this information leading to accurate estimates of accrued depreciation.

Presented at the 326th meeting of the American Institute of Electrical Engineers, New York, November 10, 1916.

CONTINUOUS INVENTORIES: THEIR PREPARATION AND VALUE

BY HARRY E. CARVER

ABSTRACT OF PAPER

Due to enactment of laws in various states requiring approval of State Commissions before issue of securities, and due to other conditions, there has arisen a demand for a continuous inventory of property owned by utility companies.

First section of this paper discusses the advisability of attempting such an inventory, giving possible uses and advantages to be derived therefrom, and the second section discusses the preparation of such an inventory, suggests the division of the property into four general groups for the purpose, and outlines general forms and methods for collecting and recording data required.

AMONG papers presented at the Pacific Coast Convention of the Institute at San Francisco in 1915, under the general heading of a *Symposium of Inventories and Appraisals of Properties*, was one by Mr. W. G. Vincent, Jr., in which the subject of keeping inventories and appraisals up to date was treated in some detail. In the discussion which ensued, it seemed to be the opinion that the amount of detail and extra work and expense which would be incurred by a company's operating force, would be too great to make it advisable or practicable to do this. At least one of the large public utility companies under the jurisdiction of the New Jersey Commission, namely one of the telephone companies connected with the Bell system, is apparently accomplishing this with an expenditure of labor and other expense which is apparently within reason, and both the New Jersey and New York Commissions are endeavoring to develop methods for keeping inventories up to date in which it is hoped that the co-operation and approval of public utility companies in general may be secured.

DISCUSSION OF THE VALUE AND USE OF A CONTINUOUS INVENTORY

The desirability and the purposes for which an inventory and appraisal of a company's property is made have been generally discussed heretofore and the necessity of making such an inventory and appraisal under certain conditions is probably sufficiently apparent to eliminate the necessity of further discussion on this matter. Such inventory and appraisal of any large company is comparable to a general census which it has been customary to make at periodical intervals for centuries. If it were necessary or advisable to have the results of an up to date census available at frequent intervals the question would doubtless arise as to the desirability of keeping a complete census of all the people in the country up to date by other means than going out and counting them every five or ten years.

In the same way, if it is advisable or necessary to have available a total inventory and appraisal of a company's property at frequent intervals of time, it would seem advisable to consider the problems involved in maintaining such an inventory at all times.

If this kind of an inventory would serve no other purpose than in making data readily available for the compilation at any time of a total inventory and appraisal of the company's property, then the feasibility of doing so depends upon at least four factors.

1. The frequency with which it may be desirable.

2. The additional yearly expenditure required, multiplied by the number of years intervening compared with the cost of obtaining the results by a complete new inventory at a later period.

3. The comparative accuracy of an inventory by the two methods and the accuracy which is liable to be required in future appraisals.

4. The speed with which it may be desirable to compile the same.

A consideration of the frequency with which complete inventories are liable to be required leads to the conclusion that they are liable to occur much oftener in the future than in the past, as the custom of requiring yearly reports to various tax commissions and government regulating commissions appears to be becoming much more general and required in more detail than heretofore.

A consideration of the other factors involved in keeping a continuous inventory brings to light a number of other reasons and advantages to be obtained by carrying out such an undertaking. Besides the company itself, considered as a unit, there are at least three other classes of people who are interested in the operation of a public utility corporation.

1. The patrons or customers of the company.
2. The investors in the company's securities.
3. The general public, including the various governmental agencies representing this public.

A perpetual inventory of a company's property would be useful to any company in the following ways:

1. Data are made available for answering any complaints as to discrimination or overcharges in existing rates and the company should be able to present promptly a full statement of facts on the basis of which a satisfactory determination can be made.

2. The increased cost of labor and material renders it probable that many rate cases in the future will involve increases, rather than decreases in rates for services rendered and the company will need to be fortified with all necessary facts as to the cost of service rendered, among which are included as two of the principle items, a fair return on the investment and a yearly allowance toward a reserve fund for replacing the property involved, at the time that such replacement is needed.

3. In many rate cases and cases pertaining to security issues, inventories and appraisals have been made and depreciation and present value estimated. Various methods have been used for making these determinations and estimates of future depreciation have been made. There the matter, in most cases, has been dropped and the future depreciation has been left to take care of itself.

The cut and dried formulas for determining depreciation used in many cases have often been challenged and criticized. The criticism has been so severe that it is not at all unlikely that new methods will be adopted in the future which will depend upon changes which actually take place as time goes on and that will have to be checked up from time to time. Probably the surest check upon accruing depreciation or an accruing renewal fund is a comparison of the fund with the total cost of the property, subject to depreciation, which, of course, can only be made by having at hand an up to date inventory. It is quite probable that, in the future, one of the most urgent reasons for making an inventory and keeping it up to date will be the necessity of having some means for judging whether or not a company is making reasonable preparation for renewing and perpetuating its property.

4. For most public utility companies, the approval of a State Commission is necessary for the issue of new securities. The labor and time involved in securing the approval of the same, both on the part of the company and of the Commission, would be materially reduced. There would be less interruption of the work performed by the operating force of the company from governmental inspectors, either in checking up construction expenditures for new securities or in making a complete appraisal of a company's property for this or other purposes.

5. The market for a company's securities would, doubtless, be increased by a general knowledge that a running inventory of all the company's property was maintained and consequently that some check was available upon the total property represented by securities issued and on the accounting methods followed by the company.

6. It would probably make available data for securing franchise extensions from various municipalities under more equitable terms than appears to be possible at present.

7. Data would be available for making investigations to satisfy the demands of labor employed in the company's operations as to whether they were, or were not, receiving a fair proportion of the company's revenue. One of the reasons privately advanced by labor union men for demanding an increased share in a company's revenue is that the books of many companies are kept in such a manner that the revenues are covered up in some way and their total income is not shown in the reports made to the stockholders or public bodies. Without commenting on the merits of this contention, it is probable that the means of proving or refuting it would be much more readily available than at the present time.

8. It is the general experience in checking up the books of various companies in New Jersey for approval of construction expenditures that comparatively little question can be raised as to the total amounts claimed, but that the distribution to the various items or accounts by which the expenditures are classified, are very frequently incorrect, which fact is generally brought out by making an inventory of the property acquired and checking up the unit prices. Hence there seems little doubt that a continuous inventory maintained by a company would be conducive to much more accurate accounting and distribution of charges between fixed capital and operating expenses as well as a more accurate distribution of general overhead charges than is possible at present.

9. Insurance adjustment for fire and other losses could be more readily and equitably obtained.

10. Tax Commission reports and yearly reports to regulating bodies could be more readily compiled.

11. At the present time a few large companies are keeping a more or less detailed record as to the location of their various items of property, especially of underground conduits, etc. Many companies, however, have very incomplete records as to just what they own or where it is located and information is not readily available as to what service they are able to render at a given location, either permanently or temporarily. As an illustration of this point, the case may be cited of a gas company which was recently called upon for service by a prospective customer in an outlying district. An employee of the company, to whom the request was made, replied that the company would be unable to make the connection to the customer's premises, as the company's mains were too far away. Later investigation proved that the company had a service connection to the house next door and that the main in the street extended to within about fifty feet of the prospective customer's lot. A continuous inventory would necessitate the keeping of records which would prevent these or similar occurrences.

12. In addition to requiring records which would give the location of property owned, the adoption of such a system in connection with a continuous inventory and appraisal would be of great value in promoting more efficient construction and operation, as detailed costs would readily be available from which the costs of rendering any particular service or of making any particular extension or betterment could be accurately determined.

Some of the advantages cited above would apply equally well to the company's customers, investors, and the public, but the above seem to be sufficient.

Preparation of the Inventory

This subject apparently implies first a complete inventory and appraisal of the property as of a given date but this is not a necessary prelude to the above, and, as most companies have not a complete inventory and appraisal of their property, it seems advisable to state that a company can readily start an inventory of all new property acquired from the present time forward and all old property withdrawn from service and either replaced or abandoned, without detailing a special force of engineers to make a complete inventory of all property. The record of the company's property in existence at the time the inventory is started can be obtained at such times as the company's engineers and accountants may be available for this work, and, in the course of a few years it might be possible in this manner to obtain a complete inventory.

The actual problem of maintaining a continuous inventory resolves itself into the question as to how small the units may be into which a property may be divided and records kept without an unreasonable expense, and how large the units of property may be taken without making indentification of any item or part of the property so uncertain as to destroy the accuracy of the inventory and subsequent changes in the capital account.

To illustrate, suppose a company builds today a large power station and ten years from now it builds an addition, removing one wall and making use of some of the material for the new work. Or, a company builds an overhead distribution system; five years later it becomes necessary to replace some of the existing wires on a certain street with a larger size; ten years later it is necessary to move a part of this same line to the other side of the street and install joint poles with another company, and fifteen years later it becomes necessary to replace all this construction with an underground system.

Is it possible to keep an accurate record of these transactions so that the capital account shall record the cost of the additions and the proper withdrawals in going through these various changes without relying on estimates of both quantities and costs to such an extent as to render the records questionable as to their accuracy? Heretofore it has been necessary to rely largely on estimates of the original cost of both labor and material in recording such transactions; but, with proper co-ordination and co-operation of the various departments concerned, we believe that the necessity of making estimates can largely be obviated, and the total cost installed in place at any particular period of time obtained without any great expense.

The fundamental requirement for accomplishing the above is an efficient "work order" system, also quite generally known under the head of "Authorizations for Expenditure" or some similar name. A work order system is in force in practically every company of appreciable size today, and with more or less modification can be adapted to give the records required.

In order to obtain the necessary records for writing off the original cost of the property when it is retired, it is absolutely necessary that one additional step be added to this system as it is generally in force in most companies; viz, *an allocation of the cost of each piece of construction or property acquired must be made in detail when the work is completed, and preferably just before the work order is finally closed*, as such an analysis will frequently disclose inaccuracies in either debits or credits. This practise is followed by many companies to a certain extent at the present time, but must be applied to all work orders, and the final cost must be reduced to the same units that are liable to be needed in making estimates for withdrawals or additions. Unless the property acquired is going to last forever or be withdrawn from capital account as a unit, such an estimate must be made sometime, and there would seem to be no time when a more accurate analysis could be made than at the time the work is done or property acquired.

An analysis of costs made at this time would aid in checking up inaccurate distribution of labor and material, and it is very important to do this, as the fact must be recognized that all of these records are going to depend primarily for their accuracy on the proper distribution of labor and material by the construction foreman, and especial emphasis must be laid on this point.

Many companies are keeping at the present time an additional set of records which can be made to fit in nicely with a continuous or perpetual inventory. These records consist mostly of cards showing the location, type, size, and dates of installation, change in location, etc., of meters, transformers, poles and attachments, and possibly, in some cases, street lamps, services and similar items. As stated in the first section of this paper, such records are valuable for other than strictly inventory purposes but they are also essential for this purpose in connection with the forms suggested below.

The items of property for the purposes of inventory may be divided into four general groups as follows:

A. Those items which are large enough to be recorded individually or in small groups with one entry, but which are liable to be altered or changed in part; *e.g.*, buildings.

B. Items which may be recorded individually and which are withdrawn from service as a unit; *e.g.*, meters.

C. Items which must be recorded in units of length, pounds, or some similar units and miscellaneous items; *e.g.*, wires and cables, insulators, arresters, etc.

D. Those items of property which are usually carried in inventories at the present time and which are usually checked up by field inventory at regular intervals; *e.g.*, materials and supplies portable tools, office furniture, etc.

There may be considerable difference of opinion as to just what method should be followed in collecting the data required, but a general scheme could be followed for either a gas, electric, railway or railroad, telephone or telegraph, water or sewer utility or a private industrial plant by classifying the property in the general groups indicated above about as follows:

A. 1. Land and right of way.
2. Building and structures.
3. Equipment of stations, buildings, etc.

B. Poles, transformers, meters and services for an electric company; meters, services, fire hydrants, lamps, etc. for a water or gas company and similar items for these or other companies.

C. Wires, cables, conduits, crossarms, insulators, for an electric company; feeder cable, trolley wire, straight track, etc., for railways; transmission and distribution mains for water, gas and sewer companies.

D. Office equipment, shop equipment, stable equipment, etc.

Forms for Group A

The general form of recording data for items in group A in detail is given on form 1.

These data should be obtained from the completion report of the work order, an extra copy of which it might be advisable to file with other inventory data.

The basis for estimating the unit prices for the cost of brick wall removed (mentioned on form 1) should be found in this completion report. A list of the quantities involved should be available from the information and plans in the hands of the engineer responsible for the new addition. With this information there should be need for very little estimating which is not based on actual facts.

The summary of all such property classified under any particular account for any particular division or subdivision could be recorded on form 2 and the totals for that account or division readily obtained by summing up the items, on such occasions as a total is desired, probably no oftener than once each year.

Form 1

AMERICAN ELECTRIC CO.—*Subsidiary Co*...........:..
DIVISION—Northern *LOCATION—14th St. Belleville* *File No.* 5
Computer..............*Checker*............*App'd by*....*Date* ..*Acct. No.* 118
SUBJECT Substation Buildings............*Reference*............*Sheet No.* 1
(*or other similar items in Group A*)

Auth. No. and page	Date acquired	Description—As originally acquired or of addition or withdrawal	Area—Size or No. of units	Original cost		Total cost corrected to date for additions, etc.	Est. remaining life
				Per unit	Total		
543-10	1911	1-Substation Building Brick on concrete fndn. Slate Roof, etc. 40′ × 30′ One Story & Basement.	1200 sq. ft. 20000 cu.ft.	$2.00 .12	$2400	$2400	50
1585-4	1916	Brick wall removed 30′x18′ High			200	2200	45
1586-4	1916	Addition 10′x40′	400 sq. ft. 6667 cu. ft.	2.50 .15	1000	3200	46.6

EXPLANATORY NOTES ON USE OF FORM NO. 1

Note 1—If any item of property subject to depreciation is acquired subsequent to date of first use, this fact should be indicated together with other information available as to original construction, date, cost, etc.

Note 2—Remaining life of 45 years is obtained by subtracting 5 years elapsed between 1911 and 1916 from 50 year life first estimated.

Remaining life of 46.6 years is obtained by computing a weighted average of $2200 at 45 years and $1000 at 50 years.

Note 3—Present value on a basis of straight line depreciation may be readily obtained by multiplying $3200 by ratio of 46.6 years to 50 years, giving 93.2% and $2982.

Form 2

AMERICAN ELECTRIC CO—*Subsidiary Co*..... ....
DIVISION Northern *LOCATION All* *File No.* 5
Computer........*Checker*......*App'd by*......*Date*.............*Acct. No.* 118
SUBJECT Summary of Substation Buildings, 1916 *Sheet No.* 101
(*or similar item in Group A*)

Ref. Sheet	Item	Location	Date originally acquired	Cost to Jan. 1	Added	Withdrawn	Cost to Dec. 31	Present value Dec. 31	
								%	Amt.
1	SS Building	14th St. Belleville	1911	$2400.	$1000	$200	$3200	93.2	$2982.
2	ditto	First St. Nutley	1906	etc.					
					Transferred to sheet No. 1-10				

Form 3

AMERICAN ELECTRIC CO.—*Subsidiary Co*..............

DIVISION Northern *LOCATION All* *File No.* 5

Computer....*Checker*....*App'd by*....*Date*.....................*Acc. No.* 124

SUBJECT 5-kw. Transformers Type X *Reference*...... ....*Sheet No.* 1

(*or similar items in Groups B or C*)

Date	Ref. sheet	Number of units				Cost per unit	Total cost	Corrected total cost to date	Years	
		Added	Withdrawn No.	Withdrawn Date orig. installed	Net total to date				Av. Life units withdrawn	Av. age units installed
Brought Fwd.		Invento	ry Ja	n.1,1916	250	$62	$15,500	$15,500		5.1
1916		40			290	61*	2,400	17,940		
1916			2	1900	288	65†	130†	17,810	16	
1916			3	1901	285	64†	192	17,618	15	
1916		Invento	ry D	ec. 31,	285	61.82		17,618		5.08
1917										

* Average costs for all units of this size for any given period—say one year.

† Prices might be averaged and one figure shown or, if not much variation in price, they might be withdrawn at the average cost of the 250 shown at the beginning of the year

Form 4

AMERICAN ELECTRIC CO.—*Subsidiary Co*............

DIVISION Northern *LOCATION All* *File No.* 5

Computer....*Checker*....*App'd by*....*Date*.....................*Acct. No.* 124

SUBJECT Summary of Transformers—1916 *Sheet No.* 101

(*or similar item in Group B or C*)

Ref. sheet	Size	Type	Number of units				Cost of units				Av. cost per unit	Present value Dec. 31	
			Jan. 1st.	Added	With-drawn	Dec 31	Jan. 1st	Added	With-drawn	ec. 31	Dec. 31	%	Amt.
1	5 kw.	X	250	40	5	285	$15,500	$2,440	$322	$17,618	$61.82	4.6	$13.143
5	10 kw	X	100	20	2	118etc							

Transferred to sheet No. 1-10

Note:—"%" under "Present Value" for straight line depreciation would usually be obtained by comparing average age of units installed with average life of units withdrawn. In this case it is estimated that a 15 or 16-year life is not long enough and life base is arbitrarily taken as 20 years. In some cases it might be desirable to consider salvage in arriving at present value but it is disregarded above for sake of brevity.

Forms for Groups B and C

The same forms are recommended for both groups B and C, but the method of collecting the data required is different.

For both groups it is thought best to use unit costs averaged for the district into which the company chooses to subdivide its territory, say a tax district, and for a certain period of time, monthly, quarterly, or yearly. The average for labor, storeroom charges, miscellaneous material items, overhead charges, etc., would necessarily need to be computed after the close of the current period or the average taken from the preceding period and final adjustments made for variation.

The total quantities for all items in group B, for which a card record is assumed to be made, can be computed either from the cards or from the completion reports of the work orders. Probably the total could be obtained more readily from the card records, whether tabulated by hand or sorted and tabulated mechanically by means of the Hollerith system of card records.

For all items in group C, the totals of both quantities and prices would probably best be obtained and reconciled with the amounts given in the completion reports of all work orders involved, although they might be obtained from field books or street maps showing construction changes for the required period, or from pole record and manhole record cards which usually indicate the wires, cables, conduit, etc., extending to the adjacent units.

Form 3 shows method of recording a group of similar units, viz., 5-kw. transformers and Form 4 shows method of summarizing units of various sizes.

Forms for Group D

Form 5 is recommended for summarizing items in this group as it is contemplated to include only such items as a company carries or could reasonably carry on an inventory which is usually made at the present time by actual count. This inventory as applied to office furniture, large portable tools, etc., usually gives the estimated present value of these items and they are carried into the property account each year at this depreciated value.

The first entry for each of these items is naturally the cost new and it is recommended that this cost new be carried in the inventory in a parallel column with the depreciated value until such time as the item is retired. Also, that the total cost new of

Form 5

AMERICAN ELECTRIC CO.—*Subsidiary Co*............

DIVISION Northern *LOCATION Belleville Office* *File No.* 5

Computer....*Checker*....*App'd by*....*Date*......................*Acct. No.* 107

SUBJECT General Equipment, Dec. 31, 1916 *Ref*...............*Sheet No.* 101

(*or similar items in Group D*)

Quantity	Unit	Item	Year acquired	Original cost			Present value	
				Ref.	Unit	Amt.	%	Amt.
2		Typewriters................	1914	52	$79	$158	75	$118
2		Typewriter desks...........	1912	35	20	40	80	32
6		Bent wood chairs...........	1916	Bill	3	18	100	18
		Totals, Dec. 31...........				$216	77.7	168
		Additions 1916.............				18		
		Total of items Jan. 1......				$198		
		Totals per inventory 12-31-15		61		210		
		Withdrawals 1916...........				$12		

Transferred to sheet No. 1-10.

Form 6

AMERICAN ELECTRIC CO.—*Subsidiary Co*..............

DIVISION Northern *LOCATION*............................*File No.* 5

Computer....*Checker*....*App'd by*....*Date*......................*Acct. No.* 1

SUBJECT Grand Summary, 1916 *Sheet No.* 10

Acct. No.	Ref. Sheet	Item	Total cost				Present value	
			Jan. 1	Added	With drawn	Dec. 31	%	Amt.
101	5	Land, etc..................						
107	101	General Equipment.........	$210	$18	$12	$216	77.7	$168
118	101	Substation Bldgs...........	2400	1,000	200	3,200	93 2	2,982
124	101	Transformers...............	15,000	2,440	322	17,618	74.6	13,143
		Totals Northern Div. 1916	18,110	$3,458	$534	21,034	77.5	16,293

EXPLANATORY NOTES IN REFERENCE TO USE OF ABOVE FORMS.

Note 1. Loose leaf sheet 8½"x11" is recommended for all forms.

Note 2. For all withdrawals use red ink.

Note 3. Forms 1 and 3 constitute the continuous record. All other forms are made up when it is desired to arrive at totals and are correct for one date only. If periods used are different than calendar year, forms would be slightly modified.

Note 4. Provision for identifying computers, etc. on forms 1 and 3 after first entries could be made by having initials inserted in date column or by providing separate column.

Note 5. Figures carried to grand summary, form 6, are merely illustrative and not the totals which would be obtained if more entries were made on forms 2, 4, and 5.

Note 6. From totals on form 6, the amount of additions for which new securities may be issued may be readily determined.

Note 7. By comparing form 6 as filled out for 1915 with year 1916, the credit which must be made to reserve account from earnings to provide for the year's depreciation may be determined.

all items be carried in the property account; and that the estimated accrued depreciation of all such items should be carried in the depreciation reserve account instead of being charged directly to operation each year and lost sight of thereafter as is the practise with many companies today.

A comparison of such an inventory at the end of any year with the preceding will indicate the total value of all withdrawals and additions and a proper adjustment can then be made in one lump sum between the capital account and the depreciation reserve.

Form 6 is to be used as a summary of all property and probably needs no explanation in addition to notes given.

To carry out the above, it would seem advisable to create a separate department under the joint supervision of the chief engineer, general auditor or controller, and the official in charge of the Public Relations Committee of a utility if such a committee exists. The man in charge of this department should understand both engineering, accounting and statistical work, and be capable of co-operating with all other departments of the company to secure the full benefits possible to be derived as outlined in the first section of this paper.

The methods indicated above would necessarily need to be modified to suit the needs of any individual company, and in actually working out the same, it is probable that some modifications of the present system of records and accounting could be adopted which would materially lessen the amount of additional work which might appear to be necessary at first glance in inaugurating such a system of continuous inventory and appraisal.

Presented at the 326th meeting of the American Institute of Electrical Engineers, New York, November 10, 1916.

GROWTH AND DEPRECIATION

BY JULIAN LOEBENSTEIN

ABSTRACT OF PAPER

It is generally assumed that a complex utility property will depreciate to an approximately fixed per cent condition. This is shown by theoretical and actual curves to be incorrect. It is shown that the manner of the company's growth affects its per cent condition.

The necessity for reserves, the manner in which they may be kept and the return which should be allowed on them, whether reinvested or not, is discussed. Several Commission and Court decisions are quoted to show the tendency to disallow a return on a reserve and arguments are presented in refutation of the decisions.

The principal points are as follows:

1. The condition of a property is dependent not only on maintenance but also on its growth.
2. Property does not settle down to a fixed per cent condition.
3. Capital is kept intact by reinvesting reserve in extensions. Under this condition, depreciated value of the entire property is the fair one for rate making purposes.
4. For a company unable to use reserve in extensions a liquid depreciation fund will be necessary.
5. The same return, available for dividends, should be allowed on a reserve as on the remainder of the property.

IN THIS article the writer tries to bring out the following points:

First, to show that the per cent condition of any property is dependent not only upon the maintenance but upon the past and present growth.

Second, to show that under practically no condition will it be necessary to bring a property back to one hundred per cent condition, but that it does not settle down to some fixed per cent condition less than one hundred per cent. It does, however, go through a repeating cycle of conditions, one point in the cycle being a maximum above which it will never rise. This maximum point will depend entirely upon the growth of the property and should be studied separately for each property under consideration.

Third, to show that under certain conditions of growth, a growing company need keep no liquid depreciation reserve fund; that it may reinvest the reserve in extensions, making renewals as they come due in any given year, from the amount set aside for depreciation reserve in that year, and that by so doing the stockholders' capital is kept intact, yet the depreciated value of the whole property is the fair one, both for consumer and stockholder, for rate-making purposes.

Fourth, to show that for a company which has stopped growing or for one which is growing at a rate not large enough to use all of the depreciation reserve for reinvestment in extensions, it will be necessary to have a continually varying amount in a liquid depreciation reserve fund, and that this amount will fluctuate in a manner depending upon the company's growth.

Fifth, to show that since such a liquid reserve may be necessary for a growing company and will be necessary for a company which has ceased to grow, that the same return should be allowed on such a reserve as on any other capital invested in the property, and that such return should be available for dividends, provided that the cost new, less depreciation, is to be used as a basis for making the rates.

The following definitions and assumptions are made in the discussion. By liquid depreciation reserve fund is meant a reserve either as cash in a bank, invested in bonds or employed in any other way so as to be readily convertible into cash for immediate use. This is to distinguish it from depreciation reserve, which is invested in extensions and betterments and which cannot be readily turned into available cash. No consideration is taken of scrap value nor of a reserve for emergencies or catastrophies as the calculations are not in any way affected by such a fund, the effect being simply to refer them to a different ordinate. All calculations are on the straight line basis and all properties considered are assumed to be kept in the best state of repair. It is assumed that the depreciated value of the property will be used as a basis for making the rates.

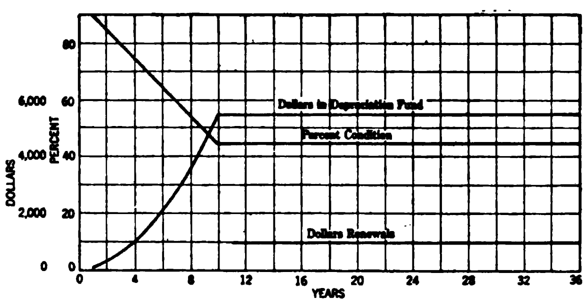
Before attempting to draw any conclusions from the tables, it is advisable to show how they were constructed and calculated. Table I is the calculation for a property in which a uniform capital investment of $1000 a year is made for ten years and the property then stops growing. All the elements of the property are assumed to have a ten year life. Table II shows a property similar in all respects but one, to that shown in Table I. In Table II the uniform investment is made for only five years of the ten. Table III is for a property the elements of which have a ten year life. In the first year the capital investment is $1000. In the second year the depreciation fund is used for

TABLE I.

UNIFORM YEARLY INVESTMENT FOR TEN YEARS

End of Growth—Tenth Year
Life—Ten Years
Depreciation reserve not invested in extensions

End of year	Capital invest. for the year	Total capital expenditures	Increment to Depr. fund	Deduction from depr. fund	Total in depr. fund	Percent condition
1	1000	1,000	100	0	100	90
2	1000	2,000	200	0	300	85
3	1000	3,000	300	0	600	80
4	1000	4,000	400	0	1000	75
5	1000	5,000	500	0	1500	70
6	1000	6,000	600	0	2100	65
7	1000	7,000	700	0	2800	60
8	1000	8,000	800	0	3600	55
9	1000	9,000	900	0	4500	50
10	1000	10,000	1000	0	5500	45
11	—	10,000	1000	1000	5500	45
12	—	10,000	1000	1000	5500	45
13	—	10,000	1000	1000	5500	45
14	—	10,000	1000	1000	5500	45
15	—	10,000	1000	1000	5500	45
16	—	10,000	1000	1000	5500	45
17	—	10,000	1000	1000	5500	45
18	—	10,000	1000	1000	5500	45
19	—	10,000	1000	1000	5500	45
20	—	10,000	1000	1000	5500	45



CURVE I—UNIFORM INVESTMENT FOR TEN YEARS

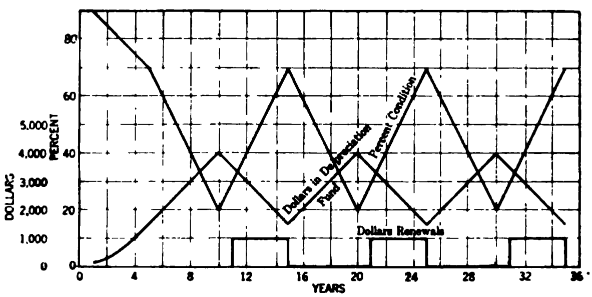
End of growth, tenth year—life, ten years—depreciation reserve not invested in extensions.

investment in extensions and enough additional capital is invested to bring the investment of both capital and reserve for the year, up to $1000. The same procedure is followed each year until at the end of the tenth year the property ceases to have any further additions. Table IV is for a property the elements of which have a ten year life. Starting with an invest-

TABLE II.

Uniform yearly investment for five years
End of growth—fifth year
Life—ten years
Depreciation reserve not invested in extensions

End of year	Capital invest. for the year	Total capital expenditures	Increment to depr. fund	Deduction from depr. fund	Total in in depr. fund	Percent condition
1	1000	1000	100	0	100	90
2	1000	2000	200	0	300	85
3	1000	3000	300	0	600	80
4	1000	4000	400	0	1000	75
5	1000	5000	500	0	1500	70
6	—	5000	500	0	2000	60
7	—	5000	500	0	2500	50
8	—	5000	500	0	3000	40
9	—	5000	500	0	3500	30
10	—	5000	500	0	4000	20
11	—	5000	500	1000	3500	30
12	—	5000	500	1000	3000	40
13	—	5000	500	1000	2500	50
14	—	5000	500	1000	2000	60
15	—	5000	500	1000	1500	70
16	—	5000	500	0	2000	60
17	—	5000	500	0	2500	50
18	—	5000	500	0	3000	40
19	—	5000	500	0	3500	30
20	—	5000	500	0	4000	20



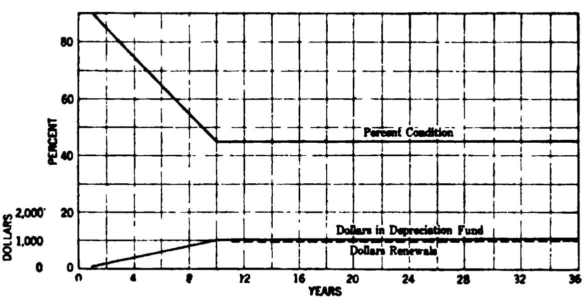
CURVE II—UNIFORM YEARLY INVESTMENT FOR FIVE YEARS
End of growth, fifth year—life, ten years—depreciation reserve not invested in extensions.

ment of $1000 the first year, the investment decreases one hundred dollars per year until the tenth year, at which time the property stops growing. The depreciation reserve is not re-

TABLE III.

Uniform yearly investment for ten years
End of growth—tenth year
Life—ten years
Depreciation reserve invested in extensions

End of year	Capital Invest. for the year	Total capital expenditure	Investment for the year from depr. reserve	Total investment capital plus reserve	Increment to depr. fund	Deduction from depr. fund	Total in depr. fund	Percent condition
1	1000	1000	—	1,000	100	—	100	90
2	900	1900	100	2,000	200	100	200	85
3	800	2700	200	3,000	300	200	300	80
4	700	3400	300	4,000	400	300	400	75
5	600	4000	400	5,000	500	400	500	70
6	500	4500	500	6,000	600	500	600	65
7	400	4900	600	7,000	700	600	700	60
8	300	5200	700	8,000	800	700	800	55
9	200	5400	800	9,000	900	800	900	50
10	100	5500	900	10,000	1000	900	1000	45
11	—	5500	—	10,000	1000	1000	1000	45
12	—	5500	—	10,000	1000	1000	1000	45
13	—	5500	—	10,000	1000	1000	1000	45
14	—	5500	—	10,000	1000	1000	1000	45
15	—	5500	—	10,000	1000	1000	1000	45
16	—	5500	—	10,000	1000	1000	1000	45
17	—	5500	—	10,000	1000	1000	1000	45
18	—	5500	—	10,000	1000	1000	1000	45
19	—	5500	—	10,000	1000	1000	1000	45
20	—	5500	—	10,000	1000	1000	1000	45



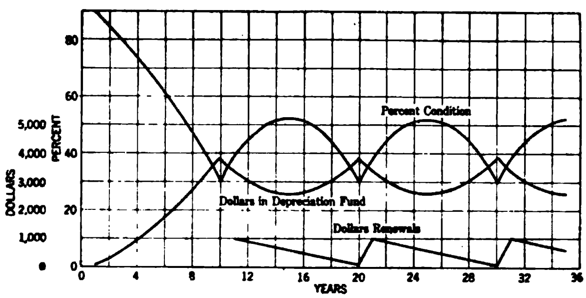
CURVE III—UNIFORM YEARLY INVESTMENT FOR TEN YEARS
End of growth, tenth year—life, ten years—depreciation reserve invested in extensions.

invested. Table V shows a property consisting of two life groups having lives of ten and twenty years respectively. Starting with a capital investment of five hundred dollars for each of

TABLE IV.

Decreasing yearly investment for ten years
End of growth—tenth year
Life—ten years
Depreciation reserve not invested in extensions

End of year	Capital invest for for the year	Total capital expenditure	Increment to depr. fund	Deduction from depr. fund	Total in depr. fund	Depreciated value of property	Percent condition
1	1000	1000	100	—	100	900	90.0
2	900	1900	190	—	290	1610	84.6
3	800	2700	270	—	560	2140	78.3
4	700	3400	340	—	900	2500	73.6
5	600	4000	400	—	1300	2700	67.5
6	500	4500	450	—	1750	2750	61.0
7	400	4900	490	—	2240	2660	54.3
8	300	5200	520	—	2760	2440	47.0
9	200	5400	540	—	3300	2100	38.9
10	100	5500	550	—	3850	1650	30.0
11	—	5500	550	1000	3400	2100	38.2
12	—	5500	550	900	3050	2450	44.5
13	—	5500	550	800	2800	2700	49.1
14	—	5500	550	700	2650	2850	51.7
15	—	5500	550	600	2600	2900	52.8
16	—	5500	550	500	2650	2850	51.7
17	—	5500	550	400	2800	2700	49.1
18	—	5500	550	300	3050	2450	44.5
19	—	5500	550	200	3400	2100	38.2
20	—	5500	550	100	3850	1650	30.0



CURVE IV— DECREASING YEARLY INVESTMENT FOR TEN YEARS

End of growth, tenth year—life, ten years—depreciation reserve not invested in extensions.

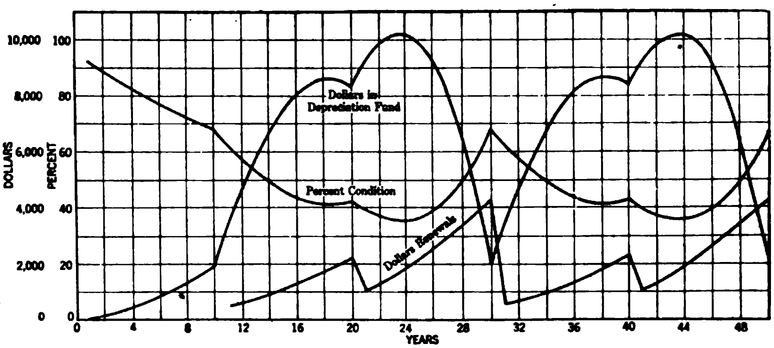
the groups, the capital investment is incrased one hundered dollars a year for each group for the ten years. In each year an equal amount has been reinvested in each life group, so that the total of such investments for any given year is nearly equal to the amount set aside in the depreciation reserve the year before. This continues up to and including the tenth year after which time further investments are discontinued, but renewals are made as each portion of the original investment reaches the end of its life.

It may be well here to point out something worthy of note which developed in the course of the calculation. It will be seen, by reference to Table V, that in every case, the sum of the dollars remaining in the fund (column 15) and the depreciated value of the property (column 17) giving (column 18) the total value of the property, is the same as the total capital expenditure (column 6). This furnishes a short method of calculating the depreciated value of the property *i.e.* by subtraction instead of by the depreciation of each year group. Take for example the tenth year: the long method is:—

Dollars	Per cent remaining value	Dollars remaining value
500	0	0.00
500	50	250.00
630	10	63.00
630	55	346.50
790	20	158.00
790	60	474.00
940	30	282.00
940	65	611.00
1100	40	440.00
1100	70	770.00
1300	50	650.00
1300	75	975.00
1500	60	900.00
1500	80	1200.00
1700	70	1190.00
1700	85	1445.00
1950	80	1560.00
1950	90	1755.00
2150	90	1935.00
2150	95	2042.50
		$17,047.00

This $17,047, the depreciated value of the property, as obtained above, plus $1953, the dollars in the depreciation fund, is equal to the total capital expenditure of $19,000. The short method is therefore, to subtract the dollars in the depreciation fund from the total capital expenditure to get the depreciated value of the property. This method was followed in the calculation of the table.

It is generally considered that a property maintained in good operating condition will be between 70 and 85 per cent new. In fact, Whitten, in his Valuation of Public Service Corporations, discussing depreciation says, (Vol. I, page 358, par. 421) "It has been stated that a street railway maintained in good operating condition will necessarily show cost less depreciation of from 70 to 85 per cent of the cost new". That this is an entirely fallacious assumption and that the percent condition of any property is not only a function of its maintenance, but also



CURVE V—INCREASING YEARLY INVESTMENT FOR TEN YEARS

Life { one group, ten years
one group, twenty years

End of growth, tenth year—depreciation reserve invested in extensions.

most decidedly of the manner of its growth, is shown by the accompanying tables and curves.

It is now an easy matter to prove that Mr. Whitten's assumption is wrong, and also to prove the first point, which is that the per cent condition of any property is dependent not only on the maintenance, but upon the past and present growth. Referring to the tables, we see that in Table I and Curve I, where there has been a uniform investment over a term of years corresponding to the life of the property, the per cent condition varies from 90 to 45 during that term, and then stays at 45 when the property stops growing. The per cent condition appears as 45 instead of the proverbial 50 because, in the calculations, the end, instead of the beginning of the tenth year is considered. In Table II and Curve II, where there is a uniform investment

...nt to depr. ... the year	Total increment for the year to depr. fund
20 year life group	
No. 11b = $\frac{\text{No. 8}}{20}$	No. 12 No. 11a + No. 11b
25.00	75.00
56.50	169.50
96.00	288.00
143.00	429.00
198.00	594.00
263.00	789.00
338.00	1014.00
423.00	1269.00
520.50	1561.50
628.00	1884.00
628.00	1884.00
628.00	1884.00
628.00	1884.00
628.00	1884.00
628.00	1884.00
628.00	1884.00
628.00	1884.00
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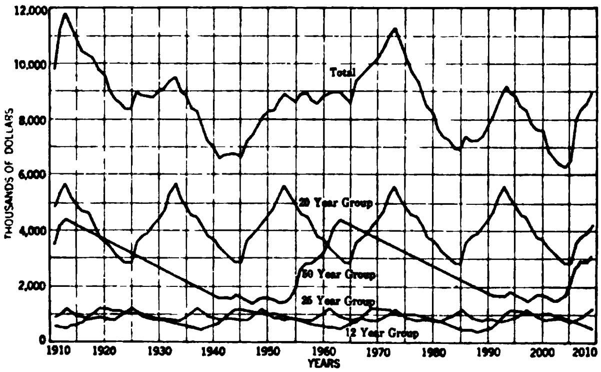
over a term of years not corresponding to the life of the property, the per cent condition varies from 90 to 70, while the property is growing. After that it varies in repeating cycles from 70 to 20 and back to 70 again. This, of course, is an extreme case, but it shows the possibilities of variation. Table III and Curve III show the same characteristics as Table I, although in Table I there is no reinvestment of reserve, while in Table III there is. Table IV and Curve IV show a more complicated property than the others. Here the variation during the ten years the property is expanding, is from about 92 to about 67. It then goes through a repeating cycle whose period is twenty years, varying from 67 to 35 per cent and back again.

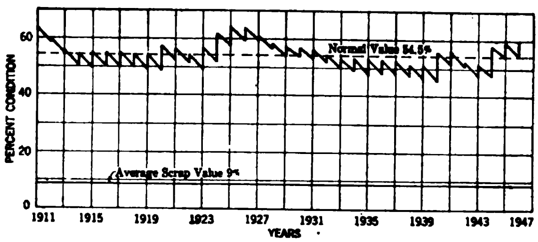
Thus it may readily be seen that a company which grows at an



CURVE VI—DEPRECIATED SERVICE VALUES OF AN ACTUAL PROPERTY
End of growth assumed Dec. 31, 1913—original service value $16,500,000—maximum per cent condition 69.0 per cent—minimum per cent condition 37.5 per cent.

increasing rate will have a lower per cent depreciation in any given year, than a company which grows at a uniform rate, all other conditions being assumed the same. Furthermore, if both companies reach their maximum growth at the same time, thereafter their per cent condition will vary one from the other; first, because of the discrepancies between the terms over which the investments have been made and the life terms of the groups (compare Tables and Curves I and III) and second, because of the dissimilar manner in which the investments have been made (compare Tables and Curves IV and V).

Moreover this is borne out not only by the theoretical calculation, but Curve VI shows this condition for an actual electric property. The company was assumed to have reached its final growth on December 31st, 1913 after which date only renewals were made. The total service value of all the property was approximately $16,500,000 yet it may be seen from the curve that the actual service value varies from $6,200,000 to $11,000,000 or from 37.5 per cent to 69 per cent. Now, even supposing that some of the assumptions as to probable life are incorrect, the property will still vary over a wide range and not be in any popularly supposed fixed condition somewhere between 70 and 85 per cent. Curve VIII is for another actual property but a much smaller one than that considered in Curve VI. The property is assumed to reach its full growth in 1912, and the remaining service value is shown for the next 53 years. The service value varies from $810,000 to $370,000 or a corresponding per cent variation from 77 to 35.



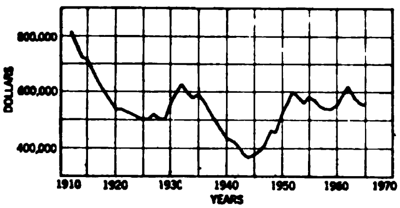
CURVE VII—TOTAL COMPOSITE THEORETICAL VALUE CURVE OF THE DEPRECIABLE PROPERTY OF THE UNITED RAILWAYS CO. OF ST. LOUIS AS GIVEN IN THE REPORT ON THAT PROPERTY BY THE ST. LOUIS PUBLIC SERVICE COMMISSION—1912

Before passing to point two, it is pertinent to quote again from Whitten, who says, (Vol. 2, page 1127, par. 1285). "We know, however, that there is a tendency for all utilities to settle down after a time to a more or less uniform condition as regards the percentage amount of accrued depreciation, and the annual requirements for renewals and replacements. After the various parts of a large public utility plant have gone through complete cycles of renewals, the plant settles down to a condition in which, saving extraordinary functional depreciation, expenditures for maintenance, repairs and renewals become practically constant. There is little fluctuation from year to year and the averages by five or ten year periods are practically identical. This settling down or equalizing process, is very greatly hastened by the fact that all large systems are constructed piecemeal."

The above theory, which the writer has tried to refute, is also supported by Mr. James E. Allison, Chief Engineer of the St. Louis Public Service Commission, who in the report on the United Railways Company of St. Louis, presents the curve which is here reproduced as Curve VII. He says, (Appendix A, page 89):

"It has been the purpose of the writer to show by diagrams that piecemeal built properties of any complexity, will eventually assume a theoretical value curve, closely conforming to the straight normal value line, halfway between 100 per cent and the composite scrap value of the property."

It cannot be denied that the curve which he gives most certainly is a uniform curve and tends to support his theory. It should be noted though, that even his curve varies over a range of 15 per cent during the comparatively short time of 13 years, and although 15 per cent is small, it takes a different aspect when considered as 15 per cent of $30,000,000, the approximate value of the property, or $4,500,000.



CURVE VIII—DEPRECIATED SERVICE VALUES OF AN ACTUAL PROPERTY

End of growth assumed Dec. 31, 1912—original service value $1,056,917—maximum per cent condition 77.0 per cent—minimum per cent condition 35.0 per cent.

As previously stated, the curve shown by Mr. Allison, is a remarkably smooth one, but when compared to Curves VI and VIII, it shows the danger of drawing a general conclusion from any one curve. Every complex property undoubtedly displays the tendency which Mr. Allison points out, but it would be decidedly unsafe to apply it indiscriminately to any property. The point is that each property should be investigated separately to determine its characteristics in this respect.

The second point, to show that under practically no condition will it be necessary to bring a property back to 100 per cent condition, has already been presented by many other writers, but it is given here again in conjunction with the conclusion from point number one. It is obvious that any property which has been built up gradually and not all at once, will have its various parts wear out in a similar sequence to that in which they were installed. Since different portions of the property will have to be replaced each year, it will never be necessary to replace all of them at once and so bring the property back to one hundred per cent condition.

As far as the point just made goes, most writers are agreed, but having reached that conclusion they claim that the property remains at a certain fixed condition, the exact per cent depending on the maintenance.

It is perfectly true that the entire property will not have to be renewed at any one time but only in the condition where there has been a uniform growth over a term of years corresponding to the life of the property (see Table I and Curve I) will the property reach a fixed condition and remain there after the property has stopped growing. Also, as long as a property is growing whether uniformly or otherwise, there will be a variation in its per cent condition. In other words, there is an obligation to renew varying amounts of property in different years in the future, and any calculation of reserves based on an assumption that because of perpetual life the company will reach a stable condition either during or after its growth is entirely incorrect.

It will be noticed from an examination of the tables that while the property is growing, the per cent condition is decreasing, the rate of decrease varying inversely with the rate of growth. When the property stops growing it has reached a certain per cent condition and thereafter it varies between that condition and some other, dependent upon the manner of growth. When the growth stops the property may be at a minimum per cent condition, as in Table IV and Curve IV, where there has been a decreasing rate of growth; or at a maximum as in Table V and Curve V where there has been an increasing rate of growth. Table IV and Curve IV show that the property will vary between 30 and 53 per cent, while Table V and Curve V show, in that case, a variation of from 35 to 68 per cent.

From the above figures it is evident that each property, should it stop growing, will go through a cycle in which it reaches a certain maximum condition less than 100 per cent, this maximum condition being entirely dependent on the manner of the property's growth.

It may be argued that the writer has made arbitrary and special assumptions in taking cases where the period of growth corresponds to the life of the property, but both Tables II and V are based on other assumptions. Besides this, it is worth bearing in mind that any property may be divided into a series of groups in which the investment term corresponds to the life term, and that each of these groups will follow a condition curve of its own. For a complex property, therefor, there would be a series of such curves which would give a resultant one. This resultant curve, however, would also vary over a considerable range. This is borne out by Curves VI and VIII of actual properties.

Since it will never be necessary to renew the entire property, some of the reserve necessary to return it to the 100 per cent condition may be dispensed with. It is not correct, however, to say that since the reserve will never be needed it should not be obtained. The stockholder has a right to expect that his capital be kept intact at 100 per cent. How then is the reserve to be handled? This is taken up as the third point.

There are three conditions which may be used as divisions for the consideration of the laying aside and use of depreciation reserve. These are:

1. Company growing at the great enough rate to permit the investment of all the reserve in extensions.

2. A company not growing at a great enough rate to permit the investment of all the reserve in extensions.

3. A company which is not growing.

Take the first case, where a company is growing at a great enough rate to permit the investment of all the reserve in extensions. It is clear that the annual charge for depreciation will, in some years be less, and in some years more, than the cost of renewals. In those years that the cost of renewals is less than the charge for depreciation, the difference may be invested in extensions, and in those years in which the cost of renewals is greater than the depreciation charge, it will be necessary to issue securities with the extensions made from reserve as a basis, using the money from the securities for the renewals. The securities, however, should not be issued to an amount greater than the depreciated value of the extensions. Wherever the depreciation reserve is invested in extensions, it is necessary to keep a careful record of property of this class. It is essential that separate accounts be kept for capital investment and reserve investment. The trouble in the past was that no attempt was made to keep them separate.

In the second case, where the company is not growing at a great enough rate to permit the investment in extensions of the difference between depreciation charge for the year and renewals for the year, and in the third case where the company has stopped growing, it will be necessary to keep the surplus of annual allowance over cost of renewal for certain years, in a liquid reserve fund, so as to be able to make up the deficiencies in other years. That some money must be so kept is now clear, for point one shows the wide fluctuations in per cent condition and in yearly renewals. How much must be so kept will be discussed under point four.

At present it is interesting to consider in what years the peak demands, requiring a security issue for the first case and a withdrawal of money from the liquid reserve in the second and third cases, will fall. In any complex property there are groups of things having different costs and different lives installed in the same and different years. If the cost is considered as amplitude, the lives as frequency, and the years as phase displacement it may readily be seen that as different waves come into step and pass out again, peaks and valleys will occur. In order to determine the variation in renewal charges it will be necessary to make tables and plot curves of the future renewals in each group. These curves will take the same general form as those in Curve VI, but will be for total replacement costs, instead of remaining service value as shown there. If tables are once compiled it is a simple matter to change them yearly as further extensions are made in the various groups. By following such a plan it will be easy to see whether or not adequate provision is being made for the handling of future extensions and to predict in what years it will be necessary to issue securities.

As described in the introduction, the second portion of point three is to show that by reinvesting depreciation reserve in extensions, the stockholders' capital is kept intact, yet the depreciated value of the property is the fair one for rate making purposes both from the point of view of the consumer and the stockholder.

Table V is for a property in which the depreciation reserve is invested in extensions. Let us consider the tenth year. Here the total expenditure on the property both from capital and reserve is $25,120, which has depreciated to $17,047. This latter sum plus $1953, which has been accumulated in the depreciation reserve during the past year and which as yet could not be reinvested, gives $19,000 the capital expenditure. Therefor, with the exception of the amount ($1953) accumulated in the reserve fund during the current year and not yet invested, the depreciated value of the property is equal to the capital investment. Omitting for the time being the question of allowing a return on the $1953 not reinvested, it is seen that allowing a return on the depreciated value of the property is practically equivalent to allowing a return on the original investment. The question of allowing a return on the amount held as liquid depreciation fund ($1953) in the above case will be considered under point five. This procedure described above, is therefor fair to the consumer, for he is paying a return on the value of the property in use, and it is fair to the stockholder for he is earning a return on his original capital.

The fourth point is to show that for a company which has stopped growing or for one which is growing at a rate not large enough to use all of the depreciation reserve for reinvestment in extensions, it will be necessary to have a continually varying amount in a liquid depreciation reserve fund and that this amount will fluctuate in a manner depending upon the company's growth.

Table V shows the condition for a property which has ceased to grow after ten years. At the end of the tenth year there are $1953 in the reserve. The sum laid aside annually for depreciation after that is $1884, yet owing to the fact that the company has grown faster at one time than at another, in some years there will be less than $1884 used for renewals and in some years more. The effect of this is to accumulate a fund over a certain period of years which is used over another period of years. Thus, starting with $1953 in the tenth year, the fund reaches a maximum of $10,149 in the twenty-fourth year; after which it decreases to $1953 again in the thirtieth year. This is graphically shown in Curve V. It is evident that since the $1953 will never be used as far as renewal purposes go, it may as well be returned to the stockholders. Since it is assumed that the company has stopped growing, the hypothesis precludes the possibility of using it for extensions and it should therefor be returned to the stockholders in the form of cash. It should be clearly understood by the stockholders that this is a return of capital and not a dividend payment.

Curve V is for the conditions assumed for this particular case. Any other manner of growth would give a different curve. In order to tell for any other property just what accumulation would take place and to determine how much, if anything, may be returned to the stockholders because it will never be used, it would be necessary to make a study similar to the one shown.

It is not very difficult to see that for a company which is growing, but at a rate too small to use all the reserve, that portion of the reserve which is not invested in extensions and betterments will bear the same relation to the renewals as the entire fund does in the case where the company is not growing at all. That is, there will be an accumulation curve for the liquid reserve which will be similar to the curve for a non-growing property.

In either case there will be a necessity for a liquid depreciation reserve for renewals and this reserve will vary from year to year. This fluctuation may be likened to the storage of energy in a flywheel. Just as there is no way to remove the energy from the flywheel except by stopping it, so there is no way of avoiding the fund as long as it is desired to make the renewals as they fall due. While the energy is stored in the flywheel it is of no direct use; yet it would be impossible to run the engine without a flywheel. The energy must be so stored to make it instantly available. The depreciation fund must also be stored to make it instantly available.

The fifth point is to show, that since such a liquid depreciation reserve may be necessary for a growing company and will be necessary for a company which has ceased to grow, that the same return should be allowed on such a reserve as on any other capital invested in the property, and that such return should be available for dividends, provided that the cost new, less depreciation is to be used as a basis for rate making.

Before trying to prove this point, the following decisions are given to show the stand taken in some cases in regard to this matter. The Nebraska State Railway Commission says in Re Application of the Lincoln Telephone and Telegraph Company, for authority to increase rates (A. T. & T. Co., Com. L.134 June 26, 1913, Nebraska State Railway Commission) "It will also be the policy of the Commission to expect of the corporation that it shall, so far as possible, use the depreciation funds . . . . in making extensions and betterment of the plant. Such part of the plant as is represented by the investment from the depreciation reserve shall be permitted to earn the same ratio of return as the stockholders' investment, but neither such reserve fund nor the earnings therefrom shall be available as dividends to stockholders, or for any other purposes than those set out."

In this decision the commission allows a return but it seems to consider the reserve as a sinking fund, the returns on which must be put into the fund. Further, it differentiates between investment from reserve and stockholders' investment as though the depreciation reserve were not also stockholders' investment.

In the Louisville and Nashville R. R. Co. v. Railroad Commission of Alabama the special master says (U. S. Circuit Co., Middle Dist. of Alabama. Report of Wm. A. Gunther, Special Master in Chancery, 1911) "The defendants further insist that interest should be allowed on the balance in the replacement account. It is a mistake to suppose that such a charge is proper."

Also in the case of the Louisiana R. R. Commission vs. Cumberland Telephone Co., (212 U. S. 425) the Court says: "That it was right to raise more money to pay for depreciation than was actually dispersed for the particular year there can be no doubt, for a reserve is necessary in any business of this kind, and so it might accumulate, but to raise more than money enough for the purpose and place a balance to the credit of capital upon which to pay dividends cannot be proper treatment."

There are two chief arguments against allowing a return on the depreciation fund. The first applies only to that portion which is not invested in extensions. It is to the effect that since the fund is lying idle, bringing no return, or is at best invested in bonds bringing a low return, that this is all the return to which it is entitled. The second argument applies either to the case where there is a liquid reserve or the reserve is invested in extensions. It is to the effect that since the money for the reserve is furnished by the consumer, he should not further be required to pay a return on it.

Taking the second argument first. The whole discussion hinges to a large extent on the question as to whether or not the stockholder may expect that his capital be kept intact at 100 per cent. How many men would go into a business of any kind if they could not make enough to replace their capital goods as they wore out and besides earn a return on their investment? That all businesses do not do this does not alter the fact that they expect to do so when they start. The recognition of depreciation and the allowance therefor is in itself an acknowledgment of the correctness of keeping the capital intact.

The capital which is wasting away is certainly the capital of the stockholder. He uses up his capital in the service of the consumer and the consumer replaces the capital so used. The consumer is making a just restitution. He is replacing something which originally belonged not to him but to some one else. Why then should the replaced capital have a different status from the original? It should not. The capital in a depreciation reserve fund should be treated the same as any other capital. It should be allowed the same return and for the same purposes.

Some argue that since the depreciation fund is lying idle (*i.e.* that portion not invested in extensions) or at best is invested where it brings only a low return, it is not entitled to more than it can earn. But is it lying idle? It has been shown that for any other than a growing company which can invest the entire reserve in extensions, there will necessarily be a continually varying amount in the liquid reserve. Besides this, even a growing company will have to carry from year to year some of the fund which it cannot reinvest at once. Is the depreciation reserve not just as necessary a part of the business as the working capital, of which there must always be a more or less fluctuating excess earning a low return, but which no one denies is entitled to the same rate of return as the capital actually invested in useful physical property? Is the liquid reserve, which is the stockholders' capital, not a guarantee to the consumer that the property will be maintained in first class operating condition and so give him the best of service? It may be said that he has a right to expect good service, but most people when not considering a public utility are willing to pay extra for good service. Thus, under competitive conditions a company which kept no reserve could give service at a lower rate than one which did, but it would be neither as good nor as reliable as that furnished by a company which kept a reserve. Would the public not be willing to pay for the greater reliability and better service?

No one questions the fairness of the proposition that the company be made to pay interest on deposits of consumers, yet in viewing that question the only consideration is that the consumer is deprived of the use of his money and should receive a recompense for it. The corporation's use of his money is not thought of for a moment in deciding whether or not such a charge is fair. To be sure, the company may devote it to a profitable use, but assuming that the company was not on a paying basis would that in any way alter its obligation to pay interest on the deposit? The stockholder is in much the same position as the consumer described above. He is deprived of the use of some of the money; but why should there be any further consideration of the justness of allowing him a return, regardless of what the corporation does with his money within legitimate limits, than there is in the case of the consumer? If the argument is to be that the funds are lying idle would it not be just as fair on the part of the corporation to say "Because the consumers' deposit will never have to be paid back in a lump sum, we will use them in our depreciation reserve and since it is lying idle we will have to pay no interest on the deposits"? What a howl would go up!

To bring out the point still more clearly, refer again to Table V. Suppose that an appraisal were made in the twenty-first year when the property was in a 39 per cent condition. It would be unfair to base rates on the $9783 which is the corresponding value of the property, when it is known that as the renewals are made the per cent condition will go up as high as 68. Under this scheme the rates would depend entirely upon the condition of the property in the year it was appraised and there can be no question as to the unfairness of such a proceeding. The rates should be based on the depreciated value of the property in any year plus the amount in the depreciation reserve, provided only that the sum is not greater than the original capital expenditure.

In conclusion it may be said (1) No matter how large a property is, it will not necessarily come to any fixed per cent condition nor anywhere near it. (2) The per cent condition of any property, the amount in the reserve fund, and the rise of the reserve fund depend upon the past, present, and future growth of the company, and that these conditions and their relations should be studied for any property whether a public utility or a private corporation. (3) Rates should be based upon the depreciated value of the property plus the amount in the depreciation reserve as long as the sum is not greater than one hundred per cent of the total capital investment.

Discussion on "The Effect of Recent Decisions on the Work of Inventory and Appraisal" (Betts), "Continous Inventories: Their Preparation and Value" (Carver,) "Growth and Depreciation" (Loebenstein), New York, November 10, 1916.

W. B. Jackson: I have been very much interested in this matter of detailed inventories and appraisals, and of the need of our electric properties and companies making the accounting of materials and plant coextensive, if I may put it that way, with the accounting of the money elements.

I believe that a detailed inventory and cost record of a public service property is valuable in giving to those in charge of the property a visualization of the property which they cannot obtain in any other way, both from the purely physical point of view and from the point of view of the spread of the cost over the property. Also it gives an exceptionally fine record by which to obtain the proper in and out charge in case of changes and improvements.

I believe that a careful record of ages should be kept of all property, for statistical purposes, but I do not believe that a so-called "depreciated value" or an estimated remaining useful life should be carried along as a part of the inventory and appraisal record, because it is likely to become seriously misleading, inasmuch as the estimated useful lives of the different parts of the property change as the months go by, almost as the days go by, and as they change, so change the estimated depreciated values.

The Wells Power Company, which is now operated by the Milwaukee Electric Railway and Light Company, the operations of which were directed by my firm for many years, carries a fully detailed inventory and cost record of its property. The records are in full detail, and as changes are made they are entered upon change sheets in like detail with the inventory. The change sheets cover the period of a year, at the end of which period the inventory is readily brought to date. These records are considered highly valuable by the managers of the Wells Power Company and the Milwaukee Electric Railway and Light Company.

Mr. Loebenstein's paper is more than anything else a demonstration of the extremely uncertain features of so-called "accrued depreciation," and of the serious danger in making it an important factor in determining the value of a property. In his consideration, he has taken the simplest possible assumptions, which do not agree with practical experience, and draws therefrom direct conclusions. Even with this relatively simple and academic handling of the subject, it is easy to see the uncertainty of the results arrived at. He has divided the property into classes of units, each class being assigned a useful life, and they are treated as though they would actually behave as they are assumed to behave, but they will not do so. Take, for example, a plant having four small steam turbine generators, to which, for illustration we may assign twenty-five years' useful life. There is not the least chance that these units actually comply with our assumption. At the end of ten years two might be displaced by a larger or improved unit, and after a while one or two more, and so on.

Let us consider another quite different character of property, such as wood poles. It is possible that fifteen years' useful life may be assigned to them. The useful life of wood poles, *per se*, may vary from six years to twenty years, and the character of ground in which the poles are set may cause a variation of 100 per cent or more in a fairly large system. And so we might analyze each class of property.

Thus, when we superimpose the uncertainties and complications arising from the variables which are found in practise upon Mr. Loebenstein's complex but relatively simple computations, we have a result upon which one certainly cannot predicate values with any reasonable degree of confidence.

Let me state, however, before closing, that where there are no figures developed from actual operation, the best estimate of the amount of annual appropriation, over and above current maintenance and repairs, that is necessary for deferred maintenance and renewals, can be obtained by the use of methods in the general line of those outlined by Mr. Loebenstein, but such year by year estimates, which may and should be revised periodically, are very different from formally predicating the value of the property on figures dependent upon such calculations.

G. W. Whittemore: In the consideration of this subject it may be worth the few moments necessary briefly to recall the several meanings of the term "depreciation", as it is generally used.

In Webster's Dictionary the word depreciation is given two meanings, viz:

1st "The act or process of depreciating", that is, the lessening in value of one kind or another.

2nd "The condition of being depreciated", or of having suffered a loss in value.

An act or process may differ from a state or condition merely as a cause differs from its effect. Yet the two meanings in this case are so lacking in identity, and the methods of expressing or measuring them so far apart, that the distinctions to be made in the unqualified term depreciation must be kept clear.

In the practical problems involved in the management of public and other utility properties, and in the consideration of the former by regulatory bodies, both of these branches of the subject of depreciation have been dealt with under various designations. Among the more common of such designations are:

Anticipated Depreciation, Theoretical Depreciation, or the Expense of Depreciation:

To the act or process of depreciation, as mentioned above, corresponds the preceding terms which are frequently used to denote this first branch of the subject.

As the term "anticipated depreciation" indicates, it implies the recognition of the fact that as time goes on, all property, as a rule, loses value, or suffers a reduction in the total quantity of service of which it was initially capable. We are accustomed to refer to permanent improvements and fixed capital. Strictly speaking, no improvements are permanent and no capital is fixed. Such property is permanent or fixed only in a relative sense, and in comparison with other forms of property of shorter life. Ultimately, all property used by a company or an individual in his business, except, generally speaking, land itself, is destined to ultimate retirement. "Repairs may postpone but cannot prevent such an outcome."

From this point of view the locomotive used in hauling a train is property consumed in operation, just as much as is the coal burned by the locomotive. The element of time is the only difference in the two cases. The coal may last a few hours. The locomotive may last many years. Eventually, both disappear as elements of cost in the conduct of the business.

Anticipated depreciation, considered quantitatively, is therefore an attempt to forecast the amount or proportion of the reduction in its initial value that will disappear from a property while ownership is retained. In other words, what is to be the total loss suffered during the process of depreciating.

Whether such loss is taken as occurring uniformly or not is a subordinate question. In any event, the final effect is the same; viz., the full amount of the anticipated depreciation is lost or consumed in the conduct of the business.

Such predictions as to the proportionate amount of loss vary, of course, for each class of property. They are estimates, and must all necessarily be based upon the accumulated experience of the past, and upon forecasts of the effects, each in its proper proportion, of the various influences recognized as tending to reduce the useful life of the particular portions of property under consideration.

The point to be borne in mind, as differentiating this anticipated from the other forms of depreciation, is that it is an attempt to look into the future and evaluate what such future may have in store.

Quite frequently, the term theoretical depreciation has been used in the sense in which anticipated depreciation has just been employed. The use of this term theoretical, however, would seem to offer some chance for misapprehension. Oftentimes the word theoretical is employed to contrast what is possible, but not likely, with what is real and certain. There is no doubt, however, about the reality and inevitability of this anticipated or theoretical depreciation. The only uncertainty connected with the subject is just how long the limited (and not unlimited), period of usefulness of the particular property in mind will continue.

In place of the term anticipated or theoretical depreciation, when the reference is to the act or process of depreciating, the uniform system of accounts prescribed by the Interstate Commerce Commission for the use of the telephone and telegraph companies, employs the term, the "expense of depreciation." Therein these words are defined as follows:

(a) The losses suffered through lessening in value of the tangible property from wear and tear that are not covered in any prescribed account covering current repairs.

(b) Obsolescence or inadequacy resulting from age, physical change or supercession by reason of any inventions or discoveries, change in public demand or public requirements; and

(c) Losses suffered through destruction of property by extraordinary casualties.

The companies referred to are compelled to include in their operating expenses amounts deemed sufficient to cover the anticipated losses of the character above mentioned, and thereby create proper reserves to recoup themselves when such losses occur.

Otherwise expressed, the particular class of expenses comprehended under the term of "expense of depreciation" are those for major repairs, replacements, or retirements, which experience shows will have to take place in any given property over and above those current minor repairs which must constantly be met.

Sometimes, as a convenient method of indicating the present expectations as to the lasting qualities of any portion of a particular property, this expense of depreciation is associated with, or expressed in terms of anticipated life of such same property. Those, however, who adopt this view should, of course, make careful distinction between what can be regarded as the gross rate at which a property is depreciating, and what may be called its net rate of depreciation. Suppose, as has been done in the examples used in Mr. Loebenstein's paper, that the expense of depreciation is taken at 10 per cent per annum. This means that in the course of 10 years it is expected that 100 per cent of the first cost of the property will have been charged against it under the head of theoretical depreciation or expense of depreciation. Suppose, however, that the property in question, say a particular machine, is from time to time the subject of renewals or replacements of parts of the machine, resulting, let us assume, in drafts upon the reserve for depreciation, amounting, on an average to 5 per cent per annum of the first cost of the property. The actual, or net, average rate of depreciation for the property would therefore be 5 per cent, and the resulting anticipated life of such a property would become 20 years, and not 10 years.

Accrued Depreciation and *Structural Value*: Corresponding with the second branch of the definition above mentioned, viz., the state or condition of being depreciated, are the other terms generally used when reference is made to this branch of the general subject of depreciation; viz., the present depreciated condition or, as the accounting system mentioned above terms it, the "structural value" of a property. These terms take into account such accrued depreciation as may be determined upon as actually existing in any particular plant. As thus used, accrued depreciation is, therefore, an attempt to measure past effects, as anticipated depreciation is to forecast future ones. The former undertakes to state what shrinkage in value can, as a fact, be found in any property not new. The latter endeavors to predict the amount of loss that will still take place in any property and, to the extent that the same can be approximated, the period of time over which such losses will be spread.

Perhaps the distinction which it is important should be recognized between the act or process of depreciating, whether called anticipated or theoretical, or the expense of depreciation, and the state or condition of being depreciated, as covered by the existing accrued depreciation of any property, whether physical or functional, can best be obtained from the accounting point of view as shown in the prescribed system of accounts already mentioned. Therein it is clearly shown that:

(a) The expense of depreciation, or its equivalent terms, refers to the future; accrued depreciation to the past.

(b) The expense of depreciation is concerned with the operating expense accounts; accrued depreciation with the fixed capital accounts.

(c) The measure of the expense of depreciation is that best estimate, based upon experience, that can be made as to the rate at which it seems likely capital will be consumed in operations in the future; the measure of accrued depreciation the best estimate possible to make of what amount of such capital consumption has, as recognizable facts, already occurred in the plant as it exists at the time of the inquiry.

(d) The time to which such expense of depreciation is to apply is the remaining life of the physical property; accrued depreciation to its expired life. During each such year that the property, or any portion thereof, will continue in use, the effort is to assess the company's earnings, in the form of an expense of depreciation, such uniform amount as will distribute, as nearly as may be, evenly throughout the life of the depreciating property, the burden of repairs (exclusive of current repairs for which provision is made under another account) and the costs of capital consumed in operations.

Both branches of the subject of depreciation into which it has been above divided are involved in appraisals and in rate investigations before commissions and courts.

One of the questions asked by commissions about any property whose fair value they may be trying to determine is this—"What is the reproduction cost, new, of such property?" Such question being assumed to have been satisfactorily answered, the commission can then be regarded as saying something like this. "We have now been told what the property would cost if created at this general time, and if it were all new. As a matter of fact, we know it is not all new. Let us remove this limitation as to newness. Now advise us as to how much less valuable this property may be, from the standpoint of how much less quantity-of-service of a proper quality it may contain, than would be a property entirely new.

The difference between the two amounts, as understood, would be the accrued depreciation that could be said to reside in such property, and which question was raised in the Idaho case referred to by Dr. Betts in his paper.

Besides wishing to ascertain the accrued depreciation in any particular property, the courts and commissions are also interested in those portions of the company's expenses which it may be charging against earnings under the heading of the expenses of depreciation, or the utility's estimate of the average rate at which the process of depreciating is in progress in the different parts of the utility's property.

To give this information to the regulatory bodies, special accounts have been set up under the prescribed accounting system. These show the results of any schedule of estimated rates of depreciation expenses adopted by the utility. They indicate, likewise, the drafts or charges being made from time to time against the reserve for depreciation resulting from such expense of depreciation charges.

Examinations of these accounts made by the regulatory body, or of the annual or other reports in which they are embodied, will indicate the rate at which such reserves may be accumulating, or, on the other hand, failing to accumulate. They also show the extent to which the appropriations for depreciation expense may have actually been meeting the particular burdens of major repairs, replacements or retirements of property which they are designed to cover, as indicated by the charges which may have been made against the depreciation reserve.

In Mr. Loebenstein's tables and curves both phases of depreciation as above indicated are taken into account, the expense of depreciation being equivalent to what Mr. Loebenstein refers to as "increments to the depreciation fund," while the present depreciated value or structural value corresponds to the per cent condition referred to in the same tables.

In determining what may be a proper expense for depreciation and, consequently, what may be the net rate at which a property is estimated as progressing toward a depreciated condition, a number of important factors must be taken into account. One of these factors is the element of growth. In some of the simpler cases, those in which this factor is the only one at work, the curves and tables shown by Mr. Loebenstein are intended to indicate what the results of a uniform expense of depreciation applied to a growing property would be upon the reserve for depreciation and the computed present condition of such property. For cases such as this the element of growth is shown to have a marked effect.

Generally speaking, it is believed that the influence of growth on the problems of depreciation is often not taken into sufficient account. Any property, particularly one of the composite character usually met with in actual cases, and one which is the subject of considerable and frequent additions of new elements, obviously will maintain a condition nearer newness than would a property not receiving such additions; so that, with respect to the depreciated condition of a property, either as to a particular time or as an average condition for any period, growth must be taken into account.

But, furthermore, if any attempt to test the reserve for depreciation as a ratio of the total plant in existence at the present time be adopted, the element of growth must here also be given its due weight. The amount in any reserve of depreciation is the result of the schedule of rates for the expense of depreciation which may have previously been in effect, and which rates have been applied to property previously in existence. Any drafts or charges which have been made against such reserves have, as a general proposition, been on account of property old enough to have reached a condition where major repairs, replacements, renewals, etc. have become necessary. Properly, therefore, the amount in such reserves should be related, as a ratio, only to that property which was in existence when such reserve was being accumulated. To refer such a reserve, so accumulated, to an entire property which might, perhaps, include recent additions, would result in a lower percentage of reserve to any plant than would have been the case if the ratio had been obtained before the additions referred to had been made. In other words, unless the element of growth be taken into a proper account, any comparison of reserve for accrued depreciation to the total present property, or any comparison of the effects of any particular schedule of depreciation expense rates to charges being made to the reserve for realized depreciation to cover concurrent major repairs, replacements, retirements, etc. may lead one into serious error.

Other elements beside growth have their effect upon depreciation in one of its phases or the other, and, as such, should be given their proper weight. Among such other influences might be mentioned any tendency which may be present to substitute the longer lived elements of a plant for the shorter lived ones now in place; another one might be improvements in design or engineering which would permit of necessary growth or enlargements without as extensive removals of previously existing plant as had before been necessary. Other influences might also be mentioned which would have their effect, either upon the expense of depreciation, or upon the accrued depreciation at any time in a property.

The value and purpose of computations such as Mr. Loebenstein has made are to be found, of course, in their demonstration of the effects that such elements can have in supposed cases.

In all instances, however, in which they enter they have some effect. And such elements have their effect even in those instances, not mathematically to be analyzed, where the actual property may, as in cases in mind, consist of 30 or more subdivisions, each of which relates to a different kind of property, each, subject to its own rate of growth or replacement, large or small, which growth or replacement may be quite irregular one year as against another; and which property subdivisions may be considered to have expectations of life ranging all the way from land, which is supposed to have no life limit, or vitrified clay conduit, whose life is indefinite, to other portions of the property which may require renewals every five or six years.

With respect to the relation of accrued depreciation to the base upon which to allow a fair distributable rate of return: as understood, Mr. Loebenstein regards as unfair for such purpose any base obtained through the deduction of any reserve for depreciation from the depreciated value of the property. Probably few, if any, will dissent from this view.

If the reserve for depreciation be deducted from anything, it would be nearer correct to subtract it from the undepreciated, instead of from the depreciated value of any property, whenever the problem under determination be the proper base upon which to allow a fair distributable rate of return.

And even in this case, such deduction of the reserve from the full 100 per cent value of the property, new, would not be based upon any consideration of depreciation, as such. Rather would it be founded upon the recognition of a divided equitable ownership in any property owing its existence, in part, to any depreciation reserve derived from the rate payers, and which reserve had been set up, specifically as such, in the company's accounts.

For the reserve for accrued depreciation, under the prescribed accounting system above referred to, can be regarded as amounts still standing to the credit of the rate payers, and representing specific provision by them for losses estimated as currently accruing in the property while they had been enjoying service from it. In time, such credited amounts will assist in covering future major repairs, replacements, or ultimate requirements of such property. Meantime, it is being held by the company, in some asset form or another, and offset by a special liability account showing the amount of such special assets, as a part of the total assets in the company's possession, until such major repairs, replacements, or retirements become necessary or economically justifiable.

Until the amounts in such reserve are actually absorbed for the purposes for which they had been collected from the consumers, it would seem correct to regard the equitable, although not the legal, title to the portion of the assets, in dollars, representing such amounts, as residing in the rate payers.

As thus viewed, therefore, if from the total assets held by the company, taken at 100 per cent of their full value, there be deducted that portion of the assets, also taken at 100 per cent of their value, new, owing their existence to the reserve for accrued depreciation as it may then stand in the accounts, the remaining assets would represent those held by the company, free from any such equitable claim of the creators of the accrued depreciation reserve.

Whether any further deductions should be made from a base derived as in the preceding, in the case of the utility which, in the past, had enjoyed earnings sufficiently ample to make full provision for any reserve for depreciation up to the amount of the real existing accrued depreciation in its property, but which had failed so to do; or whether, on the other hand, as items perhaps in its "going value", any addition to such base should be made in the case of the company which had made provisions to its reserve for depreciation, but had been compelled to do so in the face of inadequate distributions in the past to its owners, would seem to be separate questions—along with others which could be raised in this connection—for separate determination.

David B. Rushmore: There is one point concerned with depreciation which I have never heard mentioned in any discussion, and which I believe has not been taken in consideration by commissions or engineers in determining the proper figure for depreciation. Depreciation is an attempt—and it may be a very unwise attempt—to guess what the future has in store. An attempt is being made to keep the value of the capital invested intact by trying to guess just what the future will be.

When we are thinking of value, what are we thinking of? We say that the capital must remain the same, but value, as it really exists, exists only as regards the necessities of life, and the point which I have never seen considered, and on which I would like very much to hear an expression of opinion is why should not the factor of gold depreciation be considered in connection with the subject of the depreciation of property?

In the period of fifteen years from 1900 to 1915 gold depreciated on the average $3\frac{1}{3}$ per cent a year, and the man who had his money in the savings bank, that was paying that much interest, was just keeping even in his position, while in the case of a man who owned bonds which paid interest of $3\frac{1}{3}$ per cent, as some of them do, approximately, he was not getting ahead at all. Now, we are for the present moment existing under very abnormal conditions of economics, of finance, of trade, and apparently we are going to return to the same condition of gold depreciation. Therefore, why should not the permanent value of the property be measured in the value of the commodities which make up the necessities of life, and not in something which represents a medium of exchange or something which represents an artificial value, and which is not in itself fixed.

Edward J. Cheney: As Dr. Betts has very well said, it is necessary for us to abide by the decisions of the courts. It is also entirely proper that we should respect those decisions. I think, however, that the courts themselves are quite willing to be educated along the lines of these questions, which, because of their newness and complexity, are very perplexing to the judges. We should not be bound too rigidly by decisions with which we do not agree, but we should by just such meetings as this, endeavor to clarify the situation and enunciate proper principles. No one, I think, is so well qualified to put the matter in proper shape as engineers, who deal with the physical property and with actual operating conditions.

It is true that a great deal of stress has been laid on reproduction costs in valuation and rate cases of one sort and another, but that has doubtless often come about because in such cases accurate records of the investment cost were not available. I believe that when, as will in the near future be the case, records are available which show exactly what was spent for the property; and assuming that the investment was honest, prudent and timely; the money actually put in by the investors will be the proper basis for estimating a return in rate cases; and if so, it certainly will be the proper basis in purchase and sale cases.

It is a little bit off the subject, but I want to take this opportunity to register my emphatic protest against the use of two terms which are very commonly employed in connection with this subject. One is "going concern value". It is entirely misleading. I do not question at all the justice of including something for those items which are ordinarily included in the term, but the term itself is wrong. A public utility has no right to earn a return on an indefinite "going concern value" any more than it has a right to earn a return on what some have maintained was the franchise value. On the cost of establishing the business, on inadequate returns in the early stages, and on similar items, it has a right to expect a return, but let us call them what they are. The expression "cost of establishing the business" is more nearly correct, in my opinion, than anything else, and seems much preferable to "going concern value".

The other term which I object to is "contractors' profit". How many estimates we see with a percentage tacked on for "contractors' profit"! I maintain there is no such thing. The percentage a contractor gets, over and above labor and material cost, is to pay his overhead expenses and to pay him for his own services. He makes no profit. He may, it is true, make money on one job, but on another he will lose, and in the long run he gets only enough to keep him in business, and the percentage is not a profit but an item of expense. "Overhead expenses of construction" more nearly describes that item.

Relative to depreciation, public utility companies invariably expect that, in fixing rates, there be included in operating expenses the amount of estimated current and accruing depreciation. At the same time, they often, doubtlessly honestly, ask for a return on the full original cost of the property. If you lend me $1,000, you have a right to the interest on that money, but as soon as I pay back part of the principal the amount of interest is correspondingly reduced. Accrued depreciation, charged to operating expenses and paid in by the customers of the public utility company, is to that extent a return of the original capital.

William S. Franklin: I would like to point out, in connection with the question raised by Mr. Rushmore, that the influence of depreciated money or gold on the values of properties is taken account of in what is called "cost of reconstruction." The fact that gold does depreciate is an added reason for placing greater emphasis on cost of reproduction in estimating present values of a property.

The difficulty, however, is that the cost of reproduction includes another variable as well as the variation in the value of gold, namely, the variable which comes from improved methods and improved machinery, which may tend to lessen the value of the property as based on cost of reproduction, whereas the depreciation of gold alone would tend, if there were no advance in methods and machinery, to increase the money value of the property: If we could only devise some means for separating these two variables as they enter into the cost of reproduction, we could then take account of the two separate influences.

Philander Betts: In reference to the paper submitted by Mr. Carver, I want to emphasize two or three things that I have had in mind with regard to the value of keeping inventories and appraisals of a property, and of keeping them continuously up to date. The thought that has occurred to most people when you mention an inventory and appraisal is that the sole purpose has been to find out as of some given date the total amount of property in existence and its value at that time. That is only one of the reasons for making an inventory and appraisal of a property. The telephone companies for years have kept a continuous inventory, perhaps not in the same form that is usually employed in making up an appraisal, but it has been kept for operating reasons, so that the telephone company could know at any moment just where it had property, and how much it had, so that it could tell a prospective customer whether it could or could not furnish service of a certain character to a certain extent, and if it could not immediately furnish it, how soon it could furnish it.

Another reason for keeping an inventory, and along with that inventory the cost of the various portions of the plant as they are constructed, is in order to make the construction of the extensions more efficient. An analysis of construction costs is essential in the carrying on of any contractor's business. Why should not such an analysis be made of the construction costs of a public utility company? The keeping of such inventories, and accompanied with the inventory of the property the cost of the sections of the property, would lead to an analysis of the unit cost for those sections, which would show whether or not the extensions were constructed in the most efficient manner possible under all of the circumstances. Such an analysis might lead to better methods of doing the work. It might lead to doing the work at different times during the year, or, instead of doing it in certain piecemeal methods, without knowing just how much would be done, it might lead to doing it in a more systematic way.

In this connection I will call attention to what the telephone companies in the East do. Estimates are made up as to the probable growth in different directions—the probable number of new customers taken on—and estimates are also made as to where these customers will probably be located, and as to what property will probably be necessary. Orders are then entered for certain amounts of material a considerable time in advance. The total number of poles which are estimated to be used will probably be used without much change in the size and height of those poles. It may be that some changes will have to be made in the orders given for certain sizes and lengths of cables, but with a proper study based upon the running inventory, and the accompanying cost sheets, a company can certainly construct the additions to its plant in a more economical manner than is very often the case.

I want to answer some questions with regard to some of the points in my paper. I have referred to the fact that in several cases the courts have laid down the rule that what the company is entitled to earn a return upon, was the value of that which they devoted to the public use, and that this might entail deductions for property not at present in the use of the public. When I spoke of that I did not mean deductions for that portion of the property which was properly held in reserve. Every company that pretends to give continuous service must have property in addition to that demanded by the peak load in order to insure continuity of service. If companies are to take on customers from day to day, there must be some property created at least some little time in advance of its immediate use, so that there must be some reserve in the plant to accommodate these customers who come along every day. There must be some reserve in plant to safeguard against interruptions in service due to breakdowns of portions of the plant. They are every day occurrences, and must be guarded against, and the provision of a certain amount of spare plant is the usual and ordinary precaution.

I have in mind a definite case. In the southern part of New Jersey, there is a very large gas company situated about forty miles from Camden. Some years ago a project was evolved for the construction of a tunnel under the Delaware River from Philadelphia to Camden. The project was an ambitious one, some property was purchased and attempts made to float the scheme. Without going into the history of the case, suffice it to say that the scheme has never been carried through, but while the scheme was being thought of, a group of enterprising people went down into the lower part of New Jersey and formed eleven small gas companies in the towns and villages served by the railroads which would probably connect with the proposed tunnel. These eleven gas companies were later consolidated into one gas company, with a large central plant, which was built at a central point, and gas has been delivered for a number of years from that central point. In the design of that plant, care was taken to see that there was capacity for several times as many people as are found in the territory at the present time, with a view to all those who might have been found in that territory today, if that tunnel project had gone through.

Now, I submit this question, and I will leave it to you to answer it—would it be fair today to say that the people now served with gas in that territory should be charged rates that would give an adequate return on the value of the plant which was constructed and designed for several times as many people as are now making use of it? In all probability, if the promoters of the scheme had thought that the tunnel was not going through this gas company would never have been formed.

The point of it all is this: That a company, before it obtains a proper number of customers, is in such a developmental stage that it is impracticable to collect charges based upon a schedule of rates that would return a profit when the company is very small. The large gas company, to which I have referred, is in just that position. It must build its business up to a point where it will fit the plant which it has, before it can say to the customer that the rates must furnish a return on all its investment.

There is one thing which should be referred to in this discussion, and that is as to the power of the courts. The power of the courts seems to be misunderstood by some, in this way: courts have never had and do not now have the power to fix rates. The courts have the power to prevent confiscation, and to prevent, from the other standpoint, the collection of unreasonable rates. Probably all of the cases which have gone to the Supreme Court of the United States have gone there because the company contended that its property was being confiscated, and when the courts have held, as they have in some of the cases, that such returns as 3.5 and 4 per cent were not a sufficient basis for throwing the case out of court and declaring the rates improper, these decisions were based, not on the idea that such rates of return were adequate, in any sense, but that they were not confiscatory. That is all these decisions have ever said. The court can also determine whether the customers themselves are being asked to pay excessive rates.

In one of the cases before the New Jersey Commission, both the company, from its viewpoint, and the customers affected, from their viewpoint, appealed the case to the upper court. Why? Because the company, feeling that the rate was too low, contended that it amounted to a confiscation of its property.

The customers affected, on the other hand, appealed to the court, saying that the rates fixed by the commission were too high, and and involved collecting from them exorbitant charges. In that case the court did not pass on the facts, it determined that the facts had been passed on by the Commission, and the lower court decided it was neither confiscation, considered from the one direction, and did not say it was charging an exorbitant rate, considered from the other direction.

Harry E. Carver: In reference to the point Mr. Jackson brought up about the accrued depreciation on each item, you will notice that Forms 1 and 3, which constitute the Continuous Inventory Records, did not provide for the computation of the accrued depreciation on each item. They do, however provide space for recording data from which the accrued depreciation may be computed at any time it is desired. Hence, if it should seem advisable at any time to compute depreciation upon a different basis than that upon which it was previously estimated, the continuous inventory record would not be changed or altered in any way.

In connection with this subject some of you may have read the paper on "Continuous Inventories", which was presented at the last meeting of the American Electric Railway Association, held in Atlantic City, in which forms were worked out for each item year by year. I believe that these forms were made up in this manner because the taxing officials in New York State, and perhaps in some other states, require reports each year, in which information must be given as to both cost and the present value of property in considerable detail. If the depreciation is to be computed each year it seems that practically double work would be required in keeping the inventory records, because for every item of property there will have to be an entry made every year on the continuous record; whereas, if a summary only is made every year, the calculation as to the depreciation could probably be made covering a group of items and thus the amount of work would be greatly diminished. For that reason, and because of the great amount of estimating necessary in figuring depreciation, it seems to me it would hardly be advisable to attempt to make any depreciated values a part of the continuous inventories record.

W. R. McCann (by letter): It is to be inferred from a careful reading of Mr. Betts' paper, that the author submits the holdings of the courts to sanction *only* a reproduction method of valuing public-utility property, to the utter exclusion of all other methods. It is the belief of the writer that the correctness of such a deduction is to be challenged. In support of a contrary view, it may be well to examine one or two typical court decisions which apparently *may* be construed in accordance with the author's interpretation.

In the aforesaid paper, a pioneer case (*Smyth vs. Ames*) is cited to show that, in addition to the reproduction method, fair and reasonable rates should be fixed only after there have been ascertained the original cost of construction, the amount expended in permanent improvements, the amount and market value of its bonds and stock, the present as compared with the original cost of construction, the probable earning capacity of the property under particular rates, the sum required to meet operating expenses, and other matters. Certainly the case of *Smyth vs. Ames* does not support the exclusion of other evidence of value, in favor of a reproduction method as the sole and only correct theory.

The basis of the claims that the courts favor a reproduction theory is found in the language of certain judicial opinions—in language which is constructed to mean differently from what is actually stated. For instance, in *Des Moines Water Company, vs. City of Des Moines*, the court says:

"The question is not what it (the plant) cost, although such evidence is admissible as having a bearing. The question is not what the plant some day may be worth, although evidence with reference thereto may be considered as having a bearing. The question is: What is the value of the plant today?"

(192 *Fed.* 193, 196)

From such language it is argued that the value of the plant must be the reproduction value and that the words—"the question is not what it (the plant) cost", mean that an original-cost valuation is to be given no weight. There is a vast difference, however, between the price which has been paid *in toto* for a plant ("what the plant cost", to use the court's language) and a properly prepared original-cost valuation. A correct original-cost valuation has its basis in the same inventory as does the reproduction valuation; but, instead of present-day prices (or five-year average prices) being used in the appraisal, the actual cost prices are used for both labor and material, or, in the absence of records of the actual original costs of items of material and labor, the cost is estimated by a competent appraiser as of the time when the equipment was installed and under the precise conditions of its installation.

Likewise, in *Cumberland Telephone and Telegraph Company vs. City of Louisville*, the court said:

"It would seem clear from the decisions that the most material question in such cases is that the *reasonable value* of the property 'at the time it is being used for the public', that is to say, the *time at which the question arises*—it being upon the reasonable valuation at that time that the company is entitled to earn a fair return * * * * The value of a plant may depend upon good fortune, upon good management, or upon fortuitous circumstances, but in every event the reasonable value of the property '*at the time it is used for the public*' is the value we are to ascertain for the purposes of this controversy."

(187 *Fed.* 637, 642)

From the language "value of the property at the time it is used for the public" and from the similar language of other court decisions, it is again argued that the reproduction method must be used exclusively. It seems to have escaped the notice of the reproduction advocates that the language of the courts may well be interpreted to mean "the reasonable *depreciated* value of the *used and useful* property at the time it is used for the public".

Many courts have sanctioned and justified the reproduction theory because it is generally assumed that precise original cost ordinarily is difficult to secure. Usually the record before a court of review has little tangible evidence relating to a properly prepared original-cost valuation. The record may confuse the investment, the stocks and bonds, or a purchase price with the original cost of the various items embraced in the inventory. Before construing the language of a court which is reviewing a record taken in a trial court, it is well to ascertain first what that record contains on the subject of original cost.

Of a proper original-cost valuation, Ex-chairman Halford Erickson of the Railroad Commission of Wisconsin stated in a paper presented before the Conference on Valuation, held under the auspices of the Utilities Bureau, in Philadelphia, a year ago:

> "When the original cost of the existing property is desired it can be computed upon the same inventory as that used in determing the cost of reproduction and upon prices which cover the period when the property involved was put into the plant. Such price lists may be had partly from the records of the plant and partly from other sources. In this way the original cost of the existing property can be had with even greater accuracy than the cost of reproduction."
>
> (*The Utilities Magazine*, *Vol.* 1, *No.* 3, 113)

It is interesting to note that Chairman Erickson, after years of experience and participation in rate-making procedures, volunteers the opinion that even in the absence of books and records, "original cost of existing property can be had with even greater accuracy than the cost of reproduction."

Despite the many citations from court decisions favorable to some reproduction method of valuing utility property, it is noteworthy that no authority of standing is to be quoted to show that an estimate of the cost of reproducing the property (with or without deduction for accrued depreciation) is the sole and only guide to a reasonable and adequate valuation of a utility property for rate-making purposes. On the contrary, the inconsistencies of the reproduction method have been discussed time and again; it is only recently that the Supreme Court of the United States, in the *Des Moines Gas Case*, repudiated the reproduction method when applied to what, in valuation work, is commonly termed "undisturbed paving". The general unstableness of the reproduction-new theory was realized and understood by prominent proponents of the Federal Valuation Act. Senators Bristow of Kansas and LaFollette of Wisconsin, on February 24, 1913, participated in the following colloquy on the floor of the United States Senate:

Mr. Bristow:

"There is one point I wanted to bring out with regard to that feature of the bill that requires the Commission to ascertain the cost of production new. Such a finding, in my opinion, is not of any great value, so far as the rate making is concerned. It is a vacillating quantity; it does not represent in any sense the investment of the company in the construction of the road. To illustrate: In the suit that was pending, the estimated cost of the reproduction of the Northern Pacific Railroad was involved. I am informed the same engineer reported in 1907 and in 1909 as to the cost of the reproduction new, and the value fixed in 1909 was one hundred and eighty-five million dollars more than the same engineer fixed the value of reproduction new in 1907."

Mr. LaFollette (in part):

"Let me say to the Senator on this question that the Supreme Court of the United States has listed that as one of the values to be considered, and it has not yet by any express declaration eliminated it as a value to be ignored. So it seemed to the committee that we ought to give it, its place here. I will, however, say to the Senator that I am confident that the views of all the advanced commissions of the country that are doing this valuation work are that there should be very inconsiderable weight given to reproduction new."

(*Congressional Record*, 3801.)

The reproduction method of valuing property is relied upon by utilities mainly because it automatically takes care of the appreciation which has occurred during recent years in the cost-new of nearly all items of equipment and in all classes of labor. Land, in particular, falls into this classification, and a court of authority has ruled that the real property of a utility should be valued at its present-day market value, and not at its original cost plus the cost of improvements. Under the rulings of the courts, it may be argued that, even though a utility may steal equipment without being apprehended and may convert that equipment into used and useful property in the service of the public, the stolen equipment must receive due recognition in a valuation and rate-making proceeding. Whether or not this view will prevail ultimately, under a continuance of state regulation, is somewhat a debatable question at the present time. A simple case will serve to illustrate the fallacy of too great weight given indiscriminately to appreciation in utility property. Assume that an electric plant, in a state where the laws provide for state regulation, costs $100,000, and assume further that the regulatory body of jurisdiction, after investigation, has fixed rates such as will yield full operating expenses plus five per cent per annum ($5,000) for accruing depreciation and seven per cent per annum ($7,000) for a *fair* rate-of-return. At the end of five years, provided no change is made in the electric property, the utility has accumulated $25,000 (plus earnings) in a depreciation fund, and each year has paid a full and adequate rate-of-return upon this investment. During these five years, if perchance the prices of labor and materials advance so that the estimated reproduction-cost-new according to expert appraisers would be $110,000, there has been an unearned increment, over and above a fair rate-of-r turn, amounting to $10,000 in the value of the property—equivalent to $2,000 per year, or two per cent annually on the original cost. In other words, a valuation made at the end of the said five years, resulting in revised rates being fixed on an estimated reproduction theory, capitalizes an unearned increment which automatically results in rendering a nine per cent rate-of-return throughout the entire first five-year period. What has the utility done or denied to itself in order to deserve this unearned increment? Is not the public entitled to participate in the appreciation of property, at least to the extent of not having the same capitalized against it, to be borne by the rate-payers of the future? Carrying the illustration still further then, let it be assumed that the estimated reproduction value sinks to $90,000 at the end of five years; then the reverse is true, and the utility each year is deprived of just earnings equivalent to two per cent of the cost of the property. Under such conditions, would it not be argued that this deprivation of earnings would constitute a confiscation of property?

Such illustrations are indicative of the public's vital interest in what is termed "appreciation". It is to be borne in mind that "depreciation", as applied in valuation work, in no manner is the opposite of appreciation". An original-cost valuation, if properly compiled, does not presume to inflict upon a utility the losses occasioned by decreases in prices of material and labor. An original-cost valuation, however, does presume to reflect the conditions under which the bargain between a utility and its consumers was consummated. Under an original-cost valuation, the public sustains all losses due to the falling off of prices, although it participates in gains only to the extent of not having an unearned increment capitalized against it. As stated before, the courts have not stated that reproduction-cost-new (or less depreciation) must be the criterion by which to judge the present value of utility property for rate-making purposes.

The Massachusetts Public Service Commission, in its recent decision rendered *In Re Bay State Street Railway Company* (August 31, 1916), squarely recognizes that appreciation in land as disclosed by a reproduction method of valuing the same is not to receive recognition in a determination of rates:

"Considering this appreciation upon its own merits, car riders cannot fairly be expected to pay higher fares because land has increased in value, nor ought they to pay lower fares if it should decrease. If the company wishes to sell such property it is, of course, entitled to whatever profit it is able to make; but so long as land is employed in the street railway business it is dedicated to a public use and held subject to the conditions fairly attaching to such use. As the Commission has said in another connection (see House Document No. 1900 of the current year, pp. 88,89): 'While no fair-minded man will deny that those who put their money into public service by building railroads are entitled to the opportunity to earn a fair reward, that this reward is to be determined, so long as their property is devoted to public use, not by investment or by service rendered, but in large measure by the rapid expansion of real estate prices in the larger centers of population, is contrary to sound public policy. It would mean that communities would be penalized by their own growth, and would lose all advantage from the fact that their transportation facilities were created in due season under favorable economic conditions.' It should be added that, even if the doctrine of present worth were accepted, the figure to be used in rate making would clearly be present worth for street railway purposes. In this case no evidence whatever has been submitted that the land has increased in value for such purposes."

(10 *Rate Research, pp.* 120 121,)

It would seem, therefore, that engineers as a whole may well listen to the admonitions of the courts, instead of becoming partisan advocates of some theory. Such biased acts on the part of the profession are accountable for rebukes of a type such as was administered forcibly by the late Judge Smith McPherson of Iowa, who, it is claimed by some, made a grievous error in the Missouri Rate Case (168 *Fed.* 317) by apparently giving too great weight to the testimony relating to certain new theories advanced by experts. In one of his last opinions, this caustic Iowa judge called attention to the great danger of experts. Judge McPherson's life was largely behind him, and he had had more than his fair share of experience as a United States district judge in endeavoring to weigh the evidence of experts in various public-service cases, when he said in the Des Moines Gas Case (199 *Fed.* 205):

"Too often we have selfish, partisan, prejudiced, and unreliable experts engaged for weeks at a time at $100 or more and expenses per day, exaggerating their importance and making the successful party in fact a loser."

Frank Gill: If Mr. Loebenstein contends that the plant of a normally conducted undertaking does not eventually settle down to a definite per cent condition, I do not agree with him, but if he only means that there is not a similar fixed percentage condition for all undertakings, I think he is quite right.

Fig. 1 shows the amount necessary in the depreciation fund for three theoretical cases, each with the same equated life but with a different rate of continuous growth. This clearly shows that each rate of growth results eventually in a definite per cent condition.

In each case there are 10 classes of plants having lives varying from 6 to 29 years and if a greater number of classes had been used, curves would have reached a steady condition at an earlier period.

Other calculations show that the per cent condition depends on the equated life of the plant as well as upon the rate of growth.

In these cases the Sinking Fund Method (at 5 per cent per annum) has been used for reasons which I consider conclusive, but this is really an independent question.

I do not think that Mr. Loebenstein has made sufficient allowance for the fact that while a definite life can be assigned to one class of plant, the individual components of that class do not in practise need renewals at exactly the same time.

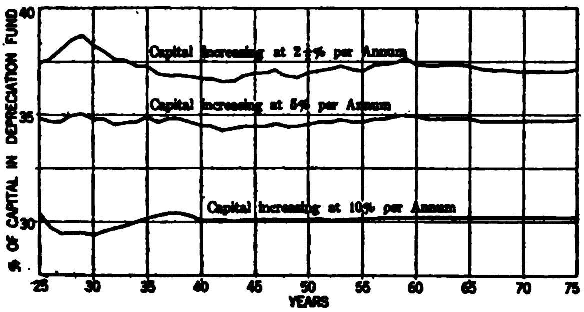


FIG. 1

I notice that in Mr. Loebenstein's calculations, he has allowed a full year's allowance for depreciation for the first year and if this is correct, it follows that the expenditure for the year took place on January 1st, and that the renewals would occur a full year sooner than shown.

L. R. Nash (by letter): It is surprising that a matter of so much importance as the effect of growth upon the average condition of physical property should have received so little attention in engineering literature. The paper on this subject by Mr. Loebenstein is very timely, particularly in view of the increasing attention to valuation studies in connection with rate regulation. The author's choice of public utilities to illustrate the points which he develops is to be commended because of the consistent growth and the predominance of valuation activity in this field.

It seems to me, however, that the illustrations which the author presents in tabular and curve form are not generally representative of average utility conditions. Most of these illustrations assume growth for a very limited period of years, after which the property remains stable. With this assumption, quite wide variations are found in renewal requirements and per cent condition. While the author points out that each of the cases assumed may be considered as one group of elements of a composite property, he still concludes that such a property would show a considerable variation from time to time in per cent condition.

Public utility history shows very few cases of property without sustained substantial growth. A few interurban railways and hydroelectric developments might be excepted, but the growth of the normal city requires continued expansion of its utilities. Even the case of the actual electric property, covering a period of one hundred years, which the author presents as an illustration, assumes that growth ceases after three years, the remaining ninety-seven years showing no expansion whatever. It is not surprising that under such an assumption the service value of the property shows a fluctuation between 37.5 per cent and 69 per cent as found by the author. It is believed that actual conditions are more nearly represented with respect to fluctuations in service value by Curve VII which the author reproduces from Mr. Allison's report on the United Railways Company of St. Louis. This curve, however, allows for no effect of property growth.

The writer had occasion about two years ago to make a study of public utility depreciation and replacement requirements, particularly their relation to total property value or investment. The general results of this study were finally embodied in a paper prepared for the American Economic Association and appearing in the *American Economic Review* of March, 1916. This paper shows by a variety of curves the effect of property growth, and gives formulas and tables for computing replacement requirements under certain assumed normal conditions. In connection with this study the writer had a table prepared showing the history of an assumed typical public utility for a period of one hundred years. The assumptions include growth at the rate of 10 per cent per year for the first twenty years, 7½ per cent per year for the next thirty years and 5 per cent for the remaining fifty years. The property was assumed to consist at all times of elements having useful lives uniformly distributed between ten and thirty years and an equal value of elements in each life group. A copy of that part of the table showing for each year the total investment, cost of replacement of discarded property and the relation between the two is presented as Table I. While this table does not directly show per cent condition, it is believed that uniformity in annual replacement requirements implies corresponding uniformity in per cent condition if, as assumed, all replacement requirements are given prompt and systematic attention. A study of the attached table shows a surprisingly close agreement among the ratios of replacement cost to total investment. There is, in fact, during the last twenty years of the period a variation of only about two per cent in the yearly percentages from their average. In earlier years there is, of course, less consistency because of changes in rate of growth and immaturity of the elements of the property. It is the writer's belief that the attached table represents fairly closely the normal condition of an urban utility, although the assumed uniformity in value of elements and regularity of life will not obtain in practise. This does not sustain the author's conclusions that no approximation to uniformity in per cent condition is to be expected even if growth continues. As the rate of growth increases, per cent condition will normally increase with full maintenance but, as the author states, a large liquid depreciation reserve is not necessary.

The author further comes to the conclusion that depreciated values should be used in determining equitable rates, basing this contention upon calculations which show that depreciated value and depreciation reserve are together equal to capital investment. If adequate depreciation reserves were always available, there would be no question of injustice to investors in using depreciated value, if a full return were available from an investment of the reserve. There are, however, state laws which prohibit distribution of income from invested depreciation reserves to stockholders. Under such circumstances the use of a depreciated value would deprive the investor of an adequate return.

The writer wishes to voice his opposition to the use of depreciated values in rate cases, recommending instead, full value or investment in connection with a sinking fund rate of accrual for replacement purposes. It is easy to show that under normal conditions the combination of a return on full value plus the comparatively small sinking fund accrual for replacements is approximately equal to a return on depreciated value together with the larger straight line accrual for replacements.

The depreciated value method involves several serious difficulties. The average utility does not earn an adequate replacement reserve in its early years, and with a reasonable hope of making up the deficiency in later more prosperous years when funds are actually needed, dividends are given early preference. The utility may fully expect to adequately provide for all the necessary upkeep of its property, but would be seriously embarrassed by an early rate proceeding which established a depreciated value before the supplementary replacement reserve was accumulated. Furthermore, in a rate case where the utility had carefully accumulated what in its judgment was a full depreciation reserve, it would probably be found that engineers of the supervising commission would find in their judgment, on examination of the property, a higher or lower depreciated value than that estimated by the utility. To the extent of the difference between the two estimates the patrons of the utility or the utility itself would be done an injustice in a rate proceeding. Such probable injustice is entirely avoided by using an undepreciated value with a sinking fund rate of accrual, which requires compounding of the annual contributions to the reserve to make up full ultimate replacement requirements. Utility and commission may disagree upon the useful life of physical property but such disagreement does not affect the investor's return, involving only the amount which patrons should contribute for the upkeep of the property. There is usually ample opportunity of adjusting and readjusting the annual accruals for replacements to meet actual requirements. If a commission finds that a utility has neglected to accumulate a suitable reserve, and at the same time has paid excessive dividends, the proper remedy, it is submitted, is to order a reduction in rate of dividends until the earlier excess has been offset rather than to permanently reduce the fair value of the property.

With the sinking fund method it is necessary to provide safe investment for the annual accruals with adequate return thereon. There is usually sufficient growth in public service properties so that they may invest their reserves in their own business, such investments being accounted for separately from property for which outside investors have furnished the funds. The requirements for a liquid reserve are not different from those under the straight line method. In the long run with approximately uniform replacements, about 60 per cent of the annual cost is provided from current contributions, the balance from income of the invested reserve which will normally accumulate during the early years of the business to approximately 40 per cent of the total investment.

The author assumes that if a utility stops growing and cannot use straight line replacement accruals for the temporary financing of extensions, such accruals might be returned to stockholders in cash, as a part return of capital and not as a dividend. It is believed that such a procedure is distinctly undesirable in the case of public utilities. Conditions might arise in which, without material growth the original property was allowed to seriously depreciate and a large proportion of its original cost be returned to the investors in addition to dividends. In case of unwise regulative restrictions, the investors might decide under such circumstances, that it would be expedient to salvage their property and discontinue the business rather than submit to further injustice. Such discontinuance of an established utility service would be very much against the public interest and its possibility should be avoided by restricting routine payments to investors, to interest and dividends only.

The writer finds it helpful to think of the public service problem as involving three distinct interested parties instead of the two parties ordinarily recognized in discussions, namely, the public and the investor. Between these two parties at interest the utility itself may be distinguished as a third party. The utility is by no means identical with the investor. It looks to the investor for funds as it looks to the public for patronage. It is no more subject to the command of one than to the other, unless it be that through regulating bodies the public has assumed a more dominant position. The utility should be looked upon as the custodian of property or an agent or trustee for both the public and the investor. As an agent it is an intermediary in all transactions; it receives the customers payments for services, disburses a part of them for expenses, taxes, etc., distributes a part to the investors who have furnished construction funds, and should retain a part for conservation of the property and for contingencies. The investor has no more right to demand a specific return from the utility for the use of his money than the public has to demand a specific kind of service. That the utility is or should be trustee of funds set aside for replacements to which the investor has no right is a point commonly overlooked

TABLE I

STUDY OF REPLACEMENT COSTS OF A TYPICAL UTILITY PROPERTY.

Initial property value $10,000. Is composed of twenty units of equal value. The first unit is discarded and replacement made at end of ten years, second unit at end of eleven years and third unit at end of twelve years, et cetera. New property is acquired at rate of 10 per cent for twenty years, 7.5 per cent for thirty years and 5 per cent for fifty years Each yearly increase represents the addition of twenty new units and these units are discarded and replacements made after the tenth, eleventh, twelfth year, et cetera, in the same manner as the original twenty units.

Year	Value at beginning of each year	Increase during year	Cost of replacing discarded property	Ratio of replacements to value at end of each year
1	$ 10,000	$ 1,000	$ ..	..
2	11,000	1,100	..	..
3	12,100	1,210	..	..
4	13,310	1,331	..	..
5	14,641	1,464	..	..
6	16,105	1,610	..	..
7	17,715	1,771	..	..
8	19,486	1,949	..	..
9	21,435	2,143	..	..
10	23,578	2,358	500	1.93
11	25,936	2,594	550	1.93
12	28,530	2,853	605	1.93
13	31,383	3,138	665	1.93
14	34,521	3,452	732	1.93
15	37,973	3,797	805	1.93
16	41,770	4,177	885	1.93
17	45,947	4,595	974	1.93
18	50,542	5,054	1,071	1.93
19	55,596	5,560	1,178	1.93
20	61,156	6,116	1,795	2.67
21	67,272	5,045	1,474	2.08
22	72,317	5,424	2,121	2.73
23	77,741	5,831	1,832	2.19
24	83,572	6,268	2,516	2.80
25	89,840	6,738	2,266	2.34
26	96,578	7,243	2,993	2.88
27	103,821	7,787	2,792	2.50
28	111,608	8,371	3,571	2.97
29	119,979	8,998	3,429	2.66
30	128,977	9,673	4,271	3.08
31	138,650	10,399	3,615	2.42
32	149,049	11,179	4,386	2.74
33	160,228	12,017	4,728	2.74
34	172,245	12,918	5,097	2.75
35	185,163	13,887	4,995	2.51
36	199,050	14,929	6,344	2.96
37	213,979	16,048	5,884	2.56
38	230,027	17,252	6,828	2.76
39	247,279	18,546	7,362	2.77
40	265,825	19,937	8,440	2.95
41	285,762	21,432	8,029	2.61
42	307,194	23,040	9,640	2.92
43	330,234	24,768	9,316	2.62
44	355,002	26,625	11,019	2.89
45	381,627	28,622	11,293	2.75
46	410,249	30,769	12,153	2.76
47	441,018	33,076	12,496	2.63

TABLE I

STUDY OF REPLACEMENT COSTS OF A TYPICAL UTILITY PROPERTY.

(Continued.)

Year	Value at beginning of each year	Increase during year	Cost of replacing discarded property	Ratio of replacements to value at end of each year
48	474,094	35,557	14,922	2.92
49	509,651	38,224	14,495	2.64
50	547,875	41,091	16,564	2.81
51	588,966	29,448	17,240	2.79
52	618,414	30,921	19,108	2.94
53	649,335	32,467	19,555	2.87
54	681,802	34,090	22,007	3.08
55	715,892	35,795	23,177	3.08
56	751,687	37,584	25,494	3.23
57	789,271	39,464	26,849	3.24
58	828,735	41,437	28,946	3.32
59	870,172	43,509	30,639	3.35
60	913,681	45,684	34,931	3.64
61	959,365	47,968	34,784	3.45
62	1,007,333	50,367	36,699	3.47
63	1,057,700	52,885	39,066	3.52
64	1,110,585	55,529	41,233	3.54
65	1,116,114	58,306	43,372	3.54
66	1,224,420	61,221	46,192	3.59
67	1,285,641	64,282	47,702	3.53
68	1,349,923	67,496	50,822	3.58
69	1,417,419	70,871	53,415	3.59
70	1,488,290	74,414	57,315	3.67
71	1,562,704	78,135	58,152	3.54
72	1,640,839	82,042	62,713	3.64
73	1,722,881	86,144	63,779	3.52
74	1,809,025	90,451	67,180	3.54
75	1,899,476	94,974	70,869	3.55
76	1,994,450	99,722	74,043	3.54
77	2,094,172	104,709	77,066	3.51
78	2,198,881	109,944	81,482	3.53
79	2,308,825	115,441	83,935	3.46
80	2,424,266	121,213	89,712	3.53
81	2,545,479	127,274	92,312	3.45
82	2,672,753	133,638	97,208	3.46
83	2,806,391	140,320	102,142	3.47
84	2,946,711	147,336	109,251	3.53
85	3,094,047	154,702	113,345	3.49
86	3,248,749	162,437	119,282	3.49
87	3,411,186	170,559	125,027	3.49
88	3,581,745	179,087	132,616	3.53
89	3,760,832	188,042	138,420	3.51
90	3,948,874	197,444	146,930	3.54
91	4,146,318	207,316	152,658	3.59
92	4,353,634	217,682	161,182	3.54
93	4,571,316	228,566	168,004	3.50
94	4,799,882	239,994	177,283	3.52
95	5,039,876	251,994	186,168	3.52
96	5,291,870	264,593	196,510	3.54
97	5,556,463	277,823	205,021	3.51
98	5,834,286	291,714	216,618	3.54
99	6,126,000	306,300	226,128	3.52
100	6,432,000	321,615	237,830	3.52

and which, if given proper consideration, would very much simplify depreciation studies.

It should be clear from the author's paper that any full pro rata accrual for replacements results in a reserve which, in a growing property, is never used. It may be of interest to note, in connection with the history of an assumed utility shown in the accompanying table, that the annual replacement requirements of this utility could be taken care of by an accrual without interest accumulations, started after the end of ten years, at the rate of 3 per cent for the next forty years, 3.5 per cent for the following fifteen years and 3.69 per cent for the final thirty-five years. Such accruals, entirely absent from the first ten years, not only take care of all annual requirements, but accumulate an unused reserve which is always slightly greater than the current annual requirements.

F. C. Merriell (by letter): The matters placed in issue by the recent papers on appraisal and inventory seem to be merely a reopening of what has always been a fruitless inquiry. The general nature of the decisions of courts indicates clearly that practise and present needs have far outrun the enlightenment of the judiciary in this matter. The only factor contributing in any great degree to the solution of the problem, which comes from the courts, is a grudging recognition that value is the matter in question rather than cost, and that generally, items of value are more various and inclusive than items of cost.

For the use of courts, commissions, and the operators of property, an accurate inventory of property is a necessity and if it can be maintained continuous, it has the added advantage and no mean one, that all the force of the operator will be educated in the business of appraisal. This is a lack sadly felt at present and the use of most inventories is greatly limited because of it. A case in point is the inventory of a large utility, with which the writer was recently associated. The necessary field force was so unversed in the elements of value resident in such property that the inventory did not at all meet the requirement which necessitated it, and had to be supplemented with much special field work to make it adequate. It was in the first instance, unusually accurate and complete as to quantity, but the saving grace of well trained and exercised judgment was not always apparent in the first listing. A continuing education in this important branch of engineering, will quite materially assist to a better appreciation of how constituent parts of property account may best be identified in inventories, and more important still, it ought to increase the knowledge of how best to apply, and when most economically to expend renewal and maintenance funds.

In his paper Mr. Loebenstein sets up a number of paradoxical cases, because he makes his appeal only on the basis of physical cost and not upon the basis of value. In order, if possible, to join the issue let an extreme case be cited.

A pole line has been built through a desolate country and provides service between the communities at its ends. It is no matter for consideration whether the property shall have been a wise investment or not, but for a specific case it may be assumed that the service is adequate and that the projectors are making a profit. Every part of the property has however, suffered a lessening from its merchant price, by reason of the handling incident to erection, and by its removal from the regular channel of trade to its present location. Thus early it begins to appear that the merchant price has ceased to be a criterion of its value, even as property merely, and the charges which have been added to the merchant cost, while necessary for the specific service are in a very real way penalties against that cost or price when all the factors going to make its condition purely as property, are considered.

The country being desolate and uninhabited, it may very well be, indeed, that the property has no commercial worth whatever, no matter what its physical state may be. Many such lines exist today which cannot be dismantled, should such a thing be contemplated. The poles are not numerous enough to pay to gather them for firewood, at the expense of the labor per pole involved. The more durable units of property cannot be sold for the cost of their collection. Irrespective of the physical cost or condition therefore, this property is quite worthless as such and neither additions to it nor extensions nor enlargements of it will in any case increase its worth as property, in its location. In this case it appears that the criterion of the value of the property is not its worth as so many units of various physical things, but in its opportunity as a conception and its adequacy as the realization or embodiment of that conception.

Therefore the physical cost is an element only in so far as it enables the entrepreneur to demonstrate that he has done an adequate thing economically and that no penalty ought to be levied against him for the cost he has so far incurred because he is supplying an obvious need; and further that this physical cost together with all the other things he has done, appraised at their proper price, which make the property a utile and reliable public institution, are to be included in determining its value.

It has been attempted to show that the physical cost or condition is really a minor factor in arriving at value, and if that inference can be drawn from the extreme case cited, what follows may seem logical. The physical cost having been admitted as one, and not the only, element of value, and specific condition being a mere derivative of the course of all things physical and the fact of their existence, a further assumption is taken. If it was worth for the original purpose of the undertaking, all it cost to place the various units of property in their present position and use, how can it be said from that time each such unit began inexorably and without qualification to become of less worth. The fact which is well known and a stubborn one, that nearly every kind of property passes through a long period after its first utilization, when the value of its service does not appreciaably lessen, is vital here, and points to the conclusion that the character of its use and the length of time it will continue to render satisfactory service, are the real criteria of its value and that physical appearance or condition is of little moment, except as it is the visible evidence of care and forethought, (or the lack of these) in maintaining the property.

The fact that renewal or replacement would be necessary did not in the first instance surprise the entrepreneur, for he accepted these things as one of the necessary risks or expenses of his business. He has never charged himself with the duty of creating a certain standard of appearance in his property to betoken a satisfactory condition, but has rather given his best perception to the effort to detect the first falling off from the highest standard of service, and has esteemed the deterioration of his property to be first betrayed by its failure to render that high type of service. He is not and never can be interested in an attempt to ascertain what percentage of condition as merchant property his plant has reached, but he is vitally interested if it appears that he must increase its facilities or replace some of its units to keep it doing what is required of it.

If he be called upon at any time to evaluate the property, it is generally agreed that he has a right in its physical condition, which might be even better expressed if it were said that he had a duty to make those changes and renewals which will serve to maintain the standard of its usefulness. If he has accumulated funds for all the charges in reasonable prospect, he ought not to be said to own less than he formerly did. If he sell his property he will expect to receive the full price of it, including the amount of his provision for the future or he will take the sum he has so set aside as a part of the purchase price and the purchaser will thereupon have to set up a similar fund in order properly to administer it. Current practise thus illustrates that the concept of depreciation cannot make its way against the logic of actuality. And the property, which, having no provision for proper renewals and needing them, is sold, suffers in price to exactly the degree in which it has been neglected, thus proving in too many cases that the protection of regulation has not at the present reached that bi-lateral efficiency which has always been so strongly urged for it.

The projector, when he undertakes the business has certain definite aims: on the one hand to supply such a commodity as will be acceptable to his public; on the other to gain as much as he may; and as a corollary of the latter he expects nothing else than that the business shall maintain all the necessary charges as well as the profit he desires, and that consensus of opinion called good practise, supports him in the idea that he ought, if he can, to make renewals and replacements in the ordinary sense from earnings, inasmuch as these are ordinary things, to be ordinarily met. If it is right therefore to take from earnings to make good these things, it is wrong to contend that the earnings so taken are a penalty against capital and reduce it by so much. If the provision is not made, the capital is indeed subject to reduction in the amount required for—what? To replace any fixed percentage of physical condition? By no means. To restore the service. If it were possible, there could be nothing more desirable than a uniform method, which could in fairness be applied, to assure that there was the proper intention on the part of the projector to continue his effort to give adequate service, which is the end really to be served by such provision, but experience demonstrates that uniformity is not in any very immediate prospect as a solution in this matter.

This view of the matter of so-called depreciation is not a new one, the writer having first formulated it to his own satisfaction in a private report some five years ago. As long as four years ago the receiver of a large utility defended and made good his defense of the attitude that he would not recognize any scheme of artificial penalization in lieu of his forethought and skill as a manager. A discussion of the whole matter from quite a similar viewpoint and with more attention to the mechanism of the scheme was published by Mr. C. E. Grunsky in Vol. LXXIX *Trans.* A. S. C. E. Finally it must be said that much of the difficulty of the whole matter at issue will be solved when it is recognized as a basis, that projectors, as corporations or the creators of corporations, are not willing to accept cheerfully any less fairness than any other component part of the public is willing to have.

J. Loebenstein: Referring to Mr. Nash's discussion, I call attention to the fact that when appraisals are made and estimates of requirements for future renewals desired, these estimates are made on the assumption that end of growth has been eached. Our predictions of what will be necessary in the futurer are based on what we know of the past. It will certainly be necessary to revise our estimates from time to time, but these revisions will in turn be based upon the past.

The Curve VII, which Mr. Nash notes, is based on the assumption that end of growth has been reached just as is Curve VIII.

In Mr. Merriell's discussion the statement is made: "If he sell his property he will expect to receive the full price of it, including the amount of his provision for the future or he will take the sum he has set aside as a part of the purchase price and the purchaser will thereupon have to set up a similar fund in order properly to administer it."

In my paper I tried to show what factors should be considered and in what manner the funds above referred to should be gathered. This cannot be done without some projected basis of renewals, based on the physical cost which Mr. Merriell considers only a minor factor.

Presented at a section meeting of the American Institute of Electrical Engineers, San Francisco, Cal., November 24, 1916.

CERAMICS IN RELATION TO THE DURABILITY OF PORCELAIN SUSPENSION INSULATORS

BY HARRIS J. RYAN

ABSTRACT OF PAPER

The fundamental requirements in satisfactory high-voltage line insulators are summarized and particular emphasis is placed upon the need for coordinated study of service durability. The effect of porosity upon durability is explained in detail and an appeal made for the establishment of a practical porosity elimination test.

The manufacture and structure of electrical porcelain is studied from the viewpoint of the ceramist, with many quotations and illustrations taken from the Transactions of the American Ceramic Society.

The author briefly states the conclusions at which he has arrived and gives a very complete list of references and notes.

DURABILITY is one of several fundamental requirements in a satisfactory high-voltage line insulator. These requiredents are:

1. Electrical Requirements.
   a. Electrical strength of dielectric.
   b. Refractoriness of dielectric.
   c. Design of electrical features.
2. Mechanical Requirements.
   a. Mechanical strength and toughness of dielectric.
   b. Design of mechanical and thermal features and their coordination with requisite electrical features.
3. Durability Requirement.
   Minimum attainable deterioration.
4. Cost Requirement.
   Best insulators that the art can produce at a minimum cost which the practise can afford.

The modern porcelain suspension insulator is generally accepted in the present state of the art as meeting the above requirements to the greatest extent. In respect to these requirements the service it renders is reasonably satisfactory except as to durability. Effort is now being made by manufacturers and engineers to produce and to accept only such high-voltage porcelain insulators as will not fail under ordinary conditions of use or non-use in ten years or more. As yet there is no assurance that this result has been accomplished. If the causes of the failure of insulators with time were fully understood, more effective work could be done to eliminate them. At present, after much effort in many quarters, these causes are known and understood only to a limited extent.

Hardly any of the requirements of an insulator stand alone and unrelated to the rest. Particularly is this true of durability. Most of the features and of the properties of the materials that constitute an insulator are related to its durability. It is not reasonable to expect, therefore, that decided improvement in the durability of the insulator can be made without a thorough going study by which full knowledge will be developed of all the facts for the materials and their forms that enter into the make-up of the insulator.

There are two distinct phases of durability:

1. Ability to endure sufficiently an adopted set of *acceptance tests*.

2. Ability to endure operating service conditions and the action of the elements during a reasonably long period of time, *i.e.*, ten years and upwards.

We may for the present call the former *acceptance durability* and the latter *service durability*.

Insulators must be bought and paid for largely through the results of acceptance tests. On account of the great length of time involved, few if any can be bought on the basis of an ultimate durability in service which years alone can determine. The present day suspension insulator was introduced nearly ten years ago and service durability results are now accumulating rapidly. It is generally conceded that the difference between acceptance and service durabilities is too great and must be reduced. The remedy is being sought for and applied through causes of failures in and out of service as related to the past and present states of the art. A large amount of coordinated effort of all concerned and able to take part is required to discover these causes. The study of the service durability of high-voltage insulators must have a number of well defined and not-to-be-forgotten *points of application* in order that the greatest advance in this durability may ultimately be attained; they are:

1. Insulators that have and have not failed in service.
2. Insulators that have deteriorated when not in service.
3. Laboratory treatments that will cause insulators to fail.

4. Factory materials, design and technique in relation to subsequent failure of insulators.

5. Laboratory science studies of everything that can be perceived about the materials, their form and assembly for insulators.

6. Coordination of all known knowledge that can have any possible bearing upon insulator durability.

Studies have to be made by factory and transmission engineers and by ceramists, geologists, chemists and physicists at all of these specified points of application. Everywhere the work amounts to little more than a beginning and much more remains to be done if the porcelain insulator is to be made thoroughly reliable in practise.

In a conference with Dr. J. C. Branner, a geologist with a wide knowledge of rock, clay and earth products, it was learned that high durability must not be expected of *porous* bodies even when they are constituted of porcelain. To retain the original integrity of clay products generally their vitrification must be carried far enough to make them virtually proof against the absorption of moisture. In witness thereof, he exhibited a porous clay product dish covered with an imperfect glaze. A student in biology for a comtemplated experiment had dissolved a salt in some water placed in this dish. Interest in the undertaking was then lost and the dish containing the solution was allowed to stand in the laboratory untouched for a number of weeks. In the meantime the solution entered quite generally into the pores of the porous dish body. Later as the water evaporated from the dish and from its porous body salt was deposited throughout the pores. The salt formed crystalline structures that developed excessive internal mechanical stresses throughout the dish. Complete ruin of the dish resulted, chiefly through the production of large and small spalls and cracks. As a structure, however, the dish had remained whole. In respect hereof materials in solution are divided into two classes:

1. Materials that expand when passing from the liquid to the solid state by freezing or by crystallizing from a saturated solution

2. Materials that do not expand in the same circumstances.[14]

The former materials only produce the mechanical injury in porous structures, though injury by electric conduction that each class of materials may cause, so long as any moisture remains in them, must ever be kept in mind.

Regarding the claim that ample vitrification of porcelain will

14. For references see notes at end of paper.

make it brittle and mechanically unreliable, it was learned from the same authority that the way out of the difficulty should be to select materials that would have to be vitrified at higher temperatures resulting in a greater toughness of product. As evidence thereof the production of satisfactory paving brick in our country was referred to. This is accomplished by ample vitrification of materials so chosen and proportioned that high temperatures must be applied for the result. The enhanced durability of the brick is worth more than the increased cost of vitrifying at the higher temperatures.

It has long been known that porcelain for high-voltage line insulators affords no dependable service durability when made by the dry process and that a fair service durability for a large portion of the product is rendered when made by the wet process. In dry process porcelain the porosity can be reduced to one per cent only with difficulty,[1] whereas in a major portion of the high grade wet process porcelain the porosity is, by comparison, very low *i.e. one tenth* per cent or less.[2] Thus practical experience establishes the fact that the lowest degree of porosity that the art can be made to produce is a service durability requirement of the highest importance. Porous porcelain when waterlogged becomes virtually an electrolytic conductor and a failure as an insulator. Its failure to insulate would be less decisive if under the circumstances its temperature-resistivity coefficient were not negative in sign and so high in value. As soon as local heat is generated the whole current flowing through the porcelain body must inevitably be concentrated upon a route so narrow that intense heating occurs resulting in fusion or burning and the production of a conducting core.

Portland cement is generally used to attach the metal pins and caps to the porcelain insulator bodies. The details of cement curing are well known. First a saturated solution is formed of the new cement in the excess of water present. When the insulator body is porous such saturated solution is absorbed. Later all free water evaporates and the material in solution in the pores of the porcelain remains as crystals producing great mechanical stresses as already shown.

Insulators are carefully designed to minimize cracking of the porcelain body by thermal expansion stresses. With porcelain sufficiently porous to permit cement crystals to form within the body it would seem to be too much to expect of any design that no cracks would occur. The combination of mechanical stresses produced by the crystals and by differential thermal expansions must inevitably produce more cracks in the porcelain body than from these causes acting alone.

Porous porcelain in an insulator captures moisture in damp weather and liberates it in dry weather. Each weather cycle will deposit, however minute, a certain quota of soluble salts. Thus eventually salt will have accumulated in the porcelain body to such an extent that it must fail as a dielectric due to cracks in dry weather increased by sudden temperature changes or by electrolytic conduction in wet weather or all together in a manner difficult to recognize. Old cement is a decidedly porous body that must also tend to swell and produce large mechanical stresses when foreign crystals have been deposited in its pores. It is thus seen that porous porcelain must eventually fail as an insulator. Likewise the porosity of the cement used in attaching the caps and pins must, for much the same reason, be a cause that aids in bringing about the failure of an insulator with time. It is said that the high grade electrical porcelain is fired to cone twelve temperature, 1355 deg. cent.[4] The maker claims that an underfired body will be tough and mechanically reliable and an overfired body will be brittle and mechanically unreliable. It is a well established fact that high-grade porcelain underfired is decidedly porous and unfit,[1] that from an electrical viewpoint only, fully fired porcelain has its pore systems amply closed (rendered vesicular) and overfired porcelain bodies are apt to have a "bleb" structure due to the concentration of gases sealed up in the pore system or to the evolution of gases in reactions that may occur.[1]

In view of these things it should not be permitted to meet mechanical loading requirements by the expedient of underfiring which is bound to reduce service durability. The assumption that the cracking of insulator porcelain bodies may be avoided by annealing[7] and by form design must in time be a disappointment if porosity of porcelain and of cement is permitted.[8]

The foregoing considerations indicate that acceptance tests must include a practical porosity elimination test as soon as it can be devised. Professor Creighton has indicated[9] and the work reported in the present papers shows that slightly porous porcelain does not by all ordinary means admit moisture quickly to any considerable portion of the body. It is true that ceramists take the amount of water absorbed by a porcelain as a measure of its porosity. However, unless the test specimen is thin it is broken into small fragments before being immersed in water. Even so it is quite likely that the best porosity measuring technique of the ceramist will have to be improved upon in order to measure with fair exactness the low values of porosity that occur in high-voltage porcelains offered for acceptance. The above remark, that it is ordinarily difficult to cause water to penetrate slightly porous unglazed porcelain, applies only to porcelain in bulk of insulator size.

The hunt is being continued for methods by which slightly porous porcelain can be made to take up water quickly to a considerable depth thereby correspondingly decreasing the insulation resistance and thus to determine electrically the existence of the porosity without injuring the insulator. The following tests were applied to unmounted insulators having caps unglazed inside and out and which were known to be porous because their resistance rose through oven treatment. The last method tried and here listed for detecting porosity did not involve water absorption:

1. Two insulators were immersed in live steam for four hours without result as to moisture absorption.

2. They were immersed in live steam for four hours during which cold tap water was circulated through the interior of the caps without moisture absorption result.

3. Using tap water electrodes, 25,000 continuous volts were steadily applied through the cap of one of these units for a period of two hours during which the current flowing was observed in the high-duty megger outfit. No change in the resistance of the insulator occurred, showing that moisture could not have been driven to considerable depths by the electrical and capillary forces during the time of the test.

4. A trial suggested by Mr. J. P. Jollyman: Dried porcelain known to be porous and non-porous insulators were megged, using 10,000 continuous volts applied through the outer layer of the cap and megged again after soaking in tap water over night. The overnight soaking caused the resistance of the porous insulators, only, to be lowered decidedly.

5. The caps of dry unmounted porous and non-porous insulators were subjected to ten kilovolts, sustained uniformly at 325,000 cycles per second for five minutes. Temperatures of the outer crowns of the caps were taken immediately before and after the test. After immersion over night in tap water the tests were again repeated. The heating of the dry porous insulators

was slightly more than of the dry non-porous while for those soaked in water over night the heating was decidedly greater for the porous than for the non-porous insulators.

6. Trial by gaseous conduction in lieu of electrolytic conduction: Dry porous and non-porous insulators were megged again with all conditions the same except that the electrode facing the outer surface of the caps was constituted of ionized gas liberated from an adjacent needle point connected to the galvanometer and properly guarded. The results showed that slight porosity can not be located by this method.

A look into the Transactions of the American Ceramic Society reveals the fact that ceramists have, in recent years, conducted

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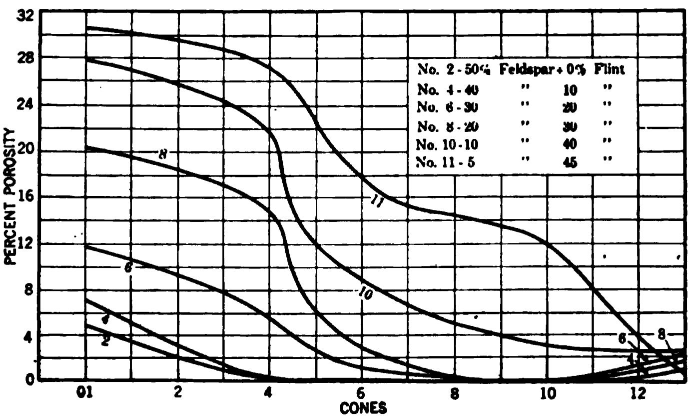

FIG. 13

several investigations of electrical porcelains that are of interest to transmission engineers. As the contents of these transactions do not appear to be generally known the author ventures to present certain diagrams and abstracts taken from these papers.

In a study of explorations to find porcelains that should be suitable for high-voltage insulators at the University of Illinois, Bleininger and Stull[2] made up about 450 separate and distinct specimens of clays, spars and flints varying in kind and proportions. By permission of the American Ceramic Society Figs. 13, 14, 15, 29, 30 and 31 of the original paper are reproduced herewith. The first three are *porosity-temperature-composition* diagrams and the last *three* are corresponding triaxial diagrams in

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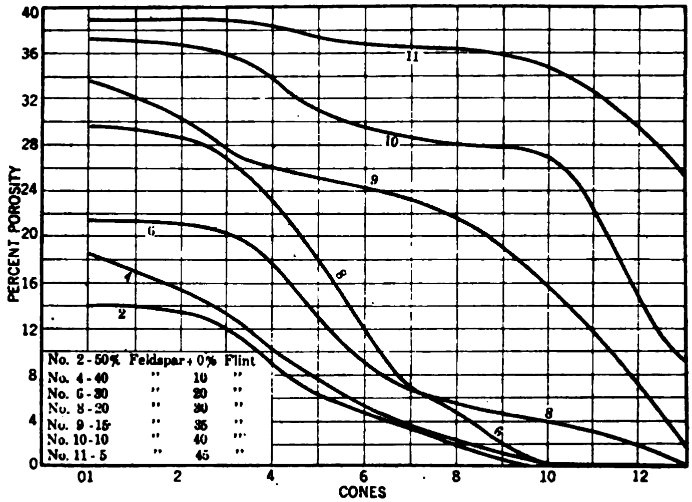

Fig. 14

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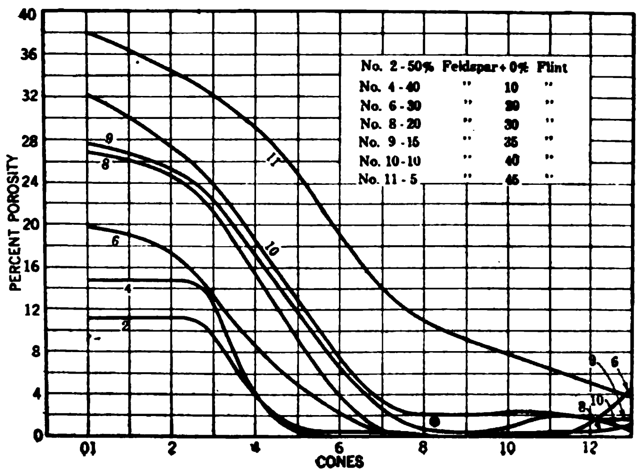

Fig. 15

which the *dielectric strength* (by slowly applied voltage required to puncture under oil) and *composition* are coordinated topographically. These diagrams are self-explanatory though a few corresponding quotations from the paper are helpful.

"All porcelain bodies absorbing not more than 0.1 per cent of water, by weight, upon boiling in vacuo are considered vitrified."

"*Tennessee Ball Clay.*" "The less refractory character of this clay is indicated by the large range covered by the temperature area below cone 10, (1305 deg. cent.)". Figs. 13 and 29.

"*The North Carolina Kaolin* offers quite a contrast to the last material, in as much as its vitrification area is quite small at

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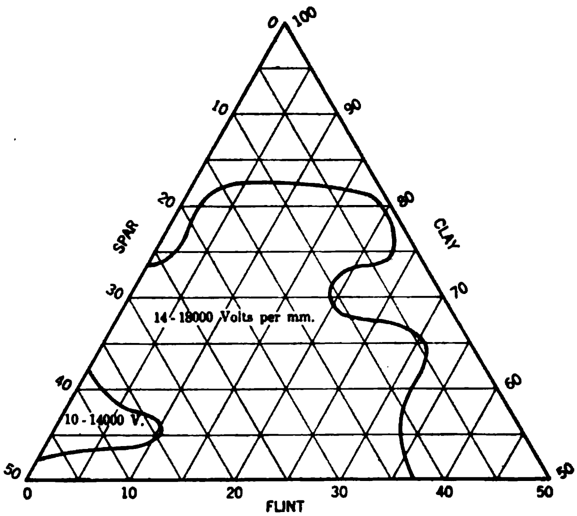

Fig. 29—Tennessee Ball Clay

temperatures up to cone 10. The range is decidedly increased at the higher temperatures." Figs. 14 and 30.

"*The English China Clay* differs from preceding clays in that its vitrification boundaries slope far more gradually in spite of the fact that its alkali content is not greater than that of the North Carolina kaolin." . . . "It is evident that this material differs considerably from similar American clays in this respect due to its structure or fineness of grain. Its vitrification area is quite large." Figs. 15 and 31.

"*Dielectric Behavior.*" The voltages have been arranged in *three* groups which are: less than 10,000 volts per mm., from 10,000 to 14,000 volts per mm., and from 14,000 to 18,000 volts per mm."

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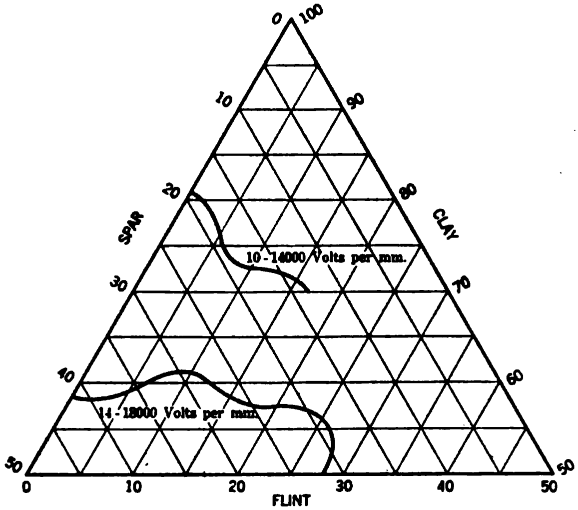

FIG. 30—NORTH CAROLINA KAOLIN

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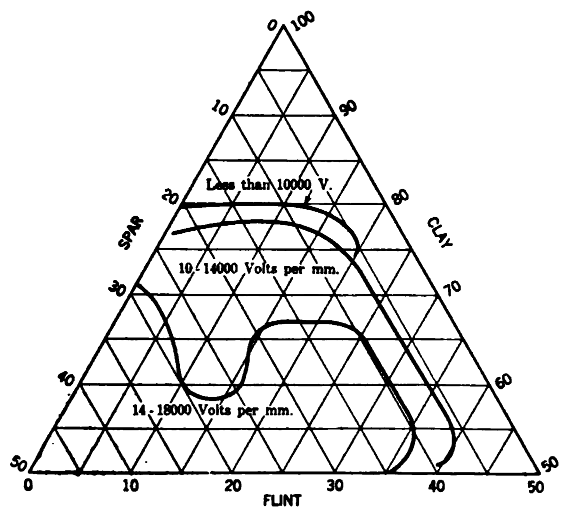

FIG. 31—ENGLISH CHINA CLAY

. . . 'The electrical resistance (strength against puncture under oil) seems to depend more upon sound vitrification and good mechanical strength than chemical composition, excepting, of course, in so far as the latter governs the vitrifying behavior." Figs. 29, 30 and 31.

Later these studies were continued at the University of Illinois by B. S. Radcliffe under the supervision of Professor Stull.[11] A number of decidedly porous porcelains were found having (when dry) high dielectric strength. The results obtained are given in the triaxial diagram Fig. 5 of this paper, reproduced herein by permission of the American Ceramic Society. Used for high-

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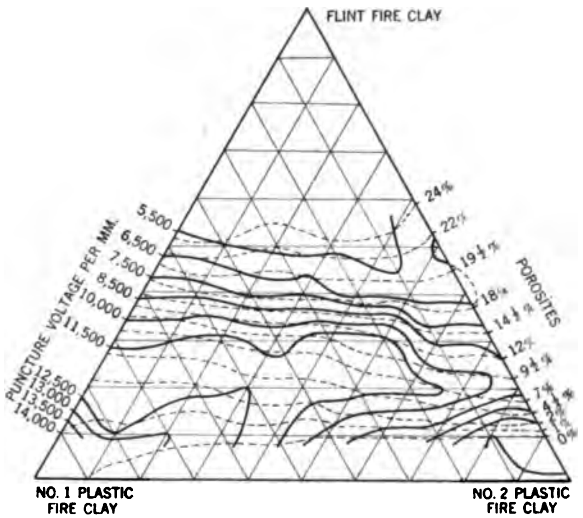

FIG. 5—RELATIVE POROSITIES AND DIELECTRIC STRENGTH OF FIRECLAY MIXTURES BURNED TO CONE 12½

voltage line insulators, however, these porcelains would in time become water-logged and salt laden and would eventually fail. Nevertheless the results are deemed of real importance to the transmission engineer for they corroborate the corresponding fact reported in the present set of papers and earlier by Bang,[12] viz. that dry porcelain when decidedly porous may possess a fairly high dielectric strength. Initial dielectric strength can, therefore, be no complete measure of the electrical service durability of a high-voltage line insulator.

In a critical study of the foregoing results in ceramics one is brought to the conclusion that the desirable qualities in electrical porcelain, refractoriness and, therefore, toughness and vitriousness or imperviousness, are to be gained only through a high content of flint fired at an amply high temperature.[15] Fused flint, quartz or silica as it is variously called is thus indicated as the limiting outcome of the use of more flint and less spar and clay. Quartz goes gradually into fluidity only at a higher temperature than platinum. In giving up its crystalline structure through heat it is subject to an extraordinary degree of cracking, whereby it captures large quantities of air or other gases in the furnace.[16] It is difficult to fluidify the quartz without evaporation sufficiently to liberate such entrained gases. These difficulties have been overcome in recent years sufficiently so that chemical ware of fused quartz can now be afforded to a limited extent. Once fused and freed of gas "blebs", quartz has incomparable electrical, refractory and thermal-mechanical properties. It is not injured if when red hot, it is plunged into cold water. When it can be fluidified by special treatment in an electric furnace sufficiently to be cleared of all entrained gas it may then be cast in cold metal moulds to form high-voltage insulators. Until this can be done with quartz or some materials having much the same properties, porcelain will doubtless remain in use for such purpose.

Wet process porcelain is roughly moulded to form in the plastic state, then dried to the "leatherhead" state, removed from the moulds, tooled to exact form, slowly fired and slowly cooled without further resort to moulds. This solid vitrification without the use of moulds and without deformation is at once its greatest advantage and disadvantage. The initial stages of the process develop a pore system in the green porcelain body that can be eliminated or rendered vesicular only by the best possible technique applied to each and every piece in all stages of the process. Since this is not practicable on a large scale it is inevitable that, in the factory production of high grade electrical porcelain some of the low grade must be produced along with it. The importance of all improvements and of tests for the elimination of structurally imperfect and appreciably porous porcelains and of the operating strategy of thoroughly shuffling the finished insulators so as to minimize the likelihood of more than one unrecognized defective insulator being mounted in the same string is made manifest by a study of these results obtained by the ceramists.

An investigation by Weimar and Dunn[18] undertaken in the department of ceramics of the University of Ohio yielded valuable knowledge as to the manner in which insulating qualities of porcelains vary with temperature. They give a table found in the Transactions of the Royal Society of London. It includes temperatures and corresponding specific resistances of a "porcelain" ranging from 1.63 deg. cent. to 81.93 deg. cent. Inspection of the contents of the paper reveals the fact that porcelain as here reported lost resistivity within the stated temperature range at the uniform logarithmic rate of 100 to 1 for the actual values in a rise of temperature of 51.2 deg. cent. The corresponding average value obtained from the results of Professor Clark as reported in his present paper is 46 deg. cent. rise in temperature. Considering the circumstances these resistivity-temperature relations are in fair agreement.

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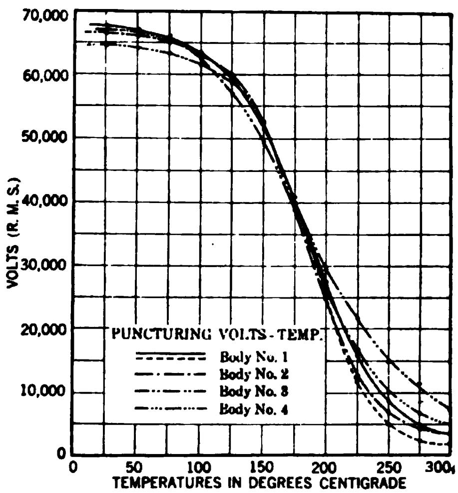

FIG. 6

Weimar and Dunn state that their work "covered that region known as the 'critical temperature' or that temperature at which porcelain ceases to be an insulator and becomes a conductor and to a small extent the effect of composition upon the same." The results obtained are charted in Fig. 6 reproduced from the paper by permission of the American Ceramic Society. The test specimens were cup-shaped 0.15 in. (3.8 mm.) thick heated in an open "electric furnace" and punctured with 60-cycle voltage steadily increased to the rupturing value.

Having in mind the heat resisting duty that porcelain in high-voltage insulators is expected to render when some forms of line "trouble" occur, it is a shock to one when he comes across these results for the first time. Above 300 deg. cent. it was found that the porcelains retained virtually no dielectric strength and that all applied voltage was consumed in setting up current through the test specimen functioning as an electrolytic conductor.

ACKNOWLEDGMENT

The author's study of the service durability of high-voltage suspension insulators would not have been feasible without the advice, helpful discussion and hearty cooperation of the following engineers, Messrs. J. E. Woodbridge, J. P. Jollyman, H. A. Barre and J. A. Koontz.

CONCLUSIONS

1. Appreciably porous porcelain should not be employed for suspension insulators. Under the action of the elements their failure must occur in due course of time.

2. Cement used for setting up cap and pin-type suspension insulators should be non-porous or rendered non-porous for reasons set forth.

3. Recognition of porosity as a contributing cause of suspension insulator failures has not lessened the importance of design features that reduce cracking through differential thermal expansions and failure through electrical overstresses and the heat of heavy flash-overs.

4. Defective materials in otherwise well designed and manufactured insulators have been responsible for most of their service-durability failures.

5. Clear fused quartz appears, technically, to be a desirable substitute for porcelain in the construction of suspension insulators.

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8. An examination of the engineers' records for more than 1000 of each of two lots of well known makes of insulators was made with respect to service durability. One lot had been made and put into service on a 100-kilovolt line, about *eight* years ago. The other lot was ordered, manufactured and delivered and stored in the open *four* years ago. They did not differ, essentially, so far as the author can see, in mechanical-thermal design features. The porcelain in the older lot was of a decidedly finer grain and less absorbent under the ink test than the newer lot. In the first *six* and *one-half* years of service, *one* and *one-half* per cent of the older lot failed. During four years in storage, *twenty* per cent of the newer lot had failed by megger test, or did fail on the application of sixty-cycle spark-over test.

Laboratory experience demonstrates that porcelain insulator bodies are subject to cracking when heated and cooled for the removal of absorbed moisture without hardware attached. For example: Three decidedly porous and water-logged insulators, *B M*4, *B M*30 and *U B*18, were heated slowly in a drying oven to 150 deg. cent. and held there for five hours. The source of heat was then cut off and the oven door opened to allow the insulators to cool. The oven being small, *U B*18, unmounted, had to be taken out when the door was opened. Its rate of cooling was naturally somewhat more than for the others. After being in the open air of the room for a few minutes, it cracked from the edge of the dish to the base of the cap. On close examination, several checks or small cracks in the inner wall of the cap were found, that evidently had occurred earlier. Before drying out, all of these insulators were so water-logged by immersion that they megged so low (a few megohms) that it was known in advance they would not sustain flash-over voltage. After drying out in two stages of about five hours each, the above was the second stage, *B M*4 and *B M*30, mounted insulators, megged with 20,000 volts, continuous, 580 megohms at 11.4 deg. cent., and 3.3 megamegohms at 11.7 deg. cent. respectively. The *B M*30 insulator was then subjected to 60-cycle *spark-over* voltage and endured 20 heavy spark-overs. The *B M*4 insulator has the characteristic of holding on to absorbed moisture tenaciously and must, therefore, be given further oven treatment before the spark-over test should, be applied. (Later, *B M*4 was given another 5 hour treatment in the oven. When cool it megged 1.6 megamegohms, 13.1 deg. cent. It withstood without apparent injury 12 heavy spark-overs at 83 kilovolts, 60 cycles.)

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Presented at a section meeting of the American Institute of Electrical Engineers, San Francisco, Cal., November 24, 1916.

EXPERIMENTS ON PORCELAIN SUSPENSION INSULATOR UNITS

BY J. CAMERON CLARK

ABSTRACT OF PAPER

The author gives a very complete description of the experiments on porcelain suspension insulator units carried on at Stanford University by him and his assistants under the direction of Prof. H. J. Ryan. He explains the preliminary organization necessary, the scope of the tests, and the unusual equipment required to measure the very high resistance of sound, dry insulators. Preliminary resistance measurements were made on all normal batches of porcelain units and the results tabulated, as also were results obtained when the units were subjected to mechanical stress, to voltages ranging from 1,000 to 30,000, to temperature variation. Another set of tests was made to determine the effect of moisture in insulators. Drying insulators for a few hours in an oven at 150 deg. cent. produced very conclusive results of the effect of moisture in lowering resistance. Attempts were made to water-log units by soaking, by soaking with a temperature cycle applied, by subjecting units under various conditions to a steam pressure of 60 lb., and by a vacuum treatment of insulators before soaking. A brief statement is given of the conclusions arrived at.

INTRODUCTION, ORIGIN OF, AND ORGANIZATION FOR THE WORK

THE *WORK of Prof. Ryan.* The work of Prof. Harris J. Ryan at Stanford University in the winter of 1915-16 demonstrated both the feasibility and the desirability of measuring the insulation resistance of suspension insulator units having resistances in the range between 5000 megohms and several millions of megohms. To illustrate: It was shown by Prof. Ryan that certain units having insulation resistances of, say, 15,000 megohms could be punctured in the air on 60-cycle voltage. The ordinary portable megger of 5000-megohms maximum scale reading will give a reading of infinity for such a unit, as it is unable to differentiate between units of 6000 and 1,000,000 megohms, whereas a dry, sound porcelain insulator will have a resistance of the order of 1,000,000 megohms or one "megameg-

*These values, as well as all other resistance values contained in this paper, are referred to a temperature of 20 deg. cent. unless otherwise mentioned.

ohm". Prof. Ryan also disclosed the fact that some units become much lower in insulation resistance when subjected to prolonged soaking in water.

Organization for tests. This work stimulated much thought among high-voltage engineers and, in particular, it aided in crystallizing a desire among them to develop a method by which it would be possible to detect faulty units with certainty, thus rendering it possible to avoid their installation. Accordingly, a committee of engineers was formed in May, 1916 to undertake experimental investigations of suspension insulator units, having as their broad purpose the production of test methods by which to detect with certainty and celerity all units which are electrically weak. Obviously, there is much difference of opinion on the classification of insulators as electrically "weak" and "strong". It is held by the committee, however, that any unit which is either weak at time of test or gives any indication whatever of the capability of developing weakness through lapse of time is to be condemned as weak.

The financial support of the work has consisted in contributions from a number of the California power companies. These companies, besides certain insulator manufacturers, have contributed liberally in test-specimens which will be found illustrated and briefly described in connection with "Preliminary Resistance Measurements".

The facilities of the electrical laboratories of Stanford University were placed at the disposal of the committee during the three summer vacation months of June, July, and August, 1916; and the writer and assistants were employed during this period to prosecute the testing work.

Experimental Work

Scope of Tests. In addition to the measurement of the insulation resistance of every insulator unit in the condition in which it arrived at the laboratory, the summer's work consisted largely in attempting to determine the influence of certain important physical conditions of the insulator units upon their insulation resistance. The physical conditions which have been thus investigated are; mechanical stress, electrical stress (using continuous voltage), temperature, absorbed moisture.

The High-Voltage Megger. Since the resistance of a sound, dry porcelain insulator at ordinary air temperature is exceedingly large (of the order of 10^{12} ohms), it became necessary to provide rather unusual equipment with which to measure this quantity. Without entering into a discussion of the possible apparatus for this purpose, it may suffice to say here that it was decided to employ 25,000 volts continuous pressure current through the insulator, and to use as sensitive a D'Arsonval type galvanometer as could be had conveniently, to measure the current.

The pieces of apparatus which, taken collectively, may be called the high-voltage megger are shown diagrammatically in Fig. 1. T_1 is a 33-kv. transformer which supplies charge to the air condenser C, at high voltage through the kenotron K. T_2 is an insulating transformer through which the heating current is furnished to the cathode filament of the kenotron. The contin-

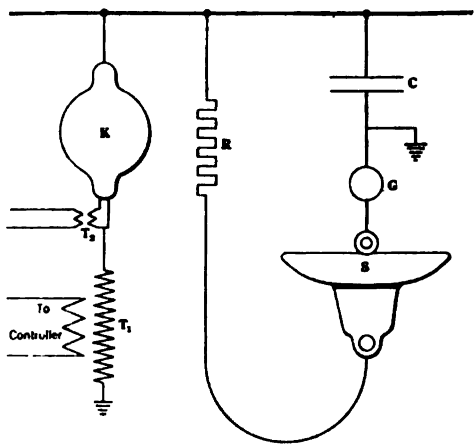


FIG. 1—HIGH VOLTAGE MEGGER—CONNECTION DIAGRAM

uous high voltage is impressed upon the insulator at S through the resistance R which is provided as a protection to the kenotron against a possible short-circuit of the load at S. R is adjusted to allow only full-load current for the kenotron to flow on such a short-circuit, and with 25,000 volts on the circuit. The galvanometer G is connected in the test circuit next to ground. The connections from the low-voltage side of the insulator to the galvanometer are described in detail below.

The use of 25,000 volts on the insulator results in an amount of surface leakage vastly in excess of that which occurs with the 600 to 1000 volts ordinarily used in megger tests. Most of this leakage is in the form of corona, and hence cannot be eliminated by any amount of careful cleaning of the surface of the insulator.

It is accordingly necessary to conduct all such strays directly off to ground by a path around the galvanometer. Fig. 2 shows the scheme used. Whenever possible, ordinary tap-water is used to make connection to uncemented porcelain blanks, and to make guard-rings, as it is very convenient in application. With units unprovided with petticoats, a felt ring saturated with water is laid on as a guard-ring, and the can guard is set directly on top of this felt ring. A grounded lead sheath protects the entire length of the wire running from insulator to galvanometer, while the instrument is remote enough from the high-voltage parts of the circuit to be immune from stray currents through the atmosphere.

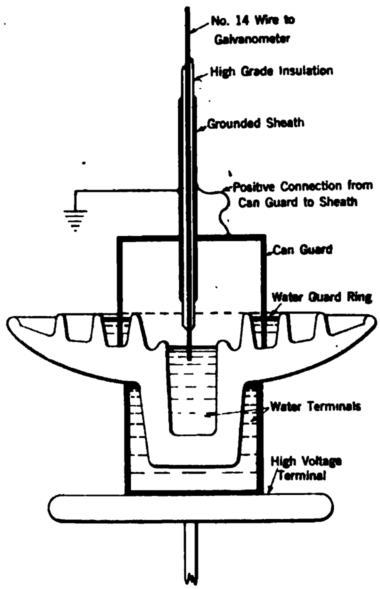


FIG 2—DETAILS OF GUARDING SCHEME

Adjustment of the megger voltage is secured by means of an auto-transformer with multi-tap secondary feeding through a controller into the primary of the 33-kv. transformer, while a voltmeter connected across this primary serves to determine the megger voltage, a calibration curve of the megger in terms of the primary voltage having been secured by means of a 7-inch (17.7-cm.) sphere gap.

Preliminary Resistance Measurements. Table I is a summary of the resistance measurements made on all of the normal batches of porcelain units immediately upon their arrival at the laboratory. The *UK* units are uncemented blanks of the same make and year as the assembled units of the *J* series. The *U H* units are blanks corresponding in every way to those used in the assembled *H* units. The photographic reproductions, Figs. 3 to 10 inclusive, illustrate all the types of units listed in the table. Table I also contains letters designating which insulator units are from a common maker. To illustrate: Units *G*, *H*, and *H M* were all made by the same manufacturer, *C*. It will thus be seen that the porcelain products of four different makers, *A*, *B*, *C*, and *D* are represented in the tests.

FIG. 3 FIG. 4

FIG. 6 FIG. 5

FIG. 7 FIG. 8

FIG. 9 FIG. 10

FIG. 13

TABLE I.

MEGAMEGOHM CLASSIFICATION OF PORCELAIN INSULATOR UNITS

(Compiled from insulator resistance measurements made on units as they were first received.)

Series	*A*	1 *A*-13 *A*	*C*	*J*	*U K*	*B*	*B L*	*G*	*H* and *U H*	*H M*	Q_1	Q_2
Figure	3	3	3	5	5	4	4	9	10	6	7	8
Maker	*A*	*A*	*A*	*A*	*A*	*B*	*B*	*C*	*C*	*C*	*D*	*D*
Date of manufacture	1912	1912	1913	1916	1916	1916	1913	1908	1916	1915	1916	1916
Megamegohm classes												
Below 0.010	..	1	..	..	..	..	3	..	..	..	..	..
0.010–0.099	..	3	..	1	..	..	..	..	..	..	..	..
0.10 –0.19	..	..	..	..	..	..	..	..	..	1	1	..
0.20 –0.39	1	1	5	2	..	..	1	..	54	9	..	..
0.40 –0.59	1	3	5	..	..	8	..	..	37	..	..	1
0.60 –0.79	2	32	17	1	4	90	..	..	3	1	1	40
0.80 –0.99	48	29	33	7	4	7	1	1	..	2	1	7
1.00 –1.19	40	20	12	51	4	..	8	5	3	8	28	..
1.20 –1.39	7	8	17	33	4	..	39	4	3	13	17	..
1.40 –1.59	3	2	..	22	..	..	31	4	..	2	1	..
1.60 –1.79	..	1	..	5	..	..	7	29	..	1	..	..
1.80 –1.99	..	..	..	1	..	..	11	33	..	1	..	..
2.00 –2.19	..	1	..	1	..	..	4	14	..	..	..	..
2.20 –2.39	..	..	..	..	..	..	1	7	..	..	..	..
2.40 –2.59	..	..	..	..	..	..	..	3	..	..	..	..
	..											
Total	102	101	89	124	16	105	106	100	100	38	49	48

In addition to the units of Table I, reference is made in this paper to various members of three additional small groups of units; namely, the *U B*, *B M*, and *F* groups. Of these the *U B* and *B M* units are specially selected soggy specimens of the same make and date as the *B L* series of Table I. The *F* units are of a new material, not porcelain. Fig. 11 shows the temperature-resistance characteristic of this material as exhibited by unit *F* 5. Fig. 13 is a photograph of an *F* unit.

Pull-Resistance Studies. A testing machine was used to subject the units to mechanical stress to determine whether this would affect their resistance. Pulls ranging from 0 to 5000 lbs. (22679. kg.) were applied to each kind of unit, but in no case was there any change in resistance from that obtaining for the unit in the mechanically unstressed condition.

Voltage-Resistance Studies. Some work was done using the high-voltage megger to ascertain whether the resistance of a unit is constant over the range 1000 to 30,000 volts. In any case where this source has been used, there has appeared to be practically no variation in insulation resistance over the range mentioned. However, some earlier work was done in the megging of very soggy units in which continuous voltages below 750 volts were used in order to hold the galvanometer current down to safe values. In every case where such a unit was later megged on 25,000 volts, the resistance thus determined is much lower than that obtained on the lower voltage. Table II shows results thus secured.

TABLE II

Unit No.	Test Voltage	Resistance, megohms
B L 19	110 25,000	13,000 820
5 *A* 6	415 25,000	21,000 6,900
B L 105	625 25,000	13,000 8,300
B L 68	635 25,000	8,300 2,200
8 *A* 4	730 25,000	60,000 20,000
8 *A* 2	740 25,000	73,000 42,000

It is not clear why there should be a difference between the resistance values obtained for these units at low voltage and at high voltage since quite a variety of low- and high-resistance units tested over a range of 1000 to 30,000 volts have shown no variation of resistance over that range.

Temperature-Resistance Studies. Early in the work it was brought forcibly to the attention of the test force that the temperature of an insulator is a factor of the greatest importance in its behavior under the megger test. To illustrate this point, Table III is presented.

TABLE III.

Unit No.	Resistance as first measured, megamegohms	Resistance as later measured, 20 deg. cent. megamegohms
1 *A*3	1.25	1.03
1 *A*4	1.04	0.99
1 *A* 5	1.09	1.12
1 *A* 6	0.93	1.09
1 *A* 7	0.60	0.74
1 *A* 8	2.08	1.01
2 *A* 1	0.83	1.11

The second column gives results which were obtained before the influence of temperature upon the resistance of an insulator was fully appreciated. The units had been lying in the hot sun for about an hour for the purpose of drying following a washing which had been given them. They had then been brought into the laboratory and laid on the floor for various lengths of time ranging from 15 to 45 minutes before being megged. It was then assumed that the room temperature (25 deg. cent.) could be taken as the temperature of the units without much error. The third column gives later results obtained after the units had reached a carefully determined steady temperature of 20 deg. cent. The lack of concord between the results in the second and third columns shows clearly the necessity for more careful work in this respect and, together with other similar observations, indicated the need of making a rather careful study of the resistance of porcelain as a function of temperature. An oven was therefore constructed which makes it possible to heat up eight units simultaneously and to megg them conveniently one after another on 25,000 volts continuous. All units rest on a common grate upon which is impressed the high voltage. Eight low-voltage connections pass out through the thick heat-insulated wall of the oven to a terminal board at which the galvanometer lead is connected to any unit desired. The temperature is determined by 10 carefully calibrated resistance coils wound of No. 34 copper wire having heavy leads brought out for convenient connection to a Wheatstone's bridge. The coils are placed at the height of the porcelain of the units and are otherwise at locations so

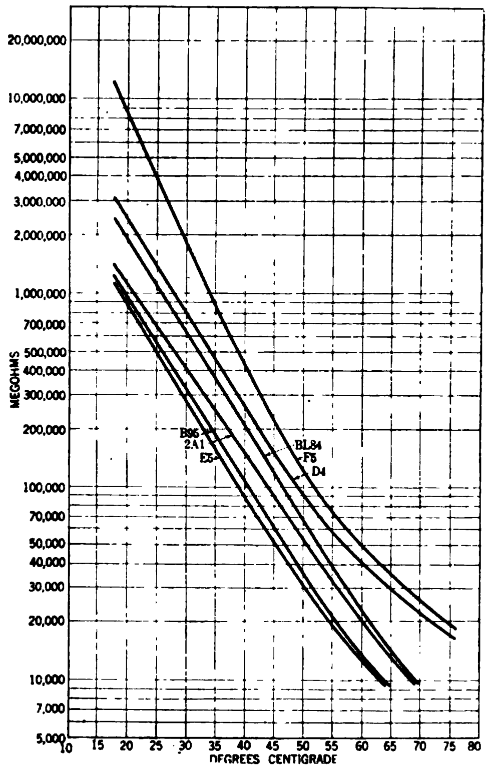


FIG. 11—VARIATION OF RESISTANCE WITH TEMPERATURE

chosen within the oven as to make it possible to judge of the resistance of a unit with a precision ranging from 0.2 deg. cent. at 25 deg. to 1 deg. at 65 deg.

The results of the study of six different insulator units are shown in the curves of Fig. 11. An exceedingly rapid rate of decrease of resistance with increasing temperature is shown by all the units, and this rate is substantially the same for all the different makes of porcelain insulators investigated. Fig. 12 is a curve derived from the temperature-resistance curves of porcelain units which has been found very useful in reducing to a common temperature basis of 20 deg. cent. resistance measurements made over a temperature range of 17 to 27 deg. cent.

MOISTURE IN INSULATORS

Results of Drying Out Insulators. That some high-voltage porcelain absorbs enough moisture to lower its resistance is shown conclusively by the results of drying numerous insulator units for a few hours in an oven at 150 deg. cent. All the insulators investigated in this way fall naturally into three classes (see Table IV) as determined by the effect of the drying upon their resistance; viz., (a) those practically unaffected by any amount of drying, (b) those raised in resistance by 20 to 400 per cent, (c) those enormously raised in resistance, *i.e.*, hundreds or thousands of times. A result of this natural division of the units has been for the test force to call classes (a), (b), and (c) respectively "non-porous", " slightly porous", and "very porous".

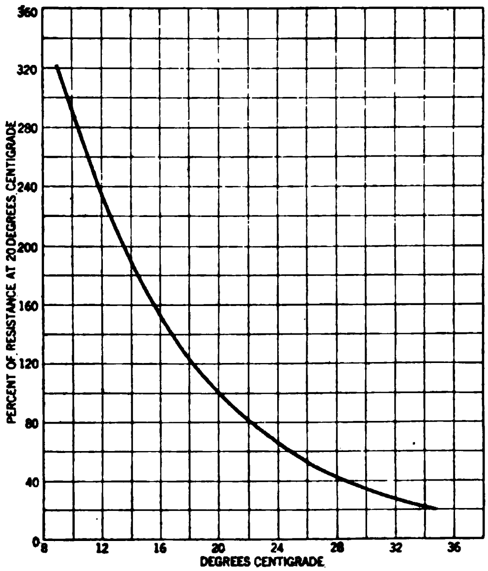


FIG. 12—PORCELAIN INSULATOR TEMPERATURE REDUCTION CURVE

Attempts to Water-log Units. It is obvious that a very easy laboratory test for the detection of porosity in an insulator is the high-voltage megger test, *provided the insulator is already water*

TABLE IV.
RESULTS OF DRYING INSULATORS AT 150 DEG. CENT.

Class (a)			Class (b)			Class (c)		
Unit No.	Total hours drying	Megohms	Unit No.	Total hours drying	Megohms	Unit No.	Total hours drying	Megohms
B 56	0	700,000	*A* 29	0	220,000	*B M* 4	0	42
	6	750,000		5	1,180,00		7	1,470,000
B 69	0	690,000	*B L* 18	0	390,000	*B M* 30	0	2
	7	700,000		5	1,390,000		3	15,700
G 9	0	1,770,000	*U K* 12	0	730,000		5½	130,000
	8	1,790,000		7½	990,000		15	720,000
H 4	0	300,000	*G* 50	0	1,160,000		33	1,550,000
	6½	320,000		6½	1,610,000		43	1,670,000
U H 37	0	300,000	*G* 50	0	1,300,000	*U B* 14	0	2,080
	6	320,000		6½	1,720,000		4	770,000
U H 79	0	320,000	*G* 81	0	730,000	5 *A* 6	0	6,800
	7	320,000		6	1,610,000		7	1,130,000
U K 14	0	1,000,000	*G* 71	0	1,080,000			
	6½	950,000		6½	1,870,000			

logged. However, many, if not all, very soggy units (*i.e.*, units reading below infinity on the 5000-megohm megger) may be raised by a few hours drying to an apparently perfect condition in which they pass a 60-cycle dry spark-over test in air. It has accordingly been regarded as essential that a method be found by which porous units may be made to take up water quickly inasmuch as any test which consumes weeks or months of time in order to establish porosity cannot be considered to have practical or commercial value.

Early in the work, the soaking of porcelain units in water at ordinary atmospheric temperatures was undertaken, but it became evident that, by this method, water enters wet-process porcelain units with extreme slowness, even in the case of units which have been called in the laboratory, "very porous".

It was then suggested that, along with the soaking, a temperature cycle be applied. It was the idea that there might exist a sort of breathing action caused by volumetric changes of the material under changing temperatures which would draw water into the extremely attenuated pores of the porcelain. Accordingly, five units which were believed to have varying degrees of porosity were selected and put through the following cycle; Put into tub of water and water brought from 30 deg. cent. to boiling, 1 hour; water being boiled, ½ hour; water being cooled to 30 deg. 1 hour, units cooled in "cold tank", (20 deg. cent.), ½ hour. This cycle was repeated two or three times per day. The results are shown in Table V:

TABLE V.
"ACCELERATED SOAKING"—RESISTANCES IN MEGAMEGOHMS.

Total cycles	*U B* 3	*U B* 5	*U B* 13	*U B* 14	*U K* 13
0	0.75	0.73	0.0085	0.53	0.80
1	0.55	0.41	0.011	0.36	0.62
2	0.66	0.57	0.030	0.39	0.80
3	0.61	0.55	0.021	0.36	0.76
5	0.66	0.84	0.046	0.36	1.27

As shown by the table, the only positive effect of this process was to raise the resistance of some of the units treated. This is no doubt due to a rapid driving out of water from the porcelain during the boiling part of the cycle.

Another "accelerated soaking" test was next attempted in which the boiling part of the cycle was eliminated, the water being carried to a maximum temperature of 75 deg. cent. The

With but two exceptions, the methods which have been tried in attempting to water-log units rapidly have been fairly successful in the cases of units known to be very porous. These two exceptions are the ordinary soaking in cold water and the attempt to accelerate water-logging by heating and cooling wherein boiling occurred during the cycle. However, no method has yet been found by which the slightly porous units can be made to take water rapidly. That efforts to this end have failed is remarkable in view of the fact that the water may be driven out of such units in a very few hours by heating them at 150 deg. cent. Whether these insulators would deteriorate in actual line service is a debatable question, the discussion of which lies outside the scope of this paper.

Conclusion

Much of the work of the summer has been concerned with the study of moisture absorption in porcelain insulators as indicated by their insulation resistance. This is largely due to the fact that few other characteristics of the specimens submitted have seemed so much worth while investigating as their porosity. In this connection, it is important to note that very little trouble with cracking due to expansion of metal parts is in evidence among the specimens, even among the older batches of units wherein little attention was evidently given to this subject. Some 60 assembled units of various makes have been subjected to temperatures ranging from 110 deg. to 150 deg. cent.—much higher temperatures than are ever encountered in service. Among these units were 30 selected as being most likely to crack owing to bad design wherein no provision was made at the base of the cap next to the disk for expansion of the cap. Out of the 60, only 3 units have failed by cracking; namely, Nos. *B L* 94, *C* 9, and *C* 76,— all of old design.

Inasmuch as the real factors which contribute to the weakness of many porcelain insulators are now much better appreciated, it is felt that some progress has been made toward achieving the broad purpose of the investigation; namely, to develop ready, sure and simple methods by which to detect the weak insulator. It is at the same time realized that a great amount of work remains to be done, and it is hoped that many others will devote themselves to this problem which it seems so necessary to solve if confidence is to attend the continued use of the porcelain high-voltage insulator.

Presented at a section meeting of the American Institute of Electrical Engineers, San Francisco, Cal., November 24, 1916.

INVESTIGATION OF SUSPENSION INSULATOR DETERIORATION

BY J. E. WOODBRIDGE

ABSTRACT OF PAPER

This paper gives an outline of the investigation of suspension insulator deterioration undertaken by Professor H. J. Ryan and Assistant Professor J. C. Clark, and explained farther in their papers. It cites the origin of the investigation, the limiting factors encountered and methods employed to overcome such handicaps.

The results of this investigation are admitted as disappointing and inconclusive on the causes of deterioration, although several causes previously considered probable have been eliminated.

THE TROUBLES experienced by operators of high-voltage transmission lines, due to deterioration with age of the dielectric strength of cemented porcelain suspension insulators, combined with the inability of ceramists and engineers to agree upon a satisfactory explanation of such deterioration, have induced the power companies of California to join forces in a scientific investigation of this deterioration. The results of this study, in so far as results have been obtained to date, are presented in full in the accompanying papers by Professor Harris J. Ryan and Assistant Professor J. C. Clark. The companies interested in this investigation to the extent of contributing to the expense of same are; the Pacific Gas and Electric Company, Pacific Light and Power Corporation, Sierra and San Francisco Power Company, San Joaquin Light and Power Corporation, and the Southern California Edison Company.

The investigation began as the outcome of discussions on the subject between Mr. J. P. Jollyman, of the Pacific Gas and Electric Company, Mr. H. A. Barre, of the Pacific Light and Power Corporation, and the writer, representing the Sierra & San Francisco Power Company. These discussions resulted in a conviction that megohm values of infinity determined by the commercial megger, that is, anything above 2000 or 5000 megohms, covered a wide range of porcelain values, an investigation of which might develop insulation resistances characteristic of durable versus non-durable porcelain. It was even thought that if deterioration is due to porosity, and if suitable apparatus could be developed for measuring much higher insulation resistances, a characteristic resistance might be found for porous porcelain, even when dry. It is obvious that if these hypotheses had proved correct, it would be possible for insulator makers to measure such porosity by electrical means in new porcelain, and determine in advance what insulators would deteriorate, which would in turn allow them to determine what method of manufacture would produce the most durable product in this respect.

It was also the idea of these engineers that insulation resistance measurements made under dielectric stresses more nearly approximating those of commercial service than the 1000 volts of the commercial megger might be of correspondingly greater value. The inherent difficulties of such measurements with alternating voltages, due to the extremely low power factor of insulator leakage, at once suggested the use of the kenotron for the supply of continuous current at the voltages desired.

A paper presented by Professor Ryan before the San Francisco Section of the Institute on March 31, 1916, described such measurements made at Stanford University under a pressure of 4000 volts d-c. derived from a kenotron with a sensitive galvanometer, the combination giving a range up to 800,000 megohms distinguishable from infinity. This equipment as then developed by Professor Ryan obviously extended the range of meggering to values 160 times greater than those of the commercial megger. A further extension of this line of investigation was then proposed to Professor Ryan with the request that he obtain the consent of the University authorities for the use of the high-tension laboratory and its equipment for this study during the 1916 summer vacation. Professor Ryan obtained this privilege and agreed to serve as a member of the committee having charge of the work, to which service he devoted the greater portion of his time during the vacation period. The necessary funds were contributed by the above mentioned companies and the work was started under the direction of Professor Ryan, the above mentioned engineers, and Assistant Professor J. C. Clark, who was employed actively on the work with assistants throughout the summer. Insulators were contributed by the various power companies above mentioned and by the Great Western Power Company, also by several manufacturers, usually in lots of 100, these insulators being of all the well known makes, and, in so far as possible, of various ages, colors and previous conditions of servitude.

The results of this investigation to date may at the outset be admitted to be disappointing, as the ambitions of the promoting engineers have not been realized. Water logged elements have been dried out and restored to insulation resistances equal to those of the least porous. By the use of continuous current at 25,000 volts and of galvanometers of great sensitiveness, infinity has been thrown above the resistance of any single piece of porcelain procurable, measurements being possible up to ten million megohms. As might be expected, this has been accomplished only by the exercise of great care and ingenuity in the matter of guarding against leakage. The characteristic resistance of porcelain suspension insulators of common shapes and sizes has been found to run between one-quarter and one and three-quarters million megohms.

Conclusive positive information on the causes of deterioration has not been obtained, but considerable negative information has practically eliminated several causes previously considered probable. Mechanical loads have been proved to have little or nothing to do with the case. Stresses set up by expansion and contraction with temperature changes appear to have little or nothing to do with deterioration in properly designed and annealed elements. There are indications that these stresses are as great in insulators without attached hardware as in those complete with cemented metallic attachments; also, that such stresses are as great in porous insulators as in those more thoroughly vitrified.

A study of porosity has shown that much, if not all wet process electrical porcelain is slightly porous, some of this porcelain being more suitable for filtration use than for the exclusion of moisture. Aside from this exception, the term "slightly porous" here means porous to such an extent that moisture may in the course of years creep into minute crevices, forming conducting paths which eventually reduce the distance between terminals of the insulator, (Considering such paths as conducting extensions of terminals into the mass of the porcelain) until the dielectric stresses between terminals will rupture the intervening material. Local heating in the non-porous barriers separating such conducting paths probably assists the final failure of the remaining dielectric strength. This investigation has shown that porcelain has an extremely high negative rate of change of resistance with temperature. Of the specimens tested, the rate of change may be stated as a loss of 99 per cent of the resistance with a rise of 45 deg. cent. from ordinary temperatures.

This partial porosity has so far been found extremely difficult of detection. We have found it impossible to devise any means of materially hastening the absorption of moisture above the rate inherent in ordinary line use, which often requires several years before the deterioration is apparent.

The difficulty in making porcelain bodies absolutely impervious to moisture is obviously due to the fact that porcelain by the very nature of its formation cannot be completely liquified in the process of vitrification as can other materials, such as glass. This leads to the consideration of materials having the desired mechanical and electrical qualities, which can be liquified and cast in a mold. Of these the most promising in both electrical and mechanical characteristics that has been brought to the attention of the committee is fused silica. This material has a high dielectric strength, and an extremely low coefficient of expansion with temperature. Its behavior when subjected to high dielectric stresses of sustained high frequency gives promise of very desirable characteristics in the qualities of dielectric strength, local heating under high potentials, and change of resistance with temperature.

It is the wish of the committee that others investigating this subject, or in a position to do so, may benefit by the ideas developed by this committee's work to date, and may carry on the work along the various lines indicated, which this committee has not been in a position to carry to completion.

Presented at the Chicago Section meeting of the American Institute of Electrical Engineers, November 27, 1916.

TEMPERATURE DISTRIBUTIONS IN ELECTRICAL MACHINERY

BY B. G. LAMME

ABSTRACT OF PAPER

The paper deals with certain fundamental principles governing heat distribution and temperature in electrical apparatus. The general problems of heat generation, heat flow and heat dissipation, upon which the resultant temperatures depend, are discussed at some length. The various paths of heat flow and the effects of the heat resistance of such paths are discussed. The effects of rapid heat flow on the equalization of the temperatures, and on their measurement, are considered briefly. Some of the fallacies in temperature guarantees and in temperature indications are pointed out. Some of the more common errors in the methods of measurement are described. In conclusion it is stated that no hard and fast rules can be made to cover the facts, except in a very general way, and that commercial temperature measurements should be considered as approximate, this being permissible because there is no sharply defined line between good and bad.

THE LAWS governing heat flow and temperature distribution are so similar, in many respects, to those governing electric current flow and electric potentials, that it is rather surprising that the former have received so little attention in comparison with the latter. Some of the laws of heat flow are so well recognized that their application to the problem of temperature distribution in electric apparatus should have been a leading feature in the early developments in such apparatus; whereas, on the contrary, it is only recently that very careful study has been made of such application.

One object of this paper is to indicate, in a comparatively simple manner, some of the conditions which fix the temperatures in different parts of electric apparatus. Before going into the general problem, certain simple conditions may be stated, such as:

1. The heat flow between two points is proportional to their temperature difference and to the heat resistance of the path or paths between them. Note the resemblance to Ohm's law.

As a corollary to the above, it should be evident that between two points at the same temperature, there should be no flow of heat.

2. The total temperature drop between any two points or media of different temperatures will be the same through all paths of heat flow.

3. There are no true non-conductors of heat, and, conversely, no perfect conductors.

4. Heat conduction and electric conduction bear some quantitative relation to each other, in the broad sense that all electric insulators are relatively poor heat conductors, while good electric conductors are correspondingly good heat conductors. There is apparently no rigid relation between the heat resistance and electric resistance of the various materials used in electric machinery, but the general relation holds and there are apparently no radical exceptions.

5. The rise in temperature at any point, due to generation of heat, is dependent (a) upon the total heat generated, and (b) upon the amount of heat which can be carried away along all available paths per degree of temperature difference. The temperature will rise until the heat dissipation equals the heat generation.

6. There are two ways to lessen the heat flow along any path. (a) By interposing higher heat resisting materials. (b) By lessening the temperature difference, as by raising the temperature of the part through which the heat is to be conducted. Conversely, the heat flow can be increased along any path by the use of better heat conducting materials, or by paths of lower heat resistance, and by lessening the temperature of any part to which the heat is to flow.

What makes the problem unduly complicated, in electrical machinery, is the fact that there are several different sources of heat generation, which may be, and often are, all active at the same time. Moreover, the heat losses may be distributed through the various heat conducting paths in such a way as to render any calculation very difficult and more or less inexact, except in a general way. For example, there is heat generated by losses in the copper conductors, obeying one law; while there is heat generated in the iron parts under a quite different law; and there may be heat generated by windage and friction, according to a third law. As these different losses may act in different parts of the heat conducting circuit, it should be evident that the problem of determining the exact heat distributions, and the temperature, is a very complex one. Such a determination is in the province of the expert analytical designer of such apparatus, but certain general conditions are of interest to all users of electric apparatus.

Consider first the general conditions of heat dissipation from an armature coil. In Fig. 1 is represented an armature slot with the surrounding iron, and with two separate "coils" per slot, as is now the most common practise. Let it be assumed that the point *a* represents the "hot spot", or part at highest temperature in the apparatus. The heat from this part can flow along two general paths, namely, longitudinally through the copper conductor itself to the end windings, and thence to the air, and

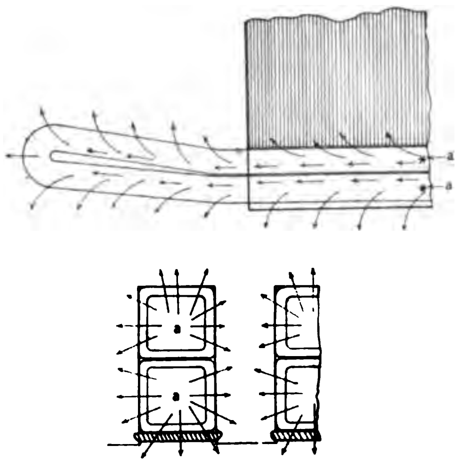


FIG. 1

laterally through the insulation to the surrounding iron, or to the ventilating ducts. From the iron the heat flow is then through various paths to the external cooling air.

LONGITUDINAL HEAT FLOW

Considering first the longitudinal conduction of heat in the coil, then starting at the point *a*, the first unit of length conductor will have a certain loss. If the heat generated by this first unit loss were all that need be considered, then the drop in temperature, from the point *a* to the end windings, would be simply a function of the heat-conducting properties of the conductor itself. But the next unit length is also generating its own unit loss, so that the heat flow from the second to the third unit length is due to two units loss; in the same way, the flow to the fourth unit length will be due to three units loss, etc. Therefore, the temperature drop, or temperature difference per unit length of conductor, increases more rapidly as the point *a* is departed from, and if it is at a considerable distance from the end winding, and the losses per unit length are comparatively high, a very high temperature may be required at *a* to conduct all the heat longitudinally to the end windings. In very wide core machines the longitudinal drop may be so great that the temperature at *a* in practise will be so far above that of the surrounding iron, that a very large percentage of the actual heat is conducted laterally through the insulation to the iron, even if the iron is at a comparatively high temperature. However, in narrow cores, the drop to the end windings may be, in some cases, so very low, possibly 5 to 10 degrees, that with good heat dissipation from the end windings themselves, the point *a* may have, for instance, an actual temperature of 40 deg. cent. If the iron next to *a* also has a temperature of 40 deg. cent. then there would be no flow of heat from *a* to the iron. Furthermore, in such a case, as the iron temperature over the whole width of the core may be fairly uniform, and as the copper temperature decreases from *a* to the end windings, obviously as we depart from the point *a*, there would be heat flow from the iron to the copper, and thus the windings would tend to cool the core. This is frequently the case with light loads on a machine, for in such conditions the coil loss is low, while the iron loss remains fairly constant for all loads. In such case there may be heat flow from the iron to the copper along the whole length of the buried portion of the coil. At some higher load, the copper loss varying as the square of the load, the increased longitudinal drop will bring the copper temperature above that of the iron so that the heat flow is from copper to iron. This condition is illustrated by Fig. 2.

It must be recognized that the lateral flow of heat, from the coil to the iron, reduces the longitudinal drop, such reduction depending upon the relative percentages of heat flow along the two paths. It must also be borne in mind that in order to have such longitudinal heat flow, the end windings must be able to dissipate their own heat at lower temperature than would be attained at *a*, or in the core. If the end windings have little or no ventilation, or heat dissipating capacity, then their own generated heat may bring their temperatures higher than those of the armature iron so that the heat flow actually may be from the end windings toward *a*, and then laterally through the insulation to the core. In such case, the hottest spot will be in the end winding rather than in the buried part of the coil. Obviously when such condition occurs there is no possibility of either the end windings or the buried part of the coil being cooler than the iron, for the heat flow throughout is toward the iron.

Lateral Heat Flow

Considering next the lateral flow of heat through the insulation to the iron, the amount of heat conducted is a function of the temperature difference and the resistance of the conducting path. Or, in other words, if a given amount of heat is to be conducted through a path of given resistance, the temperature in the heat generating part will rise until the required heat is conducted away.

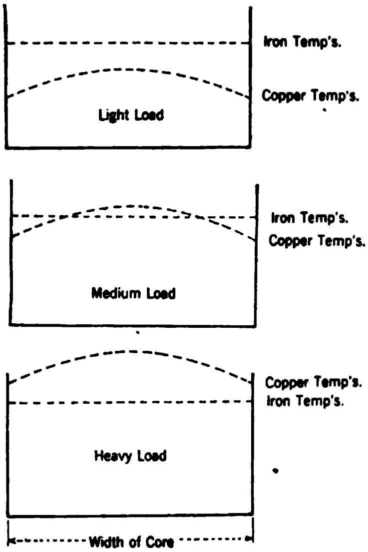


Fig. 2

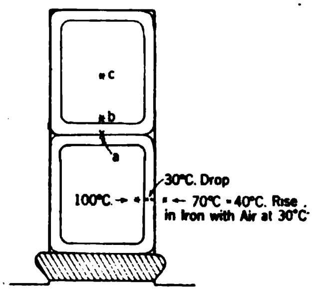


Fig. 3

To illustrate this problem more concretely, let Fig. 3 represent the temperature conditions in a section of an armature. Assuming, for example, the temperature of the copper inside the coil insulation as 100 deg. cent., the iron temperature as 70 deg. cent., and the air temperature as 30 deg. cent., then the following conclusions may be drawn.

(a) From the outer coil (the one next to the air gap) through the wedge to the air gap, the temperature drop will be 100 — 30 = 70 deg. cent. Obviously, any temperature measurement made outside the wedge, next to the air, will approximate the temperature of the air and not of the copper. Any temperature measurement made beneath the supporting wedge will measure some intermediate temperature between the copper and the air. If the temperature drop through the wedge should be equal to that through the insulation, then a measurement underneath the wedge should show half the temperature drop through insulation and wedge, and obviously, the measured temperature would be far below that of the copper.

(b) If the temperature is measured at the outside of the coil, between the iron and the insulation, it would approximate the average of the temperatures of the iron and of the outside insulation, or practically the temperature of the iron. If the iron should be at different temperatures at the sides of the slot and at the bottom, then obviously different readings would be obtained, depending upon the location of the measuring device. It is evident that such temperature measurements give no indication whatever as to the true internal temperatures of the coil, for the heat flow and the resistance of the insulation are nowise involved in the measurement.

(c) At a point *a*, between the two coils, there should be but little heat flow through the insulation, unless the copper is comparatively narrow. If there is but little heat flow through the insulation at this point, then eventually the temperature at the point *a* must rise to approximately that of the copper in the two coils. Therefore, a measuring device located at *a* will approximate the temperature of the copper itself, and is, in general, a good indication of the hot spot at that part of the winding. Therefore, as a practical method of temperature determination, a thermo-couple located at *a* is about the most satisfactory device that we have. However, the location of the point *a* along the slot is also of importance on account of the longitudinal flow of heat in the conductor and the consequent temperature drop. In other words, the direction of heat flow in the coil itself, must be taken into account. Therefore, a thermo-couple located as above, is only satisfactory when the general location of the hot spot is known beforehand. This is usually determined, in a general way, for a given type or line of machines, by locating several thermo-couples along the slots.

With narrow slots and comparatively thin conductors, and especially with very heavy insulation, there is some flow of heat through the insulation which lies between the two coils, this heat passing out sidewise to the iron. In such case, the point *a* may be of somewhat lower temperature than the copper. It may happen also, in some cases, that, due to unequal losses and heating of the two coils in the same slot, one is at a higher temperature than the other. In such case, due to the heat flow between the coils, the temperature indication at *a* will not show better than an average of the two temperatures. Furthermore, if the temperature at *c*, in a coil subdivided into many insulated conductors, is materially higher than at *b*, then the temperature indication at *a* may not be a close approximation to the maximum temperature.

Flow Through Iron Parts

In the ordinary armature, after the heat passes from the copper to the iron, there is still quite a problem involved in the dissipation to the surrounding medium, which is usually the air. The direction of the heat flow to the iron will depend, to a considerable extent, upon the arrangement and location of the heat dissipating surfaces. There are two general paths of heat conduction in all armature cores; namely, a flow along the laminations to where their edges come in contact with the air or with other material, and a flow across the laminations toward heat dissipating surfaces. The flow along the laminations may be calculated with fair accuracy. Across them it is difficult to determine such flow, largely because the laminations are insulated from each other by materials which are poor conductors of heat. Also such flow is affected not only by the insulation between laminations, but by the perfection of contact. In other words, the heat flow may be affected by pressure. According to the various figures available, the heat flow per unit volume of material along the laminations is from ten to one hundred times as great, for a given temperature difference, as across them. Obviously, therefore, heat dissipation from the iron by flow across the laminations should be considered relatively inefficient, yet in the vast majority of rotating machines the heat dissipation is largely across the laminations. The reason for this is that by placing ventilating passages or ducts, parallel with the laminations, at frequent intervals in the core, the cross section of the heat path in the intervening iron sections, may be made very large compared with the heat to be dissipated, so that the density of flow is very low. By the same procedure the length of the heat path is made quite short. Thus in practise, the temperature drop through the laminations themselves may be made relatively small compared with other drops. However, not all the heat in the iron passes across the laminations to the ventilating ducts, for where the length of the path, along the laminations to any heat dissipating surface, is not large, a very considerable amount of the heat may be dissipated from the edges of the laminations themselves. In fact, in certain types of machines with very shallow iron cores, experience has shown that the ventilating ducts, parallel with the laminations, may be omitted, provided good ventilation is obtained over the edges of the laminations. It is evident, therefore, that the flow of heat and distribution of temperature are dependent upon the arrangement of the iron, dimensions and location of the ventilating surfaces etc.

Heat Flow to the Air

After the heat has passed from the copper to the iron, the resultant of the copper and iron heats must be conducted to the cooling medium, which is usually the surrounding air. In the case of air, there is usually a considerable drop in temperature from the solid surface to the cooling air itself, the amount of such drop depending upon the ventilating conditions. In practise, there appears to be a film or layer of air which adheres very closely to the solid surfaces. This forms a sort of heat insulating film, retarding the flow of heat to the cooling air. In air ventilation, the effect of any considerable air movement over the surface appears to be that of scouring this hot film away from the surface and *replacing it with a film of cooler air.* Merely scouring or rubbing the hot film away from the surface is not particularly advantageous unless some means is furnished at the same time for supplying an ample quantity of cooler air to take the place of the removed hot film. Rapid air circulation, by means of a supply of air from the outside, appears to accomplish both results in one operation. Thus, one of the principal actions of air ventilation appears to be that of scouring away the hot contact film, while a second action is to carry the hot air away without mixing it with the incoming cooler air. Whatever portion of the dissipated heat is absorbed by the incoming cooling air adds that much to the temperature of the air itself and eventually to that of the apparatus to be cooled. Thus mixing the outgoing with the incoming air makes a sort of Siemens' regenerative furnace and the machine becomes cumulatively hotter and hotter until the dissipation through other paths becomes equal to the heat generated. In such cases the ventilation of the machine may only be useful in equalizing or redistributing the temperatures in the various parts.

From the preceding analysis, it would appear that the temperature at the hottest part of the coil is fixed principally by the heat flow through the copper, and its surrounding insulation, directly to the air, and by the flow from the copper to the iron, and from the iron to any exposed air surfaces, and then to the air. Along the first path, there are three principal temperature drops; namely, in the copper itself, then through the insulation, and then from the outside surface of the insulation to the air. Along the second path, there are also three temperature drops; namely, from the copper through the insulation to the iron, then from the iron to the exposed air surfaces, and then from the surfaces to the air. Along the first path each part of the copper path is generating its own heat, to be conducted away, in addition to that which is to be conducted from other parts of the path. In the second path, each part of the iron path may be generating its own heat, which adds to that coming from other parts. The relative amount of heat conducted along each path is dependent upon so many conditions, which vary with the load, that no one but an analytical designer backed by experience could even approximate the values by calculation. However, it should be obvious that any measuring device applied to the outside or cooling surface does not, and cannot, directly approximate the temperature of the hottest part, except in those rare cases where the hottest part is dissipating heat directly to the air. This is true only in very special cases such as series coils of bare strap, etc. In any coil or part of the apparatus which is heavily insulated, that is, which is covered by poor heat conducting materials, an external temperature measurement is an extremely poor indication of the true internal temperature, unless many other conditions are known which may give an indication of the internal temperature drops. In different types and constructions of rotating apparatus, hot spots may hold quite different relative positions with respect to the cores and windings, so that no reasonable rule can be made to cover all cases. Moreover, in some classes of apparatus, it is not practicable to make any temperature measurements until after the apparatus is shut down, and this introduces other very important errors which should be considered, such as cooling effects as a whole, during the period of shut-down, equalization of temperature due to internal conduction, etc.

Equalization of Temperature, etc.

When there are hot spots, or zones, or areas, of different temperatures, in an armature winding, for instance, such difference in temperature is maintained by the continual generation of heat in the various parts. But the moment that such generation of heat is stopped there is immediately a tendency for equalization of temperatures by flow of the stored heat from the hotter parts to the cooler. In good heat conducting materials, as copper, such equalization may be very rapid, so that a temperature indicating instrument of a sluggish type may not indicate anything like the true maximum temperature of the spot where it is placed, if applied after the load is removed, especially if the rate of heating of the thermometer bulb is much less than the rate of heat transfer from one part of the winding to another. If located on a hot spot, the reading may rise to some intermediate value and then drop off as the hot spot cools by heat conduction to other parts. If located upon a cool spot, it may rise slowly for a considerable period, due partly to sluggishness of the thermometer and partly to the cool spot rising in temperature by conduction of heat from some other part. The conditions are so varied that no reliable conclusions can be drawn, from the action of the thermometer alone, in regard to the coolest or hottest spot.

A second condition which tends to make such temperature measurements fallacious, lies in the cooling action in the interval between load removal and shut-down to take temperature measurements. In apparatus which depends upon a high degree of artificial cooling, such cooling effect may be very considerable. This is particularly true of high-speed machines which require considerable time to come to a standstill. It is, therefore, desirable in such machines to obtain all possible temperature readings at normal speed and with load. In rotating field machines, this is, to a certain extent, practicable, but in most rotating armature machines, the armature temperatures usually are not attainable until the machine is brought to a standstill, and even then some error may result from sluggishness or delay in taking the readings. One method which has been proposed at times, for lessening the sluggishness, is to heat the thermometers up to practically the normal operating temperature of the part to be measured, while the machine is still carrying load. At the moment of shut-down the heated thermometer is applied. This, to a certain extent, removes the factor of sluggishness in the thermometer itself, but is only a partial compensation. It must be considered that the outside of the insulation is at lower temperature than the inside, and that, therefore, the body of the insulation itself must have its temperature increased by flow of heat from other parts.

Fallacies in Temperature Guarantees and Measurements

In the older methods of determining temperatures, it was assumed that the thermometer readings, obtained on a winding, for instance, were a true indication of the temperature of the winding as a whole. The manufacturers of electrical apparatus long ago recognized the fallacy of this method, as they had found from bitter experience that there were liable to be hotter parts in the machine than any thermometer readings would indicate. They, therefore, designed machines with regard to the possible hot-spot temperatures as encountered in service, rather than any temperature which the exposed parts of the machine would show. Thus in designing a certain machine for safety at the hottest part, not infrequently the exposed parts of the winding would show, by thermometer, comparatively low temperatures, such as 25 deg. to 35 deg. cent. rise. Therefore, as the observable temperature readings came so low it became the fashion to call for 35 deg. cent. guarantees and, in many cases, the operating public lost sight of, or perhaps never knew, the real meaning of such low temperatures. Among the designers of electrical machinery, it was recognized that a temperature rise of 35 deg. cent. in itself was absurdly low, but that the object in operating at such low temperature on a part which could be measured was simply to protect the machine in some inaccessible hotter part, where the temperature could not be measured. From the present viewpoint, it is astonishing what reliance has been placed upon temperature readings in the past. For example, if a 40 deg. cent. machine showed 41.5 deg. cent. rise on test, it was unsafe, while if it showed 38.5 deg. cent. rise, it was good. We now recognize that neither of these temperatures have any controlling value, unless many other conditions are known. To the experienced man they simply mean that compared with the other machines of similar constructions and characteristics, which have proved satisfactory in service, they are reasonably safe. To the designer they mean that when proper corrections have been made for the various internal temperature drops, the highest temperature attained, at any point, will be within the limits of durability of the insulating material used. The whole problem is a good deal like that of a determination of the voltage generated in a given power-house, by measuring the voltage at the end of a transmission-line. If we know all the constants of the line, and know the current flowing, etc., we can figure back to the generated voltage. Otherwise the voltage at the end of the line means but little. However, we know that if the system is designed with reasonable regard to economy in general, there may be from ten to twenty per cent voltage drop from power-house to the end of the line. Therefore, by adding an approximate correcting factor to this voltage, we can make a reasonable estimate of the generated voltage. In the same way in electrical apparatus of certain types, a reasonable internal temperature drop may be approximated, which added to the observable temperature, gives a fair approximation to the hottest part, but *the result is an approximation and must be recognized as such.* Primarily, the manufacturer must make a safe machine for a specified service regardless of the temperature guarantees, and the temperature measurements made on most classes of apparatus should be considered simply as rough approximations to indicate that the manufacturer has made a reasonable attempt at a safe machine. This may seem a rather bald statement, but nevertheless it is a fair statement of the case.

Errors in Temperature Measurement

It has been shown in the preceding that the usual observable temperatures are in most cases only crude approximations to the real temperature conditions. It may now be shown that even the observable temperatures, obtained by the usual means, are in themselves only crude approximations, in many cases. Take, for instance, the determination of temperature by increase in resistance; when the coil is heated its temperature may not be, and very frequently is not, uniform throughout the coil. As an extreme example, if one-fifth of the coil length has a temperature of 80 deg. cent., while four-fifths of it has a rise of 30 deg. cent. then the increase in resistance of the coil as a whole will correspond to a rise of 40 deg. cent. Thus, by increase of resistance, the temperature may be more than safe, while actually one-fifth of the coil is far above the safe temperature for ordinary fibrous insulations. In other words, the resistance method gives only average results and may be very misleading. However, in those cases where it is known, by past experience and otherwise, that there is very little liability of hot-spots, the resistance method of determining temperature is often quite satisfactory. However, the method is limited to comparatively few types of windings.

Considering next the thermometer method of measurement, the theory of this is quite simple, but apparently it has been very much misunderstood. In windings, except in rare cases, the thermometer is not applied directly to the heat generating material itself, but is applied outside of an insulating covering. Usually the temperature drop through this insulating covering does not receive any consideration, and yet everything depends upon this. Assume, for example, an insulated coil, thermometer and covering pad, as shown in Fig. 4. Assuming the copper inside the coil as being of uniform temperature, and the cooling air at *a* and *b* as also at a uniform, but much lower, temperature than inside the coil; then the temperature drop from the copper to *b* will be the same as through the insulation, thermometer

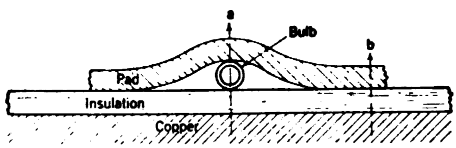


FIG. 4

bulb and covering pad to the air at *a*. Obviously if the temperature drops through the insulation and through the pad are equal, then the thermometer bulb will show a midway temperature. This is, of course, assuming that the surface drop to the air, previously referred to, is very small, or that it is included as part of the drop through the pad. Obviously, if the drop through the covering pad is made very much higher than that through the insulation proper, then the thermometer bulb more closely approaches the copper temperature. Thus it is seen that all kinds of results may be obtained, depending upon the relative drops through the pad and through the insulation. In a low voltage machine, with relatively thin insulation, the pad may take most of the drop. With very heavy insulation, the pad may take proportionately less and the thermometer reading departs accordingly from the copper temperature. It might be suggested that a big thick pad of very poor heat conducting material might be used. This apparently would tend toward more accurate temperature readings, but, on the other hand, harmful effects may be introduced by the use of a large pad. The resistance to heat dissipation being increased in the area covered by the pad, obviously less heat will be carried away at this point and, therefore, the heat generated under the pad must be conducted to adjacent parts of the coil. This means an increased temperature at this point, due to the use of the pad. Again, the use of the pad, in some cases, may affect the normal ventilation of certain parts of the coil not directly covered by the pad. For instance, if there is a ventilating space between two adjacent armature coils, through which air is normally driven, a pad which covers this space even partially may create more or less of an air pocket, and thus materially affect the heat dissipation, and the temperature directly under the pad. Experience has shown that both of the above conditions are obtained when good judgment is not used in the application of the covering pad. This, of course, applies particularly to those cases where temperature readings are obtained while the machine is in operation. Of course, after shut-down, most questions of ventilation and of generation of higher temperature under the pad need not be taken into account.

There are so many conditions entering into the interpretation of the thermometer and resistance methods of determining temperature, that in certain classes of apparatus it has been very desirable to find more accurate methods. One of these is in the use of so called resistance coils. In this method a coil of fine wire of a known temperature co-efficient, and of known resistance at a given temperature, is placed at the spot where the temperature is to be measured, and the temperature rise is determined from the increased resistance of the coil. One serious objection to this arrangement, is that the resistance coil must have considerable length and breadth so that it really indicates the average temperature of a considerable area instead of a point. When placed between two coils, as indicated in Fig. 5, it usually occupies so great a proportion of the slot that it indicates an average temperature considerably lower than at *a*. Furthermore, on account of the length of such coils, there may be a considerable difference between the temperatures at the two ends. Thus the resistance coil, like the resistance measurement of the windings themselves, gives an average result, but this average may be limited to a comparatively small area, whereas, in the resistance method in general the indicated rise is an average of the whole winding. However, in the resistance method, the temperature of the conductors themselves is measured, whereas, with the resistance coil the temperature measurement is outside the insulation. The resistance coil method is, therefore, a relatively crude approximation, although when brought out it was really an important step in advance. In its early application, many misleading results were obtained, due largely to lack of understanding of the principles governing temperature distribution and temperature drop. In some cases, the resistance coil was placed under the wedge as at *b* in Fig. 5. In other cases, the coil was placed at the side of the slot next to the iron, or at the bottom. Very rarely was it placed midway between the two coils, probably because this was a more difficult application and

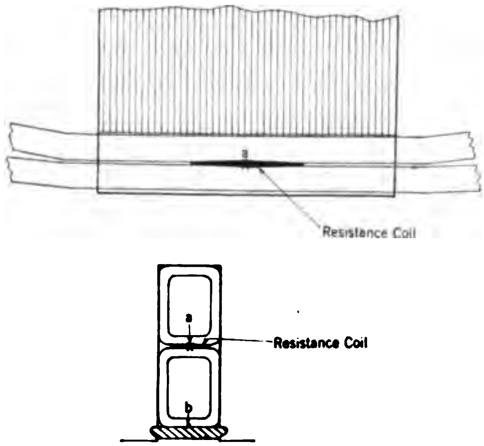


FIG. 5

also because the greater accuracy of such location was not recognized. From the use of resistance coils many good engineers drew the conclusions that the upper limit of permissible temperature for fibrous insulations was only 80 deg. to 90 deg. cent., because with the coils located in certain ways and places, deterioration of insulation at some other point was liable to begin, if the above temperatures were exceeded. The error was in not recognizing the temperature drop between some hotter spot and the average location of the resistance coil. When this condition was recognized, the results obtained by resistance coils became more consistent with the facts.

A later development than the resistance coil is the thermocouple as a practical device for measuring temperature. One great advantage of the thermocouple is its very small size, so that it can indicate the temperature at practically a point instead of a very considerable area. Moreover, as it is a zero current method of measurement, when used with a potentiometer no question of size or length of the connecting leads need come up. The thermo-couple is so small and has so little mass, that it can follow very quickly any temperature changes where it is located. If properly placed it furnishes the most accurate temperature indicator which we now have, as it can be located in all sorts of normally inaccessible places. However, its use is practically limited to stationary apparatus. In rotating apparatus, or rotating parts it can be used only after shut-down, which introduces errors, as already shown.

Many-Conductor Coils

In all the preceding considerations it has been assumed that the copper inside the coils itself is at a uniform temperature, in any given unit of length. This is practically true, provided the coil is made up of a single conductor, or of a relatively few conductors with only a moderate amount of insulation between them. When several coils or conductors are placed side by side, as in Fig. 6, it would appear at first glance that the middle coils should heat much more than the outer ones. But, in reality, unless there are many layers of coils, the temperatures of the different coils will not vary greatly from each other. For instance, in Fig. 6, the heat generated in the middle conductor is only one-third that of the total generated in the coil, and yet the two side surfaces through which this heat passes to the adjacent coils aggregate almost as much as the total outside dissipating surface of the whole coil, through which all the lateral heat flow is dissipated. Considering further that the insulation between the middle coil and its neighbors is relatively thin compared with the outside covering, it is obvious that the temperature drop from this coil to the adjacent ones will be comparatively small,—possibly not over ten per cent of the drop through the outside insulation.

However, with a large number of coils side by side, the conditions become cumulatively worse. Here, the drop from the center conductor to the next one, may be small. But the drop from the second conductor to the third is considerably greater due to the heat of two conductors being transmitted. From the third to the fourth there is a drop corresponding to the losses of three conductors, etc. Thus, there is a gradually increasing temperature drop from the center of the coil toward the outside surface, and if the coil be very deep, that is, if it consists of many insulated layers, the sum total of the drops may be quite large. Or, putting it in another way, with a comparatively deep coil the temperature rise from the outside surface of the coil itself toward the center will be very rapid at first, and gradually taper off, as indicated in Fig. 7. This is indicated very clearly in the case of an over-heated field of coil of fine wire. Here the first outside layers will usually be found in a fairly good condition, but at a comparatively little distance inside the coil there may be severe roasting or evidence of overheating, which may be

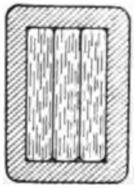


FIG. 6

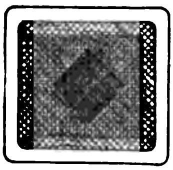


FIG. 8

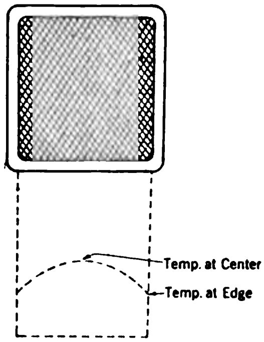


FIG. 7

almost as bad as at the center. (See Fig. 8.) In such case, the temperature measurement on the outside of the coil is no satisfactory indication of the hot-spot temperature. A temperature measurement by resistance, while a closer indication than that by thermometer, also may be very misleading. It may be stated that modern design tendencies are toward comparatively shallow field coils, largely on account of this condition.

CONCLUSION

The whole object of this paper is to show the problem of temperature distribution and temperature measurement, as it actually is. It is the writer's desire to show that no hard and fast rules can be made for determining the facts in the case, and that the best rules and methods now practicable are only approximate. The present limitations set for insulating materials are much higher than were considered practicable only a few years ago. This is not because the limits have been raised, but because, through a better understanding of the facts, the real upper limits of temperature as fixed by durability of insulation, are now known to be considerably higher than was believed to be the case only a short time ago. If the real limits were in accordance with former beliefs, then all the evidence of the more accurate modern tests and data would indicate that the vast majority of the existing electrical machines should have "roasted out" comparatively early in their operation. The higher temperature limits were there, but were not recognized. Now we recognize them and attempt to make reasonable allowances for differences between the measurable temperatures and the actual hottest parts. The present method may be crude, but we are not going at it blindly, as was formerly the case. Formerly the manufacturer took the real responsibility for making a machine that was safe for the service, whatever the guarantees called for. Today the responsibility is still his, but he is attempting to educate the public to a knowledge of his real problems, and to a recognition that temperature determination is far from being an exact art. There is no sharply defined line between *good* and *bad* in the insulating materials as affected by temperature, consequently there is no sharp line between *safe* and *unsafe* temperatures.

Presented at the Chicago Section meeting of the American Institute of Electrical Engineers, November 27, 1916.

RATIONAL TEMPERATURE GUARANTEES FOR LARGE A-C. GENERATORS

BY F. D. NEWBURY

ABSTRACT OF PAPER

The paper is an argument for the standardization of temperature guarantees when the guarantee is based on internal temperatures as measured by thermocouples. It is recommended that in all cases the maximum safe operating temperature of the insulation be used as the temperature guarantee, instead of using a lower temperature. The standardized guarantee, 50-deg. rise by thermometer, is cited in comparison with the present wide range of temperature rises, from 60 deg. to 100 deg., that have been called for in specifications when the thermocouple method of measurement is used. Arguments are presented from the stand-point of both the designing and the operating engineer for the use of this standardized temperature rise. Curves are shown illustrating the temperature conditions in both stator and rotor of a typical large, high-voltage turbo-generator. Examples, based on these curves, are given to show that a low temperature rise guarantee for the stator does not necessarily result in margin for overloads. This margin for overloads is the main argument that can be advanced in favor of low temperature rises. The only way in which the purchaser can be certain of overload margin is to have the specifications call for the maximum rating desired, in which case the maximum safe operating temperature may logically be made the temperature guarantee.

OPERATING engineers are familiar with the use of a single standardized guarantee of temperature rise by thermometer for large single-rated generators, and particularly for turbo-generators. During the past five or ten years, such generators have been purchased very generally on the basis of a 50 deg. rise, measured by thermometer. This standard rise was fixed at 50 deg. because it was felt, by reason of general experience, that this represented the maximum safe rise. It was recognized that with guarantees based on the temperatures of external surfaces, a single limit could not be fixed that would fit all cases; yet a single limit was fixed and has been adhered to in practically all commercial transactions. This standardized guarantee, moreover, takes no cognizance of the inherent variations in the actual temperature performance of individual units. A high-voltage generator and a similar low-voltage generator under some conditions should be designed for quite different temperatures as measured by thermometer (on account of greater temperature drop due to thicker insulation with high voltage) yet both these units would be guaranteed for a rise of 50 deg. in accordance with this established practise.

In the commercial introduction of the thermocouple or resistance-coil methods of measurement, as a basis for guarantees there has been a tendency to lose sight of this idea of a standardized guarantee. When this method first appeared in contracts about three years ago, guarantees for "hot-spot" rises as low as 40 deg. were required in some instances. As the real significance of the results obtained by these internal measurements became better known, the specified temperature rises based on this method have gradually increased up to the relatively high values consistent with the safe operating temperatures of mica insulation. With built-up mica insulation, a safe operating temperature of 150 deg. may be guaranteed, and the corresponding temperature rise guarantee may be 105 deg., or, in round numbers, 100 deg. Yet even today there is no uniformity in guarantees. Temperature rises of 60 deg. are often called for in specifications, even when mica insulation is employed, and practically all temperatures between 60 deg and 100 deg. have been used as guarantees on one occasion or another.

In discussing maximum permissible rises, the author has in mind the limits allowed when mica or other Class B insulations are used. The maximum safe rise allowed by Class A insulations is only 60 deg. and this is so near the familiar guarantee of 50 deg. rise by thermometer that there is no tendency to give guarantees below the possible maximum when this class of insulation is employed.

From the standpoint of the designer of large generators, the desirability of a standardized temperature guarantee that is consistent with the safe operating temperature of mica insulation is apparent. When other conditions permit, full advantage can be taken of the heat-resisting properties of the insulation and the most efficient and economical design can be produced. In the largest two- and four-pole generators, it is not only desirable, but in many cases it is necessary that such advantage be taken in order that the safest mechanical design may be produced. It is good common sense that the copper and the sheet steel cores be pushed to the limit, electrically and magnetically, so that greater factors of safety may be provided in the all-important mechanical features of the design. There are so many real limitations imposed by the physical characteristics of the available materials that demand careful consideration in the design of high-speed machinery, that the imposition of additional "man-made" restrictions should by all means be avoided. They only serve to uselessly impede progress.

In a fair, sensible contract there should be no conflicting or inconsistent guarantees. It is now customary to include in many contracts for large generators a guarantee covering the total temperature that the insulation will continuously withstand without injury. Such a guarantee of the insulation is virtually a guarantee of maximum capacity—so far as capacity is determined by heating—and so covers, broadly, the same ground as the guarantee of temperature rise. Obviously, the two guarantees should be equivalent. An example will make this clear. With suitable mica insulation, 150 deg. is frequently used as the safe limiting temperature guarantee. Assume that this guarantee is made and also that the generator is guaranteed to deliver its rated kilovolt-amperes without exceeding a temperature rise of 80 deg. Two different guarantees will have been made; one that the generator will deliver its guaranteed load with a total existing temperature of 125 deg. (adding 40 deg. air temperature and 5 deg. allowance to the guaranteed rise in accordance with the A. I. E. E. Standardization Rules); and another that the generator can be safely operated up to a temperature of 150 deg. The guaranteed temperature rise should have been 105 deg. to make the two guarantees consistent and rational.

In considering the subject of low versus high temperature rise guarantees, one is apt to look upon a low rise in itself as an advantage just as low loss in a generator is an advantage. A temperature rise guarantee, however, is radically different in nature from a loss or efficiency guarantee. In the case of efficiency the operator is interested in what the apparatus will actually do; any reduction in losses is of direct benefit, and the greater the reduction, the better will be the generator. With temperature, on the other hand, the operator is only interested in temperature rise to the extent of knowing that it is safe; he is not primarily interested in temperature figures. If the operating temperature is safe, a lower temperature will be no safer and of no particular value.

The importance to the operator of a temperature guarantee lower than that permitted by the characteristics of the materials is frequently over-estimated. It is felt, naturally enough, that this margin permits the generator to safely carry heavier loads than contracted for or to safely operate under abnormal conditions in emergency. The fact that the value of the guaranteed safe limiting temperature is based on continuous service gives sufficient margin for emergencies. For limited periods—and this can safely amount to months of service in the aggregate—considerably higher temperatures are permissible, and this margin will cover any probable combination of emergencies. A completely mica-insulated generator has seldom, if ever, failed on account of insulation breakdown due to excessive loading in emergency. The limiting load is usually reached because of some other factor, such as turbine capacity, ability to maintain voltage, etc.

It may still be argued that a low stator rise is desirable on account of the margin it gives for continuous overloads. There would be a better basis for this argument if an equal margin were provided in the design of the generator in all other respects—in rotor heating and exciting voltage particularly. But this is seldom, if ever, done. While practise in stator temperature rise guarantees is still somewhat unsettled, the practise in rotor temperature rise guarantees is pretty well fixed. For the generators under consideration, a rotor rise in the neighborhood of 100 deg. by resistance at the maximum rating is well established. Thus, even if a rise as low as 60 deg. be guaranteed for the stator, a rise of 100 deg. is often given for the rotor of the same generator. This at once makes it impracticable to take advantage of the assumed reserve capacity of the stator. Any increase in load, resulting in an increase in the temperature of the armature winding will cause a much greater increase in field winding temperature and voltage drop with this initial field temperature. Consequently, if an overload is contemplated, the temperature rise of the field winding at the nominal load should be approximately the same as that of the armature winding.

Some fundamental relations in large turbo generators are illustrated by the Curves, Figs. 1, 2, and 3. These curves will be used to explain, among other things, the above statement. Fig. 1 shows the variation of armature temperature rise with changes in load on the basis of 100 deg. rise at 100 per cent load. The rises in different parts of the stator are shown by the several curves. These curves are based on careful factory tests of various generators, approximating 20,000 kv-a., at 1800 rev. per min. and 13,000 volts. They may be considered as typical of the large, high-speed, high-voltage generator. Temperature tests were made at normal voltage and open circuit and at normal voltage and at various percentages of rated load. The temperatures at other than tested loads are taken as proportional to the losses involved. In the case of the cooling air, the temperature rise varies in proportion to the total losses of the generator; in the core, the temperature drop varies with the total stator losses (neglecting the relatively small loss dissipated through the coil ends); and in the case of the winding, the temperature drop through the insulation varies with the total loss in the embedded copper. These curves are only roughly approximate but are sufficiently accurate for the present purpose. They give a picture of the temperature conditions in the stator of many of the large high-voltage turbo-generators that have been placed in operation during the past three years.

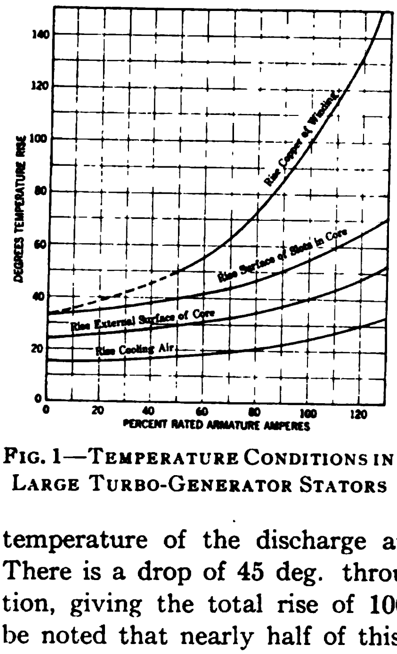


FIG. 1—TEMPERATURE CONDITIONS IN LARGE TURBO-GENERATOR STATORS

According to these curves, in such a turbo generator, at 100 per cent of rated load, the cooling air rises 25 deg.; the outside surface of the core rises 40 deg. above the entering air, or 15 deg. above the temperature of the discharge air in contact with this surface. There is a drop of 45 deg. through the armature coil insulation, giving the total rise of 100 deg. in the copper. It will be noted that nearly half of this total rise is accounted for by the temperature drop through the insulation and consequently, any material reduction in the total rise must involve a substantial reduction in the temperature drop through the insulation. In considering these curves it must be borne in mind that they represent the average generator of a particular class and are based on generators designed to operate at 100 deg. rise in the stator copper at rated load.

On account of its importance, it is well, at this point to consider in detail the reasons for this relatively large temperature drop through the coil insulation and the factors that determine it. The temperature drop through the insulation is probably the most important single item in determining the copper temperature and is directly responsible for the greater part of the difference between temperature measured by mercury thermometers placed outside of the insulation on the coil ends and by thermocouples placed so as to approximately measure the true copper temperature.

The general principles on which differences between internal and external temperatures depend have been explained in the paper by Mr. Lamme, on *Temperature Distribution in Electrical Machinery*, and need not be given here. The particular points that apply to the present problem may, however, be briefly stated.

The most important path of heat flow in the stator of a generator having a long core is in the plane of the laminations, that is, from the copper of an armature coil, through the insulation, and through the sheet steel of the core to the air. The most important part of this path is the insulation. As Mr. Lamme points out, the temperature drop through the insulation is proportional to the heat transmitted (watts loss) to the length of the path (the thickness of the insulation) to the cross sectional area of the path (the surface of the insulation in contact with the core laminations) and the heat resistance of the material.

A measure of the resistance to the flow of heat, or, more properly, a measure of the thermal conductivity, is that rate of heat flow, expressed in watts, that will cause a drop of one deg. cent. when transmitted through an inch length and a square inch section of the material; just as in the electric circuit the conductivity might be expressed as the value of current flow that will cause one volt drop through an inch cube of the material. Values of thermal conductivity of composite forms of insulation are difficult to determine because different samples, apparently similar, give widely differing results. This is largely due to the effect of air pockets in the insulation. The tighter the insulation, the higher will be the conductivity. For example, in tests made by Symonds and Walker*, solid mica was found to have a thermal conductivity of 0.00915 watts per inch cube, while built up mica coil insulation had a conductivity less than one-third of this. Glass (to consider another solid ordinarily

*"Heat Paths in Electrical Machinery", Harold D. Symonds and Miles Walker, *Journal I. E. E.*, Vol. XLVIII, 1912, p. 674.

thought of as a poor heat conductor) is about ten times as good a conductor as the usual coil insulations. It is safe to say that the degree to which air spaces exist in the insulation has more influence on the heat conductivity than does any difference there may be in the conductivities of the various component materials such as paper, cloth, varnish, mica, etc., From the best data available it appears that the heat conductivity of coil insulations, commonly used, varies from 0.0025 to 0.005 watts per inch cube of the material; the lower range of figures applies to the older hand-wrapped materials while the higher range covers insulation applied under heat and heavy pressure by machinery. From the standpoint of heat conductivity and temperature drop the importance of tightly wrapped, compact insulation is obviously very great.

When the rate of heat flow, expressed in watts, and the thermal conductivity and dimensions of the insulation are known it is possible to calculate the temperature drop through the insulation with a fair degree of accuracy. The determination of the rate of heat flow, however, involves two factors that require considerable experience to estimate; one, the proportions of the total heat that are transmitted along the copper to the coil ends and through the insulation to the core; and, the other, the increase in loss due to eddy currents in the copper.* Since the present purpose is only to show the order of magnitude of this drop and the reasonableness of the figure given for the typical generator in Fig. 1, it will be sufficiently accurate to assume that one factor offsets the other; that the eddy current losses are equal to the loss transmitted longitudinally through the copper. It will also be assumed that the insulation is as compact as it is possible to make it and has a thermal conductivity (including the air space† between the coil and slot) of 0.0035 watts. It is usual in units of this class to work the copper in the neighborhood of 1600 amperes per sq. in. which results with slots of usual

*It is interesting to note that the eddy current loss in the copper, in a well designed generator is only a small part of the load loss measured with the generator short-circuited, and that there is no method, so far as the writer knows, of accurately calculating this loss. The theory and formula developed by Field, Rogowski and others only cover the limiting cases of solid conductors or infinitely laminated conductors.

†Still air has a thermal conductivity only one-tenth that of built up insulations. Even with the closest possible fit between the coil and the laminations, which present a more or less rough surface to the coil, there is an appreciable decrease in the conductivity due to this "joint."

proportions, in a loss (considering only I^2R loss at the operating temperature as previously explained) of 0.6 watts per square inch of insulation surface. For 11,000 or 13,200 volts, a reasonable thickness of insulation from copper to core may be taken at 0.25 inch. Using these figures the temperature drop may be calculated thus:

Thermal drop (in deg. cent).

$$= \frac{\text{Watts} \times \text{thickness of insulation (inches)}}{\text{Surface of insulation (sq. in.)} \times \text{thermal conductivity}}$$

or:

$$\text{Thermal drop} = \frac{0.6 \times 0.25}{0.0035} = 43 \text{ deg. cent.}$$

This checks with the 45 deg. used in the typical curve.

It is apparent that this drop can be reduced by decreasing the watts per sq. in. (by decreasing the current density or increasing the slot surface or by both) by decreasing the thickness of the insulation or by improving its thermal conductivity.

With existing insulating materials and methods it is not feasible to materially reduce this temperature drop by these latter methods. Neither can the slot surface be materially increased nor the current density be reduced except by correspondingly increasing the dimensions of the stator, and this may be undesirable or even impracticable in the largest two- and four-pole generators on account of mechanical limitations.

The thickness of the insulation and therefore the thermal drop is a direct function of the rated voltage. At 2400 volts for example, the thickness of insulation and the drop are roughly half the corresponding figures for 11,000 volts. While it is generally recognized that the internal temperatures in high-voltage generators are greater than in low-voltage generators for equal surface temperatures, it is, perhaps, not so generally appreciated that the temperature drop varies so directly with the thickness of insulation and amounts to such a large figure.

This question of temperature drop through the insulation has been considered somewhat in length because it is the most important single factor in determining the hot-spot temperature in large high-voltage, high-speed generators. If the magnitude of the temperature drop through the insulation is recognized, the difference between a 50 deg. guarantee by thermometer and a 100 deg. guarantee by a properly placed thermocouple is immediately explained. It will be noted that in the typical generator, illustrated by Fig. 1, the temperature rise of the core surface is only 40 deg. and the temperature rise of the exposed end windings would be in the neighborhood of 50 deg. using ordinary methods of applying thermometers. In other words, this generator which has a hot-spot temperature rise of 100 deg. would probably meet a 50 deg. rise guarantee based on surface temperatures.

Fig. 2 shows the increase in field temperature and voltage drop with increase in field current. The temperature curve is based on the assumption that the temperature rise at rated load is 100 deg. and is proportional to the loss at other loads. The loss and temperature rise increase considerably faster than in proportion to the square of the current, due to the increase in resistance with temperature. This factor becomes of very great importance at the relatively high temperatures at which turbo fields are ordinarily worked. Thus, with a 10 per cent increase in field current, above 100 per cent of rated current, the temperature rise increases 33 per cent, where only 21 per cent would have resulted if the resistance had remained constant. Due to this effect and also to the second-power relation between the current and loss, the temperature rise increases at a greatly accelerated rate for current above normal. For example; the first 100 deg. of rise is produced by 100 per cent of normal full-load field amperes; the second 100 deg. rise is produced by an additional 25 per cent of normal amperes; and the third 100 deg. of rise is produced by only 15 per cent of normal amperes. In other words, to obtain an increase of 40 per cent in ampere turns, the loss must be tripled and the temperature rise must be increased from 100 deg. to 300 deg. There is also a correspondingly rapid increase in required exciting voltage for field

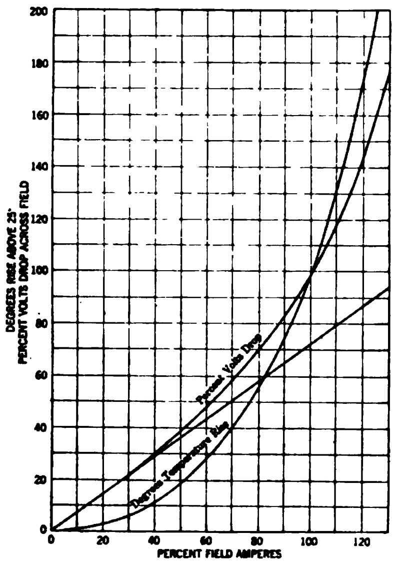


FIG. 2—TEMPERATURE RISE AND VOLTS DROP IN LARGE TURBO-GENERATOR ROTORS

currents above normal. Even though the drop increases only in proportion to the first power of the current, the further increase due to the increase in resistance makes the total rate nearly as great as in the case of the loss and temperature rise. The drop on the basis of constant resistance is shown by the straight line in Fig. 2. The difference in the ordinate of this straight line and the total drop shows graphically the large effect of the change in resistance at currents above normal. To obtain only 25 per cent increase in exciting ampere-turns, an increase of 60 per cent in exciting voltage is demanded. This increase in exciting voltage is, in the majority of mica insulated generators, the real limit to overload capacity. The insulation used in the rotors of large turbo-generators with which the author is familiar is solid molded mica between the copper and ground, and mica and asbestos tape between turns. Such insulation can obviously withstand temperatures of several hundred degrees, yet the total temperature is limited to 150 degrees, on account of the prohibitive increase in exciting voltage, just described, that occurs with higher temperatures. Thus, so far as the rotor is concerned, temperature is not directly a limit to capacity.

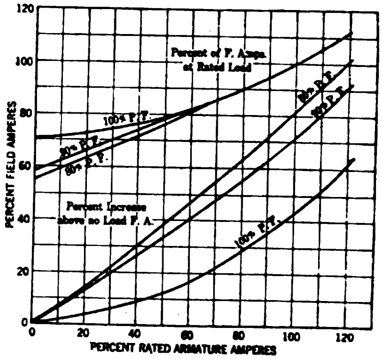


FIG. 3—RELATION BETWEEN ARMATURE CURRENT AND FIELD CURRENT IN LARGE TURBO-GENERATORS. RATIO OF FIELD AMPERES TO GENERATE NORMAL VOLTS ON OPEN CIRCUIT TO FIELD AMPERES TO CIRCULATE NORMAL ARMATURE AMPERES ON SHORT CIRCUIT EQUALLING 1.00

Fig. 3 shows the relation between armature amperes and field amperes in a large turbo-generator of average design proportions, and ties together the data given in Figs. 1 and 2. While differences between individual units will change this relation to some extent, the change will not be of such magnitude as to affect the conclusions reached. The three lower curves show the *increase in field current above the no-load value* for different power factors. In the upper curves these same data have been expressed as the *percentage of the full-load field amperes* at each of the three power factors. These curves show that in three different generators, one designed for 100 per cent power factor operation, a second for 90 per cent power factor, and the third for 80 per cent power factor, all having the same ratio between armature and field strengths, the increase in field current expressed as a percentage of full-load field current will be the same between 70 per cent and 120 per cent of rated load. For the present purpose, operating power factor may therefore be disregarded, *providing the generator is assumed to operate at the power factor for which it was designed.*

These curves may now be used to prove the statement, previously made, that, in order to provide additional capacity in a generator beyond the contract rating, it is necessary that the temperature rise guarantees of the armature winding and of the field winding be approximately equal. If a generator has a true hot-spot rise of 60 deg. in the stator and a rise by resistance of 100 deg. on the rotor the promise of margin for overloads given by the low armature temperature will prove to be fruitless. To restate this in the words of the original proposition; a low stator rise does not guarantee margin for overloads.

The question will be considered in two ways; first, to show what field winding temperature rise and exciting voltage are consistent with an armature temperature rise of 60 deg.; and second, to show what field winding temperature rise and exciting voltage will result when the load is increased so as to increase a low armature temperature rise to the safe operating temperature with a generator having an initial field temperature rise of 100 deg.

Let it be assumed that a purchaser believes more margin in stator temperature rise is desirable in order to obtain margin in capacity for contingencies, and specifies that the stator temperature rise as measured by thermocouple shall not exceed 60 deg. What rotor temperature rise and what margin in exciting voltage should be specified in order that this expected margin may be realized? This condition requires that a consistently designed generator be assumed; that is, a generator capable of operating at the anticipated maximum load within the guaranteed safe limiting temperature of the insulation in both armature and field, and requiring an exciting voltage within that available, or, in other words, a generator having characteristics shown in Figs. 1, 2, and 3, at the maximum expected rating. This generator, as illustrated by Fig. 1, must be derated from 100 per cent to 66 per cent rating to meet 60 deg. rise in the stator, so that a high-voltage generator, of these relative core and copper temperatures, that meets 60 deg. rise at its nameplate rating, can carry 50 per cent overload continuously, and still operate within the safe temperature of mica insulation. The relative core and copper temperatures may be varied somewhat in different designs, but on account of the magnitude of the core loss and windage loss, as compared with the stator copper loss, the feasible variation is not large.

From Fig. 3, 66 per cent of rated armature amperes requires 84 per cent of the field excitation at 100 per cent load. From Fig. 2, the temperature and exciting voltage at 84 per cent field excitation are 64 deg. and 76 per cent respectively. Thus, consistent guarantees would be 60 deg. by thermocouple, for the armature, and 60 deg. by resistance for the field winding, and the generator should be designed to require not more than 90 volts exciting voltage (on the basis of 125 volts available). In taking the required field current at the nameplate rating from 66 per cent rating on Fig. 3, we have, in effect, maintained the assumed unity relation between armature and field strengths at the capacity rating. This results in a ratio of 1.5 at the nameplate rating, which is a higher ratio than would probably be used for a large two- or four-pole turbo-generator. In other words, in an actual design, the field would be relatively weaker than in the above case, and the increase in field current, temperature, and exciting voltage, would be greater than in the example and the guaranteed figures for the rotor should be correspondingly lowered. To complete the story, then, this ratio or an equivalent design figure, must also be specified.

The determination of consistent guarantees that will make certain a desired margin in generator capacity, no doubt appears, from this example, to be a complicated matter. It is, if the purchaser attempts to secure margin in capacity in this indirect fashion. If this margin is really desired, the purchaser should make the desired maximum rating and the contract rating the same, when all these difficulties will disappear. The low temperature rises will, incidently, also disappear from the contract.

To illustrate the second form of this question, assume that a generator has been purchased on the basis of a stator rise of 60 deg. by thermocouple and a rotor rise of 100 deg. by resistance. It is assumed that both armature and field are mica-insulated. Thus there is a margin in capacity in the armature equal to 50 per cent of its rating, while there is no margin, on the basis of the guarantees, in the field. If the load were increased to the limit of the armature, there would result a temperature rise in the neighborhood of 400 deg. in the field, and an exciting voltage would be required nearly three times normal. Of course, these are impossible operating conditions;— with these assumed rises of 60 deg. and 100 deg. there is no possibility of taking advantage of the low armature temperature. Consider then a less extreme case. Let the armature rise be 80 deg. when the field rise is 100 deg. Then an increase in load of 14 per cent (from 86 per cent to 100 per cent, Fig. 1) is permissible, without exceeding the limiting safe rise of 100 deg. This requires an increase of 9 per cent in field excitation (Fig. 3); and results in a rise of 130 deg. and a voltage drop across the field winding of 117 per cent. This would require an exciter voltage of approximately 150 volts on the basis of 125 volt excitation.

These examples illustrate the point already made, that a low temperature rise guarantee for the armature is not in itself a guarantee of operating margin; that the only way in which this margin can be surely obtained is for the purchaser to draw his specifications for the maximum rating desired. Obviously, at this maximum rating the maximum safe temperature rise may be used.

After all is said, the demand for low temperature guarantees usually has back of it a skepticism as to the real safety of the limiting temperature claimed for the insulating materials. Operating engineers may safely leave this question with the designers. In this particular field of design, assumed limits are being continually exceeded and extended. New designs are, from necessity, based on an experimental study of materials and on an analysis of constructions and of complex phenomena involved in the operation of the generator to a greater extent than on direct experience with similar machines. On no other basis could sizes of high-speed units have been increased in single steps from 10,000 kv-a. to 20,000 kv-a. or from 35,000 kv-a. to 50,000 kv-a. Under these conditions, the guarantees made in the contract are really of secondary importance as compared with the ability and experience of the designers. The situation is quite different from that existing with smaller medium-speed machines where the temperature and other guarantees are, in many cases, the operators's principal safeguard. With these large turbine units, each one representing an investment of several hundred thousand dollars, the designer must be conservative; chances cannot knowingly be taken. Whether the temperature rise guarantee is 100 deg. or 50 deg., or, if in the future it should become 150 deg., the engineering public may rest assured that, everything considered, it is conservative. Those responsible for the fulfillment of contracts cannot afford to have it otherwise.

DISCUSSION ON "TEMPERATURE DISTRIBUTION IN ELECTRICAL MACHINERY" (LAMME), "RATIONAL TEMPERATURE GUARANTEES FOR LARGE A-C. GENERATORS" (NEWBURY), CHICAGO, ILL., NOVEMBER 27, 1916.

Alexander Gray: Mr. Lamme has pointed out the difficulty experienced in making and in interpreting temperature measurements, and has suggested that the expert designer can predict hot-spot temperatures more closely than they can be measured. Mr. Newbury in addition has pointed out the absurdity of the low temperature guarantee sometimes demanded on large generators, with the idea that a large overload capacity may thereby be obtained, when such overload capacity is not available because of some limitation other than heating.

Most engineers are now satisfied that 150 deg. cent. is a safe operating temperature for mica insulation and Mr. Newbury, in support of a plea that designers and manufacturers of large machines be not restricted to lower temperatures, brings out the following points:

(a) The higher the permissible temperature the smaller the machine for a given output and the safer it is mechanically.

(b) Generators completely insulated with mica have seldom failed on account of insulation breakdown due to emergency overloads.

(c) The limiting load is generally fixed by turbine capacity, by ability to maintain voltage, or by some cause other than heating.

(d) The overload margin provided by a low stator temperature is not available because of rotor heating and because the exciting voltage is limited.

(e) The customer should secure the desired margin of capacity by making the desired maximum rating and the contract rating, one and the same thing.

(f) With large turbine units representing an investment of several hundred thousand dollars the designer will not take chances.

These statements are not all free from criticism. It is true that the use of high temperatures has allowed the use of smaller and safer machines for a given output, but it has also allowed the original machine to be rated up without any increase in safety. Furthermore, it does not seem reasonable that exciting voltage should necessarily be a limitation in such machines. The point of the whole matter is rather that the designers are willing to bet several hundred thousand dollars of the manufacturers money that 150 deg. cent. is a safe temperature for large generators properly insulated, but the operating engineers are still doubtful.

Just as the older generation of steam engineers had to be weaned away from the reciprocating engine, so the electrical engineer, accustomed to associate low temperature with safety, will have to be educated to the use of higher temperatures. The operating engineer feels that there is an essential difference between the stator and the rotor guarantee, because the rotor voltage is low with seldom more than one volt between turns, while the stator voltage may be 13,200 volts with 100 volts between turns. If any one of these stator coils is loosely wrapped a hot coil will result, also it is possible that tightly wrapped insulation will become loose due to vibration and to the gradual disintegration of the binding varnishes. Is it then surprising that, of two machines offered, alike in price and in operating characteristics, the purchaser will select the one with the lower stator temperature guarantee because, even although the margin of safety is not available in additional output, it is available in that it gives an additional sense of security?

For my own part I have great faith in mica insulation, and I agree with Mr. Newbury that all parts of the machine should be run as hard as they will stand. Most engineers, however, are not constantly in touch with new designs, new insulating materials, and a great mass of test data, and so they are more conservative than the designer who has such data at his disposal.

W. J. Foster: It is, indeed, surprising that more attention was not given to the laws governing heat flow by the earlier designers of electric machines when we consider how well these laws had been formulated by physicists many years before much attention had been given to electricity. Many of our physical laboratories—not only those of the universities and colleges but of our secondary schools—did considerable experimental work in connection with temperature distribution before any electrical engineering school was established.

The ideal heat remover is water, by reason of its great capacity for heat, but such difficult problems are involved in making use of water for rotating machinery and the risks of serious damage, due to accidents, are so great that very little use has been made of water in the cooling of electric machines. Circulating air is almost the sole agent for heat removal. The problem then resolves itself into the proper control of the air flow. It is evident that the more rapid the speed of the air on any surface, the more heat that can be removed, and also that it is of great importance that that circulating air be conducted to all surfaces exposed to the air and that none of the air be allowed to return. It is extremely difficult in certain types of machines to prevent the eddying of the circulating air and considerable skill is required in designing so as to prevent eddies. As intimated by Mr. Lamme, a designer can now predict very closely—by taking into consideration the quantity of heat generated in the several parts, the paths for flow, the consequent rate of flow and the heat resistance of the various materials in the paths—the internal temperatures in any given type of machine. Perhaps the most important factor in his equation is the quantity of heat generated in any given case. The source of heat he knows fairly well, with the possible exception of the eddy currents. There is no doubt that the greatest element of uncertainty in the prediction of temperatures is the eddy currents. Hence, it is of great importance for the designer to have methods of predetermining eddy currents in much the same manner as he predetermines the strength of the metals used in the mechanical parts of the machine by measurements in the mechanical laboratory. Static impedance methods have been developed for the measurement of eddy currents that are found in practise to be quite reliable. Hence, it is inexcusable for the modern designer to make a serious blunder in the ordinary electric machine. This statement does not apply to radically new machines or those where great risks in eddy currents must be taken by reason of the extreme difficulty of obtaining a safe mechanical structure.

In connection with the diagram shown by Mr. Lamme to illustrate temperature drop through the various media that are interposed between the copper of the winding and external circulating air, it is interesting to note that the allowances over and above determined temperatures for the "hot spot" as now standardized in the A. I. E. E. are quite wide of the mark. If through any media we have a temperature drop of 20 deg. cent. at a certain heat flow, it is obvious that with double the heat flow the drop will be doubled. Let us assume that any measuring device—like a thermocouple or temperature coil—will be a few degees removed from the hot spot. If with a certain heat flow it is 5 deg. removed, with double flow it will be 10 deg. removed. Consequently, when the load is so adjusted that the temperature rise as measured by this device is 100 deg. above room temperature, the allowance over and above for the hot spot should be twice what it is when the indication is 50 deg. cent. rise above room.

Referring to Mr. Newbury's plea for the use of higher temperatures in contracts in mica insulated windings and his discussion of the safe temperature of different materials, I question whether the line of demarcation between safe and unsafe can be absolutely drawn for any insulation that is built up and more or less composite in its nature, as is practically all insulation on the windings of electric machines. With more margin of safety, longer life will result. This fact, more than the expectation of possible overloads, is undoubtedly responsible for some operating companies specifying the 60 deg. rise, and at the same time asking for a guarantee of a safe operating temperature which is higher than they ever expect to obtain. Often the insistence upon temperature rise in the stator not exceeding 60 deg. when 85 deg. or 100 deg. is permitted in the rotor, results in a machine of higher efficiency, as the reduced copper losses more than offset the increased iron losses in the deeper teeth. It should be remembered that higher temperatures exist in the rotor than in the stator from the nature of the machine. In the largest and highest speed turbo-generators there is a limit to the space that can be given up to the copper and to the weight that can be carried, whereas such limitations do not exist in the stator.

In connection with Mr. Newbury's paper, I am inclined to think that there is some danger of the impression becoming established that no electric machine is safe that does not have high temperature insulation. I think this will be just as unfortunate as to have the impression abroad that the rotor parts of a small low-speed engine-driven dynamo should be constructed of the strongest material, such as nickel steel or just the same as used in the largest and highest-speed steam-turbine-driven dynamo. It is a well known fact that the lower temperature insulations known as "Class A" in the A. I. E. E. Standardization Rules are superior in certain characteristics to the high temperature known as "Class B." Therefore, such insulation should be used where the conditions of service are such as to produce low temperatures under all conditions of operation.

C. J. Fechheimer: Since the time that so-called temperature detecting devices (including resistance coils and thermocouples) have been employed for the purpose of determining the maximum temperature of the stator windings in large a-c. dynamo electric machinery, the purchasing public has been to a large extent of the opinion that such devices were the means of determining with considerable accuracy the temperature of the hot spot in the stator. Especially have they been of this opinion when the temperature measuring device was placed between the upper and lower coils, when the usual lap or wave windings were employed. Our knowledge of the subject of temperature measurement is now slightly greater than it was at the time the hot-spot question was under considerable discussion, and we now know that unless all the facts pertaining to the case in question are known, the temperature detecting device may give indications which are considerably in error. Mr. Lamme has pointed out certain sources of error, and we wish to call attention to a number of others.

If the device is placed between the coil and the iron as, for example, at the bottom of the slot, the reading will be nearly an indication of the iron temperature and does not allow at all for the thermal drop from the copper to the iron. Therefore, the correction given in the Institute Rules for devices placed in this manner is, in our opinion, worse than an estimate or approximation. Even though such temperature indicating device at the bottom of the slot, plus a correction, were near the copper temperature for that particular part of the coil, it might be far from registering the temperature of the copper in part or in the whole of the upper coil (or upper part of the one coil, if there be but one per slot) as indicated so well in Mr. Newbury's paper of about a year ago.*

Unless coils are very well laminated, the loss in the upper coil may be considerably greater than in the lower coil, especially when there is a large depth of copper in the slot. A temperature device placed between coils can then read only an approximate

*Trans, A. I. E. E. 1915, Vol. XXXIV, Part II p. 2747.

average of the temperatures of the lower part of the upper coil and the upper part of the lower coil. This is borne out pretty well in Mr. Newbury's paper referred to above. For example, at 1000 amperes, the temperature between core and bottom bar is found to be 92 deg., between bars 170 deg., whereas the bottom bar was found to be at 140 deg., and the top at 210 deg.

When heat flows conductively, a certain amount of time is required for the transfer of heat from one place to another; therefore a certain amount of time is required for the temperature device to assume the same temperature as that of the copper in the coil when insulation is interposed between the copper and the temperature device. Hence, when the temperature device is placed between the upper and lower coils, and the machine has not reached constant temperature, the temperature device reading must lag behind the true temperature of the copper. Especially for short-time overloads, will the temperature indication of the device placed between upper and lower coils be liable to considerable error. It is also probable that resistance coils would be slightly more in error than thermocouples owing to the fact that it would require slightly more time for the entire resistance coil to assume the temperature of the surrounding medium than it would for the thermocouple.

It is also probable that with a spacer placed between the upper and lower coils, the indication of the temperature device would be slightly more in error than were such spacer omitted, owing to the fact that heat in that case, will flow from between coils to the laminations, thus tending to produce the same effect as pointed out by Mr. Lamme under, "Errors in Temperature Measurement."

We are calling attention to these errors in measurement, as enumerated above, for the purpose of indicating the futility of the customer relying upon the indications as recorded by such devices, and furthermore upon relying to any great extent upon the temperature guarantees embodied in the contract. We are familiar with other errors in measurement which we have not mentioned, but we believe that those cited should be sufficient to prove our point.

Referring now more specifically to Mr. Lamme's paper, it is interesting to note that whereas heat and electrical insulators obey the same general laws insofar as a comparison of insulating and conducting materials is concerned, the laws no longer hold in all cases for insulating materials only. For example, air is one of the best heat insulating materials known and yet it is by no means the best electrical insulator. Mica will withstand several times the dielectric stress that air will, but air is a considerably better insulator for heat than is mica.

V. M. Montsinger Since electrical apparatus of today is being rated at its maximum capacity, the question of temperature distribution has become a very important factor not only in rotating but also in stationary machinery. As an addition to these two papers which consider, primarily, motors, generators, turbines, etc., I should like to say a few words, in regard to the conditions existing in stationary apparatus, that is, in transformers.

It is, of course, recognized that from a thermal standpoint the conditions existing in transformers are not as complicated as in rotating machinery, for the reason that the copper windings and iron core are not in such intimate relations with each other, that is, there is practically no transverse flow of heat between them, as we have in moving machinery. For this reason we are able to calculate more accurately the internal temperatures of transformers. However simple it appears to be, it really is not so simple and the fact remains that the maximum temperature may in some cases be considerably higher than the average temperature as observed by change in resistance. In making guarantees by average temperature, certain corrections or additions are made for hot spots. Although this is an advancement over the old method of not recognizing that there were any hot spots, the present method must still be recognized as an approximation.

Some of the reasons why the present method of allowing a standard correction to take care of the maximum temperature is not an exact method of getting at the real conditions, are as follows:

1. It is impossible to observe the average temperature at the instant of shutdown, consequently there is always a cooling off of the windings between the time of shutdown and the time of observing the resistance. A correction, therefore, has to be made and it is not always possible to be absolutely accurate in making this correction. It may be stated, by way of parenthesis, that a careful study of this question has been made and the writer hopes, in the near future, to present the results of this before the Institute.

2. No two transformers unless of the same design have the same difference between their maximum and minimum temperatures. For example, if the coils are in a vertical position the upper portion is necessarily operating at a higher temperature than is the lower portion. The same is true if the coils are in a horizontal position, except that here the temperature of the top coil is higher than is the temperature of the bottom coil. This difference between maximum and minimum becomes more marked as the height of coil or coil stack increases.

3. Transformer coils necessarily have to be braced for mechanical reasons and in doing this a certain portion of the coil surface is covered. By properly arranging this bracing, however, the effect of overheating due to this may not be objectionable for ordinary normal load operation.

Considering then the many types or different designs of transformers, each of which has a different temperature gradient, it seems that there is room for improvement over the present method of making guarantees by average temperature.

Mr. Newbury advocates that temperature guarantees, for rotating machinery, be based upon a safe maximum temperature, as determined by thermocouples rather than upon a certain temperature rise observed by thermometers. It seems that the position he has taken is a most logical one and should be applied wherever possible to all types of electrical machinery.

For oil-immersed transformers, thermometers cannot be employed for exploring the temperature of the coils. For this reason guarantees are now based upon average temperatures. While the difference between the average temperature and the maximum temperature of an oil-immersed transformer may not be as great as the difference between the highest observable temperature by thermometer, and the hottest-spot temperature observed by thermocouple in moving machinery, yet it seems that the problems of the two types of machinery are somewhat analogous. Unfortunately the thermocouple is not as suitable for transformers as for generators, etc., because of the potential danger and in order to have a satisfactory temperature indicator for transformers it will be necessary to use some other scheme. Assuming that we had a satisfactory temperature indicator for transformers, it would be interesting to know how operating engineers feel about the practical side of observing the temperature by an indicator as compared with the present method of observing the maximum oil temperature by either indicating or alarm thermometers immersed in oil.

P. Junkersfeld: Some local experiences had a little to do with stirring up this subject about ten or eleven years ago. I refer to the first few years in which we operated turbine-driven generators. Previous to that the engine-driven generators did not present any great difficulties because the surfaces were large, but with the turbine-driven generators a considerable amount of heat had to be dissipated in a small space. That brought up a good many new problems at once, and particularly the problems of insulation and ventilation.

I think it was early in 1907, or nearly ten years ago, when we were fairly certain that these generators were running much hotter than we originally expected, when one of them suddenly bu nt out on a test. That alternator was designed for a nominal load of 8000 kw. and 12,000-kw. overload for two hours. It had been running at normal rating and then increased rapidly from 8000 kw. to a load of 12,000 kw. It had only been running at 12,000 kw. for less than an hour when it burned out with the thermometer on the end windings showing a total reading of only 85 degrees. That showed, of course, at once that there must have been some parts of that machine a good deal hotter than 85 degrees. It was suggested that possibly some scheme of exploring coils would be advisable. When that machine was rewound, exploring coils were put into that machine. It took only a very few months of experience to prove quite conclusively that the preceding practise of building and designing turbo-generators involved at least two fallacies: First that there was a very great difference between the temperature as recorded by the thermometer and by the exploring coil; second, that the windings reached a constant temperature when operated at 12,000 kw. in about fifty minutes.

That demonstrated the fallacy of rating generators of that kind on a two-hour overload. In other words, the experience indicated that such a machine gets about as hot as it will ever get at the end of an hour. This finally resulted in rating such turbo-generators on a maximum continuous basis without an overload in addition.

P. M. Lincoln: Mr. Lamme starts his paper by stating that it is rather surprising that we had not gathered more information concerning the laws of temperature distribution and heat dissipation.

This after all is not so surprising, when we come to consider the difficulty of dealing with heat measurements. We have no heat ammeter or heat voltmeter or heat wattmeter, and thus it is exceedingly difficult to get the data on the amount of heat flowing, and the differences in thermal voltage, if we may call it so, that is, differences in temperature which cause heat flow. It is the inherent difficulty in securing these measurements that is, to a large extent, responsible for our lack of information upon this subject; I can testify, from my own study, that there is a very decided lack of information upon this general question of heat flow.

In referring to the comments of Mr. Foster, I want to call attention to one point. He states that the more rapid the air flow across a surface from which heat is being dissipated, the more rapid will be the escape of heat.

Now, that is perfectly true up to a certain limit, but beyond that limit it ceases to be true. That is, the friction of the air upon the surface will give rise to heat of itself, and we cannot carry the speed of air across surfaces up indefinitely and expect the escape of heat to continue to be dependent upon this rate of air movement. In our modern turbo-generators, we are getting very close to that point. The rise of temperature through the generator, due to the windage within the generator, is a very considerable amount, and we cannot force it a great deal higher than we are now doing in our modern generators.

Now, coming back to this question of allowable temperatures in generators: I do not think that there is any one who has given critical thought to the subject who will deny that it is perfectly safe with our modern insulation to go at least to 150 deg. cent. The real question is, how much further can we go? The standards committee of the A. I. E. E., I understand, placed this limit of 150 degrees, because they felt that there was not a sufficient amount of practise in the past to justify their placing a higher limit. When we come to consider, however, the actual point of danger in our modern insulations, and the experiences we have had with them, I see no reason why we should not go higher than 150 deg. cent. Just how much higher, is the question. I have devoted a little time to studying that question, and I think we can say that there is a definite limit beyond which we cannot go in temperature, that definite limit depending to a very large extent upon the temperature coefficient of the thermal conductivity of the insulation employed.

Let me put it down in figures. Suppose we have a coil, like an armature coil in a generator, insulated, and we put a certain current through that coil; it will of course have a certain amount of watts produced in it which I will call W_1. If we call I the current in the coil, and R its resistance, this wattage is equal to $I^2 R$, a familiar expression. We can go further. The R is dependent upon the temperature of the coil. If we take R_0 as the resistance of the coil at 0 deg. cent., its resistance at any other temperature is given by the well known expression $R = R_0 (1 + at)$ where t is the temperature in degrees cent., and a is the temperature coefficient. Therefore, the watts entering the coil are $W_1 = I^2 R_0 (1 + at)$. The usual value assigned to a is 0.004.

The watts that escape from the coil, which I will call W_2, are evidently proportional to thermal drop and inversely proportional to the thermal resistance. If therefore, we call t the temperature of the copper of the coil, t_1 the temperature of the cooling medium (surrounding air) and e the thermal resistance, the watts escaping, W_2 become $W_2 = \frac{t - t_1}{e}$

Now, this quantity e also has a temperature coefficient; and if we represent this coefficient by a', the expression for W_2 becomes $W_2 = \frac{t - t_1}{e_0 (1 + a' t)}$ where e_0 is the thermal resistance at 0 deg. cent.

Now Mr. Lamme has enunciated the general principle in his paper, that heat conductivity and electrical conductivity have a certain relation to each other, that they are roughly proportional to each other.

Now, if we assume—and this is the big *if* in my calculations—if we assume that the above law holds with respect to the temperature coefficients both of thermal and electrical resistance, that is, that a' is equal to a and that a has its usual value of 0.004—it can easily be shown that when the temperature exceeds 250 deg. cent., above the cooling medium, it comes into a state of unstable equilibrium. In other words, the amount of heat generated, increases with increasing temperature while the ability of the coil to dissipate heat decreases with increasing temperature. Evidently, there must eventually come a point where the coil is unable to get rid of the heat put in and the temperature tends toward infinity. Furthermore, the I^2R that gives a temperature of 150 deg. cent., will only have to be increased about 25 per cent in order to arrive at 250 deg. cent.

Let me put this in graphic form. Refer to Fig. 1, where temperature in degrees cent. is laid off on the vertical axis and the watts on the horizontal axis. The straight line marked W_i shows the manner in which the watts input to our coil, will vary with changing temperature, and the curve marked W_s will indicate how the watts dissipated will vary under the same conditions. In plotting this curve, the cooling air is assumed at 40 deg. cent. It is of course, obvious that the watts put in and the watts taken out, must be the same; that is, $W_i = W_s$.

If these two curves are made to intersect at 150 deg. cent. (the maximum now allowed by the Rules of the A. I. E. E.) the curve W_i will have a given inclination. If we increase this inclination by about 25 per cent, we will arrive at the point of tangency between W_i and W_s, and it is obvious that for higher inclinations, W_i and W_s will never meet. The point of tangency between W_i and W_s therefore, fixes definitely, a temperature beyond which it is impossible to operate.

Now, if we go further and put a "b" term into our temperature coefficient equation and give it the form $R = R_0\ (1 + a\,t + b\,t^2)$ the point of tangency is further reduced and with the usual values of a and b, the maximum allowable temperature becomes about 200 deg. cent. above the cooling air.

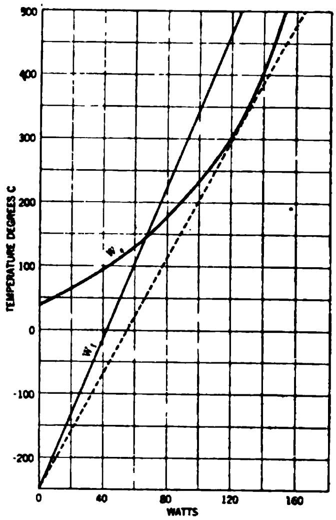


FIG. 1

The crux of what I have to say, comes in the assumption that temperature coefficient for thermal conductivity is equal to that for electrical conductivity. Now, I am simply making that assumption, and above results are based on that assumption. Whether that assumption is correct or not, I do not know. I have not been able to get any accurate data on this point. But if they are equal, the above results follow.

Mr. Lamme has shown that some of the heat in a generator, escapes by flowing along the copper, and we do know that the temperature coefficient for thermal resistance of copper, is a quantity very close to that for the electrical resistance. However, most of the heat in our generator, escapes by flowing through the insulation and on the temperature coefficient of the thermal resistance of this insulation, there are practically no data available. Upon the value of this quantity, depends the amount of curvature of W_s in the Fig. 1 and the point of tangency obviously depends upon the degree of the curvature. I would strongly urge that steps be taken to obtain accurate data upon this point, covering the standard insulations that are used in electrical machinery.

W. C. Bauer: There is a very important point in temperature discussion which is very seldom brought up, and it is this: Some manufacturers seem to fail to realize the double function which insulating material must perform. It is used, of course, to limit the flow of current along the desired path and to keep it from short-circuiting along other paths. The manufacturer says, "The more insulation, the better my machine becomes." He fails to realize that the more insulation he puts on the more difficult it is for heat to get out; and there may be a point reached when, if he puts on four layers of insulation, the machine is not as safe as it would be if he put on only one layer. I do not know to what extent research along this line has been carried out, but what I think should be carefully investigated, is, the safety of the machine as a function, not of the thickness of the insulation but as a function of the thinness of the insulation.

N. J. Conrad: The authors emphasize the idea that the operating engineers usually measure temperatures at points which operate at relatively low temperatures as compared to the "hot spots", and also that measurements made with exploring coils or resistance coils are crude as compared to measurements made with thermocouples.

Ten years ago, and also later, we found it quite difficult in some cases to convince the designers that the temperatures indicated by exploring coils, were not considerably higher than the actual maximum temperatures existing in turbo-generators.

The Commonwealth Edison Company began the use of exploring coils the early part of 1907 by installing them in an 8000-kw. turbo-generator while it was being rewound after a burnout which occurred during an overload test. This generator had an overload rating of 12,000 kw. for two hours. It is interesting to note that in this case the exploring coils were placed between the two armature coils in the slots, which is now recognized as the best location.

Some of the facts brought out by this installation of exploring coils were very interesting.

With a load of 10,000 kw., the maximum temperature rise, obtained by means of an exploring coil between armature coils in the slots, was 78 deg. cent. while the average rise of four such coils was 73 deg. cent. The maximum rise, as indicated by four thermometers placed at the hottest spots that the thermometers could be placed, was 56 deg. cent., while the average rise of the four thermometers was 48 deg. cent. The difference between the maximum rise by exploring coil and thermometer was 22 deg. cent.

At the time that this generator burned out while carrying a load of 14,000 kw. the thermometers placed on the windings indicated a temperature rise of 58 deg. cent. The highest load tests run on this generator after it was rewound with the old type of winding and with exploring coils installed, were at 10,000 kw., but extended curves of temperature rises show that at 12,000 kw. the temperature rise would have been about 94 deg. cent.

A check test was made on these exploring coils in the following manner. The machine was run with a load of 9000 kw. until the temperatures indicated by the exploring coils were constant. The average temperature as shown by 10 exploring coils was 86 deg. cent. The load was taken off and the machine shut down. It required three minutes to take the load off the machine and 18 minutes more for the machine to come to rest after it was taken off the system. When the machine came to rest the average temperature, as indicated by the exploring coils, was 61.5 deg. cent., while the average temperature, as indicated by armature resistance measurements was 63 deg. cent. The decrease in temperature, between the time the load was decreased and the time the machine came to rest, was 25 deg. cent.

A matter which has not been mentioned in these papers is the importance of periodic heat tests in connection with increased heating caused by the accumulation of dirt in turbo-generators.

Temperature readings were taken on a 12,000-kw. generator with a load of 8,000 kw. The maximum rise of the copper with this load was 55 deg. cent. The maximum rise of the core was 62 deg. cent. These temperature rises were very much higher than usually obtained with this load on machines of this particular type. The normal temperature rise at 8000 kw. being 32 deg. cent. for the copper and 28 deg. cent. for the iron. It was hardly reasonable to suspect that the accumulation of dirt in the machine would cause such a large increase in the temperature rise. It was, however, decided to remove the field and make an inspection.

It was found that one of the bearings of this unit had been throwing oil. This, combined with the fact that a great deal of building reconstruction had been going on, had resulted in a very great accumulation of dirt on the armature. In fact this accumulation of dirt was so great that about 90 per cent of the ventilating ducts had been entirely choked up. The increase in temperature rise amounted to 80 per cent on the copper and 123 per cent on the core.

C. A. Keller: Referring to Mr. Lamme's statement that one great advantage of the thermocouple is its very small size, so that it indicates the temperature at practically a point instead of a very considerable area. This type of temperature coil may be desirable for factory tests, but after the machine has been in service for some time and the slots and openings partially filled with dirt collected from ventilating air, a temperature coil with considerable area to cover some of the hot spots which it is difficult to ordinarily predetermine would be more practical.

I wish to ask Mr. Lamme if there has been any scheme devised for taking temperatures in rotating elements such as the armature of a railway rotary while running under load conditions.

M. M. Flower: There is one point I do not think has as yet been brought out very clearly. Mr. Newbury has brought out clearly the limiting features of the rotor temperature. The limiting feature is the exciter voltage and not the temperature rise. The temperature rise in the rotor can never become dangerous, or in other words, the exciter voltage acts as a safety valve, which will always limit the temperature rise in the rotor. This limitation does not exist on the stator as the operator can keep on loading the generator until the safe temperature limit of the stator is exceeded.

B. G. Lamme: I have made up a sketch which brings out much better than any description, some of the fundamental differences between Class "A" and Class "B" insulations. These might be called the time-temperature curves for these insulations. These must be considered as approximations only, as, from the very nature of the materials themselves, no exact curves are possible. The important feature to be considered in the curves, is the general shape rather than any absolute values.

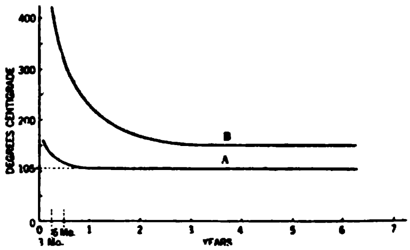


Fig. 2

We have made a great many temperature tests of insulations to determine their durability; also we have made examinations of a very large number of windings which have been in service for many years, but for which we had only approximate data as to temperatures. Obviously it is impracticable to carry on an accurate life test covering a long period of years, so what we did in most of our tests, was to carry the temperatures up to such points that destruction was either reached or indicated in a comparatively limited period of time.

In Fig. 2 curve *A* indicates approximately the durability of class A insulations for various temperatures. This should be recognized as being approximate, but it is optimistic rather than pessimistic.

Curve *B* applies to well built class B insulations, as now furnished by some of the electrical manufacturing companies. Such insulations contain a large percentage of heat resisting materials with a comparatively small per cent of binding material and the insulation is applied so tightly that deterioration or destruction of the binder does not appreciably loosen up the true insulating material.

Considering curve *A*, taking 105 deg. cent., as the ultimate temperature limit for long life without undue deterioration, then with a very slight increase in temperature, say to 115 deg. cent., the life is shortened very much, and at 125 deg. cent. such insulation is good for only a very few months at the most. At 150 deg. cent. it has an exceedingly short life.

Next considering curve *B*, our available data indicate that for over twelve months operation at 200 deg. cent., the insulation is in first class shape; in fact, much better than class A insulation at 110 deg. cent., for the same length of time. At 300 deg. cent. for six months, the insulation really shows better than class A insulation at 115 deg. cent. for the same length of time, and, at 400 deg. cent., the class B insulation for three months is better than class A insulation at 125 deg. cent. for the same length of time. If we now assume the continuous life for the class B insulation as 150 deg. cent., then it is seen that a 33 per cent increase in temperature for one year is no more harmful than a 5 per cent increase in temperature over the 105 deg. cent. for class A insulations for one year. Also a 100 per cent increase in temperature above its continuous limit for six months is comparable with a 10 per cent increase in temperature for class A insulation for the same period. For still higher temperatures the percentage is far more in favor of class B.

What I want to bring out in particular by means of this diagram, is that the factor of safety for overloads is vastly greater for class B than for class A insulations, on the basis of continuous life being taken as 150 deg. cent. and 105 deg. cent., respectively. Part of this difference is inherently in the characteristics of the materials themselves, but no doubt part of it is due to the fact that the arbitrary 150 deg. cent. limit set for properly built class B materials is considerably too low in comparison with 105 deg. cent. for class A. But, whatever the explanation, the difference is there.

In regard to the very high temperatures for class B insulations, such as 300 deg. and 400 deg. cent. shown in curve B, attention should be called to the fact that unless there is an exceedingly high temperature drop through the insulation itself, any outside supporting layer or wrapper of fibrous materials is liable to become unduly heated and may disintegrate. Therefore, while the insulation proper might stand 400 deg. cent., for instance, yet if this was continued for any considerable length of time, so that the outside supporting material became excessively heated, such material would have to be of something else than the usual treated tape or fibrous wrappers. However, it so happens that very high temperatures are rarely attained in practise, except in the case of armature conductors buried in slots. In such case the surrounding iron assists very materially in cooling the finishing wrapper on the coils, unless the high temperature is maintained for a very considerable period.

Some are inclined to look askance at mica at 150 deg. to 200 deg. cent., but it must be remembered that in certain heating apparatus mica is used up to 500 deg. cent. and, in some cases, even up to 750 deg. cent. Practically all micas will stand up to about 600 deg. cent., without undue deterioration, and some grades will stand up to 1000 deg. cent. From this viewpoint, the temperature of 150 deg. to 200 deg. cent. in armature coils appears to be very low and the whole matter turns upon the way such mica is used. If the percentage of mica in the insulation is relatively high and the mica is put on so tightly that the binding material can disintegrate and loosen up and yet the natural elasticity or springiness of the mica can hold the insulation tightly in place, then such insulation can stand very high temperature without injury. But, if the mica is wound or placed so loosely that this disintegration of the binding or supporting material allows the mica part to loosen up materially, then the insulation qualities may still be very good from the dielectric standpoint, but may be in such poor shape mechanically that vibration or shocks may shift it or displace it sufficiently to injure it as an insulator. The defect here is a mechanical one and not in the quality of the material itself.

Mr. Junkersfeld has spoken of some of his early experiences with high temperature, and he mentioned that the data which he and his associates obtained have had a marked influence in leading the manufacturers toward better grades of insulation. This is no doubt correct, but I wish to call attention to the fact that the manufacturers were also following this matter independently of the operating companies, with the same end in view. For instance, the company with which I am associated, insulated the 1894 Niagara generators with mica. We did not know whether such insulation was required, but we thought it was good material and so put it on. Later tests showed that this was a very fortunate decision, and now, after twenty years of operation, this insulation is still in very good shape, although subjected to very much higher temperatures than originally contemplated, 150 deg. to 200 deg. cent. being not uncommon according to later tests.* Also in 1898 and 1899 the large engine-type Manhattan Railway generators had mica insulation, in the form of wrappers, on the armature coils. Following this, mica insulation was used for quite a number of years, mostly on large high-voltage alternators. About 1904 we built some large capacity 60-cycle turbo-generators on which we used mica wrappers on the armature coils. In service, one of these machines was injured from some mechanical cause and we had to rewind it. One of the fads about this time was special oiled-linen tape insulation, and quite a pressure was brought to bear upon us to rewind this machine with such oiled tape. With this insulation the armature broke down in a comparatively short time (within a few months, if I remember rightly). When the coils were

*Trans. A. I. E. E. 1915, Vol. XXXIV., Part 11, p. 2747.

removed, the outside layer of insulation next to the iron was found to be apparently in fair shape, but next to the copper the insulation showed indications of being excessively heated; in fact, it was badly carbonized in some places. We then reinsulated with mica and the machine was operated for many years without trouble. Here was a direct comparison between class A and class B insulations. I do not know how hot those coils ran, but, judging from the appearance of the oiled-tape insulation, it must have been materially above 125 deg. cent. Here was a fortunate instance where the machine was first insulated with mica tape and then afterwards insulated with fibrous materials, so that actual comparison was obtained with the two materials. This was ten to twelve years ago, so that it cannot be said that experience showing the relative merits of these two types of insulation is only of recent date.

In the same way similar experience was obtained with field insulation. Practically all our early turbo-generator fields were insulated with fibrous sheet materials. Numerous instances occurred where such insulations deteriorated so much that rewinding was required. This led to numerous tests for temperature. In some of these earlier machines there was evidence of practically uniform overheating throughout the whole winding, thus indicating practically uniform temperature. In such cases it was comparatively easy to approximate the ultimate temperature from readings of the field currents and the field volts, thus obtaining the increase in resistance and from this the temperature rise. Such tests soon developed the fact that temperatures of 110 deg. to 125 deg. cent. were not uncommon on the earlier turbo-fields, while with the increased capacities and higher speeds, toward which we were continually tending, the indications were that still higher temperatures would be attained. This led to the development of mica insulation for the field windings of turbo-generators. In 1906 and 1907 a number of the earlier hot fields were rewound with mica and such fields have been operating up to the present time, or until discarded in favor of larger units. The record with these mica insulated fields has been extremely good. In some of the tests which we made on these earlier machines to determine the suitability of mica for field insulation, we carried one field up to 250 deg. cent. for forty-eight hours, and would have continued the test very much longer, but the conduction of heat from the core through the shaft to the bearings was sufficient to overheat them. However, at the end of this test the insulation was found to be in absolutely good condition. This was a very mild test, in view of our later investigations on mica, but at that time it was considered wonderful. I am simply bringing up such points to indicate that mica has been used quite extensively on turbo-generators for many years.

I was much pleased to hear Mr. Conrad's remarks regarding the effects of dust and dirt in limiting the ventilation of high-speed machines, and in turbo-generators in particular. Very few people have any conception, in the case of turbo-generators, as to how much air is put through the machines. A modern turbo-generator puts through itself practically its own weight of air every forty to sixty minutes. If there is a very small per cent of dust in this air and it lodges in the machine, it is obvious that it will not take long to clog up the ventilating passages. However, dry dust appears to go through the machine with very little deposit. Apparently the velocity of the air is sufficient to keep the dust moving. But, if there is a little free moisture in the air, or a little oil in any form, then such moisture or oil lodging on the surfaces of the ventilating passages will collect dust and eventually interfere with the ventilation. Such interference appears in two ways—it covers the heat dissipating surfaces with a poor heat conducting material, and it also cuts down the cross section of the air path and thus reduces the amount of air which can get through. In one case of a turbo-generator which I examined, the inlet passage at the air gap appeared to be much smaller than when the machine left the factory. There appeared to be a ridge of iron projecting inside the iron laminations. I tried to cut it with a knife and found it almost as hard as iron, but it developed that it was a mixture of dirt and oil which had solidified at this point. We had a second case of this sort where a turbo-rotor burned out after about a year's operation. Upon dismantling the winding it was discovered that the roasting was all at one end and that the other end was in good condition. Further investigations showed that the ventilating passages at the one end of the machine were almost completely clogged up, while at the other end they were fairly open. It was then found that a small amount of oil had leaked into the machine in the form of fine spray and this had caused the trouble.

In modern machines this problem of dirt is taken care of in many cases by air washers. The functions of the washer is principally to remove dirt, but it does cool the air a little, but this is of minor importance compared with the other effect.

Mr. Keller asked whether there is any effective method of measuring temperature in rotating apparatus without shutting down. In case of rotating fields, a pretty good idea can be obtained from measurements of the field current and voltage during operation, these giving the increase in field resistance. This is a very good method in those cases where the temperature is reasonably uniform throughout the field winding. In turbo-generators it is apparently a fair approximation. However, in d-c. armatures there is no very effective method of determining temperature except by the thermometer. Thermocouples cannot very well be used on rotating apparatus due to the necessity for moving contacts to make connection with the external indicating apparatus. After a long series of investigations we found the results so variable that we gave up the method. Such tests, if successfully carried out, would require laboratory refinements which are not usually possible in ordinary commerical work.

F. D. Newbury: Professor Gray brought out a number of interesting points. I am glad to know that he agrees that the maximum safe rise is the proper guarantee, even though he questions whether engineers in general will accept it.

He stated that he doubted whether the purchaser would buy a high-temperature generator if there was the alternative of purchasing a low-temperature machine at the same price. That, however, is not the question. The question we are discussing is much broader than that. It is not the individual case that interests us, but whether in the long run the high-temperature machine is the more economical machine, the machine that should survive. If my opinion is correct, the high-temperature generator is the more economical generator and will be the generator of the future.

Professor Gray also stated that he did not think the exciter voltage should be a limit to rating. Such an easy thing to overcome should not be permitted to become a limit. That, however, is begging the question. While it is an easy matter to provide any desired·margin in exciter voltage (although at the expense of increased exciting current), it is not possible to provide the heat dissipating capacity in the rotor that would be necessary in order to use the higher exciting voltage. In many stations there is a common exciter bus maintained at a definite voltage. In such cases, the exciter voltage, directly, is a limit to rating.

Professor Gray also spoke of the higher voltage of armature windings as compared with windings on rotors. Practically all the larger machines, even the 13,000-volt machines, have only one or two turns in each armature coil, so that the problem of insulating between turns is not a difficult one.

Mr. Foster brought up a number of interesting points in connection with generator design, to some of which I must take exception.

Mr. Foster stated that the use of Class B insulation was not justified in all cases. It is justified in my opinion in all the cases that we are now considering; that is, in large, important machines.

For the reasons brought out in Mr. Lamme's discussion, there is no margin of safety if fibrous insulation is used in machines with a temperature rise of only 60 deg. measured by thermocouple. Even though the temperature rise is 60 deg., it is not wise to use fibrous insulation in important machines where reliability is so important. The difference in margin with fibrous insulation and with mica insulation is very well brought out by the tests Mr. Lamme mentioned. We found it very easy to cause the cotton, linen, or paper insulations to fail after a few weeks' test at 150 deg. In no case were we able to break down properly constructed mica insulation with temperatures up to 400 deg. In my mind there is no question that with Class B insulation subjected to 150 deg., the margin of safety is very much greater than with Class A insulation at 105 deg.

But this question of safety at 150 deg. has been discussed before the Institute at a previous meeting and it was quite generally agreed that 150 degrees was safe. Mr. Foster concurred in this opinion.*

Mr. Foster correctly stated that mechanical stresses limited the amount of copper that could be carried by the rotor, but that no such limitation existed in the case of the stator. Consequently, according to Mr. Foster's discussion, a very easy remedy for high temperatures in the stator was the use of deeper slots. He also very properly called attention to the dangers of excessive eddy-current losses in the armature winding of these large turbo-generators. But to deepen the slots is incurring the danger of eddy currents, and it is very easy to increase the loss by the addition of copper instead of decreasing the loss. So there is, in my opinion, no remedy for high armature-coil temperatures that does not involve an appreciably larger generator.

Professor Bauer brought up the interesting point that increasing the thickness of insulation, while it increases the safety of the machine by an increase in dielectric strength, decreased its safety by increasing the temperatures. It illustrates the point that the design of machines of this class is a series of compromises. Safety in mechanical stresses must be balanced against safety in temperature; safety in insulation against safety in temperature, and so on through the list. Any advantage we can gain through the use of better materials is an advantage in the direction of a more economical and better machine.

Mr. Keller mentioned the advantage of a long resistance coil as a means of measuring temperature, as opposed to the short thermocouple. I might explain that the thermocouple is merely a welded junction of two metals, and as constructed is a quarter of an inch wide, (6.35 mm.) and the junction is practically a line; so that it does, as nearly as any device we know, measure the temperature at a particular point. The resistance coil, on the other hand, has to be fairly long in order to obtain a sufficiently high resistance in the coil to make it accurate; and if it is to measure temperatures above 100 deg., the adjacent turns must be separated, so that with the deterioration of the enamel or silk insulation on the wire, the turns will not short-circuit. Resistance coils may be anything from six inches (15.24 cm.) up to a couple of feet in length, so that the resistance coil indicates the average temperature through that length. The thermocouples can be ruggedly insulated with mica so that they will withstand any temperatures that the coil insulations will withstand. For these reasons, I prefer the use of the thermocouple, but, after all, the main thing is that one or the other be used, and internal temperatures be determined.

Mr. Fowler made the point that a higher temperature was

*TRANS. A. I. E. E. 1915, Vol. XXXIV, Part II, p. 2767.

allowable in the rotor than in the stator, because the available exciting voltage placed a limit upon the current that could be circulated in the rotor, while no such limit existed in the case of the armature. The armature current, however, cannot be increased beyond the corresponding maximum available field current unless the armature voltage is allowed to fall. So that the same safety stop exists in the case of the armature as in the field, unless the generator voltage is allowed to decrease in case of overloads.

Presented at the 327th Meeting of the American Institute of Electrical Engineers, Boston, Mass., December 8, 1916.

RUPTURING CAPACITIES OF OIL CIRCUIT BREAKERS

BY STEPHEN Q. HAYES

ABSTRACT OF PAPER

This paper is really a series of more or less disconnected notes dealing with the question of rupturing capacity of oil breakers. It makes no attempt to go into the theory of circuit-breaker design, and its main object is to open up a discussion regarding the advisability of using the term "Maximum Safe Rupturing Capacity" to describe the result obtained by the root-mean-square of the maximum peak of the current wave that occurs while the breaker is opening, multiplied by the root-mean-square of the open-circuit voltage that occurs immediately after the breaker opens. Attention is called to the different ratings due to use of peak values and root-mean-square values of current and voltage.

It is recommended that an oil switch or an oil circuit breaker should be given a rating on the basis of maximum safe rupturing capacity that it can handle, and that a breaker after opening a short circuit up to its rating, should be immediately reclosable, and able to again open up a similar short circuit; breaker should open three successive short circuits before contacts need be repaired or oil replaced; these short circuits may be as close as two minutes apart.

THE OBJECT of this paper is to suggest the proper basis for the guarantees to be made by manufacturers of oil circuit breakers or switches to enable the prospective user to determine the suitability of the breaker to the proposed service conditions. This guarantee should be a specific statement of what the oil switch can do, and should preferably be free from any assumptions as to reactance in circuit, generator characteristics, use of relays or similar features.

It is self evident that oil circuit breakers for large power systems must be suitable for the service they are to perform, their current-carrying parts must be ample, their insulation good, and they must be capable of rupturing any amount of current they may be called upon to open. Such breakers should not only clear the circuit, but should be immediately reoperative without the necessity of inspection, adjustment, or repair, although inspection is advisable at the first suitable opportunity.

The term "ultimate rupturing capacity," as usually employed by American switchgear manufacturers has been applied in such a manner that it really meant the maximum size of system on which a breaker could be safely used, and even when used in this manner, it was necessary to explain fully, the basis of calculation, and the various assumptions that had been made. This method of rating, involves the momentary and sustained short-circuit characteristics of the machines, the various reactances in the circuits, the speed of tripping of the breakers, and other similar features.

It has been standard practise to assume that the breaker is connected directly to the buses, and may have to open any amount of current that can be received from that bus in case a short circuit of negligible impedance occurs just beyond the breaker. In most cases it is the reactance of the circuit rather than the resistance, that limits the current flow at times of short circuit, so it is usual to consider the reactance rather than the impedance of the circuit in calculating current flows. For cable systems or high-tension transmission circuits, the capacitance has to be considered. All of the generators and other synchronous apparatus connected to the bus, will tend to feed into the short circuit whatever current they can deliver under these conditions, this current as a rule, being limited only by the inherent reactance of the machines, and any external reactance that may exist between the machines and the point where the short circuit occurs.

Due to inertia, it is impossible to have a breaker trip out instantaneously, consequently no breaker is ever called on to open the momentary short-circuit current that occurs during the first few cycles, but it has to be strong enough mechanically to resist the magnetic stresses set up during such a short circuit. With a-c. coils energizing the mechanism direct from the current transformers, large capacity breakers can be made to open in about 0.2 second. With the usual shunt trip relays, the time of opening is about 0.3 to 0.5 second, while with time-limit relays, the opening can be delayed either for some definite time, or for a time that varies inversely with the load. With a non-automatic breaker, the time of opening is left to the discretion of the operator. As most generators reach the condition of continuous short-circuit current in not over 0.8 second, it is figured that a definite time limit of two seconds or even less, secured through a relay, is equivalent to non-automatic service, in so far as rupturing requirements are concerned.

Whether a breaker is to be used for automatic or non-automatic service, it can only open a certain fairly definite amount of power at the arc. This amount being fixed, it should be noted that for non-automatic service, the size of plant to deliver this would be determined by the sustained short-circuit characteristics of the generators, and other synchronous apparatus. For automatic service, this same amount of power could usually be delivered by a smaller plant, as the momentary short-circuit current is almost always higher than the sustained.

In order to allow for certain of these variables due to the machine characteristics, one American manufacturer gives ratings for his oil switches for automatic and non-automatic service for two classes, A and B, the latter being systems where one or more generators are of the turbo type with reactances of less than 8 per cent and the former applying for all other systems.

This A and B method of rating based on data published some years ago assigned for most of the smaller sizes of breakers about 25 per cent greater rating for the non-automatic A class than the corresponding non-automatic B, the automatic rating for the A class was usually about 50 per cent of the non-automatic A and the automatic B rating about 33 per cent of the non-automatic. On the larger sizes, however for 15,000-volt service, one size was rated 70,000-kv-a. class A non-automatic, 56,000-kv-a. class B non-automatic, 70,000-kv-a. class A automatic and 46,000-kv-a. class B automatic.

It would seem that the automatic service would be more severe than the non-automatic and the breaker may be under rated for non-automatic or over rated or automatic.

The class B service is based on using turbo generators of 8 per cent reactance or less. Usually such machines have a lower sustained short-circuit rating than water-wheel-driven units of higher reactance than 8 per cent, so that there would be less current for a non-automatic breaker to open in a 20,000-kv-a. plant fed from turbo generators, than a similar plant fed from water-wheel generators. On this basis the non-automatic B rating should be higher, not lower than non-automatic class A.

Another American manufacturer explains the ratings assigned by using a standard assumption of generators or other synchronous apparatus, having an average reactance of 8 per cent, a momentary short-circuit current of 12 ½ times normal falling to half of this amount, or 6¼ times normal by the time the breaker opens, and a continued short circuit of one quarter, or three times normal. With this explanation, it is evident that a breaker rated as having 10,000-kv-a. rupturing capacity should be capable of handling 62,500 kv-a. at the short circuit. This same breaker for non-automatic service where the machines are assumed as delivering three times normal, could, therefore, be used on a 20,000-kv-a. system, or would have a non-automatic rating of 20,000 kv-a.

This relative method of rating automatic and non-automatic breakers only holds true for the one set of assumptions made, and will be incorrect when applied to a system fed from low-reactance machines having a high momentary short-circuit value and a low sustained short-circuit value. The statement that the automatic rating could be multiplied by 6¼ to determine the amount of power the breaker could rupture gave some real data regarding the rupturing capacity.

In comparing the nominal rupturing capacities, the one line of breakers was usually given its class A automatic rating while the rating of the other line was the instantaneous overload rating practically corresponding to the class B automatic.

In systems of large generating capacity, where current limiting reactors are used, or where the reactance of transformers and lines may limit the current flow on short circuit to a point well within the capacity of the system to supply continuously, it will be found that the breakers provided with time-limit relays, or used for non-automatic service, have as severe rupturing conditions to meet as those used for automatic service.

These methods of rating are not directly applicable in all cases, and are open to many objections, and do not readily take into account certain features that really are vital in determining the adaptability of breakers to specific service. The rate at which the short-circuit current of a generator dies down varies with its design, so that the short-circuit current of a generator may die down from the initial rush to the continuous short-circuit value in a period of time ranging from 0.2 to 0.8 second. The initial wave may be as high as 20 times normal, and the continuous short-circuit value may be as low as 1.4 times normal.

In case of an unsymmetrical wave, experience seems to show that the strain of opening does not differ appreciably from that produced by a symmetrical one. A current wave ranging from a positive maximum of 10,000 amperes to a negative one of 2000 amperes can be taken care of as readily as one ranging from plus 6000 to minus 6000. This may be due to the longer time required for the arc to reestablish itself in the case of the unsymmetrical wave where the negative maximum is small. By the time the breaker actually opens the circuit, the amount of assymmetry has greatly diminished from that experienced during the first few cycles.

As most power circuits are three phase, the rupturing capacities assigned to circuit breakers are those applying to three-pole breakers on that service. The corresponding rating for two-pole breakers on a single-phase circuit is 70 to 75 per cent and the rating of a four-pole breaker on a two-phase circuit is considered 140 to 150 per cent of the corresponding three-phase rating.

Under some certain conditions, smaller switches could be used, for instance, in substations where limited transformer capacity is installed between the oil circuit breaker, and the line, or on substation feeders where a breaker of higher capacity is interposed between the breaker in question, and the substation bus.

When considering switches for connection to buses fed from the generator units of motor-generator sets, the capacity of the system supplying energy to the motor-generator set, need not be considered. In such cases, the sum of the rated capacity of the generator units, on the motor generator sets should come within the limits assigned to the breakers.

The kv-a. ratings usually assigned to breakers are based on the listed voltage rating of such breakers, and any change in operating voltage from the listed voltage rating will usually change the kv-a. rating in about the same percentage, that is, an increase or decrease in voltage of 20 per cent would decrease or increase the kv-a. rating by the same amount.

While this percentage rule is not strictly adhered to, a typical example might be noted of a certain moderate capacity breaker designed for 22,000-volt service with a nominal rupturing capacity, assigned by its builders, of 10,000 kv-a. at 22,000 volts, 12,000 kv-a. at 16,500, 13,000 at 13,200, 17,000 at 7500 and 19,000 at 4500 volts or less.

On the assumption, more or less justified, that the strength of the breaker tops, insulators and fittings have been properly proportioned to the tank strength and that the speed of opening is satisfactory the rupturing capacity of an oil breaker may be considered as a function of the tank dimensions.

When a breaker has been installed, it should be remembered that with increase in capacity of system, failure to maintain breakers either as regards mechanism or insulation, changes in reactance, changes in method of operation and defective relays may so change the duty on a breaker as to lead to its destruction.

Almost all of the oil switches and oil circuit breakers now in service, are operating satisfactorily, but it is realized that they are far from perfect, and it is possible that some of the commercial breakers being sold, are over rated. By having some definite rating in kv-a. to work to, breakers of the smaller sizes could be tested to see that they actually met their guarantee.

In order to simplify this question of breaker rating, it is proposed to use "maximum safe rupturing capacity," or some similar term to describe the result obtained by the root-mean-square of the maximum peak of the current wave that occurs while the breaker is opening, multiplied by the root-mean-square of the open-circuit voltage that occurs immediately after the breaker opens.

All modern transmission systems employ generating apparatus giving essentially a sine wave for current and voltage, which sine wave has a ratio of peak value to root-mean-square value of 1.4 to 1. A breaker capable of rupturing 10,000 amperes maximum value at 10,000 volts maximum value, if rated on the root-mean-square basis, would be considered capable of handling 7100 amperes at 7100 volts, or would be given a rating of 50,000 kv-a. If the peak value of the current, or 10,000 amperes, is used with the root-mean-square value of the voltage, or 7100 volts, the rating would be 71,000 kv-a. If the peak value of the current, or 10,000 amperes, is used with the peak value of the voltage, or 10,000 volts, the rating would be 100,000 kv-a. All of these ratings would cover the same duty to be performed, but as all power measurements are regularly based on the root-mean-square values of current and voltage, this is undoubtedly the logical basis for circuit-breaker rating.

The kv-a. rating obtained as above is that which this breaker should be guaranteed to open, the breaker being immediately reoperative, without the necessity of replacement of oil or adjustment of contacts. It might be well to fix this rating at such a point that the breaker could be guaranteed to open this amount at least twice, and to be immediately reclosable, and in condition to open the same circuit kv-a. the third time.

In a-c. railway work, and similar installations where repeated short circuits are apt to occur, the breaker should be capable of opening such a short circuit at least ten times within the course of an hour; such short circuits not occuring closer together than two minutes to allow time for the gases that may be formed due to the short circuit to be properly vented from the breaker before a second short circuit occurs.

It might be pointed out that there is a difference between rating a circuit breaker in terms of the maximum kv-a. which it can open, and in terms of the maximum current which it can open. On certain systems with the machines of certain characteristics, heavy short-circuit currents are usually accompanied by reduced voltages and this point has to be given careful consideration. After opening a very heavy short circuit, thus relieving the system, the voltage frequently has a tendency to rise immediately to a point somewhat greater than normal, and this point should also be considered in the rating of the breaker; in other words, while a certain breaker might be able to open 10,000 amperes successfully where the circuit voltage immediately after the short circuit only went back to normal, it might not be able to function satisfactorily if the open-circuit voltage went up to points considerably above normal.

It is realized that it will be extremely difficult for an engineer

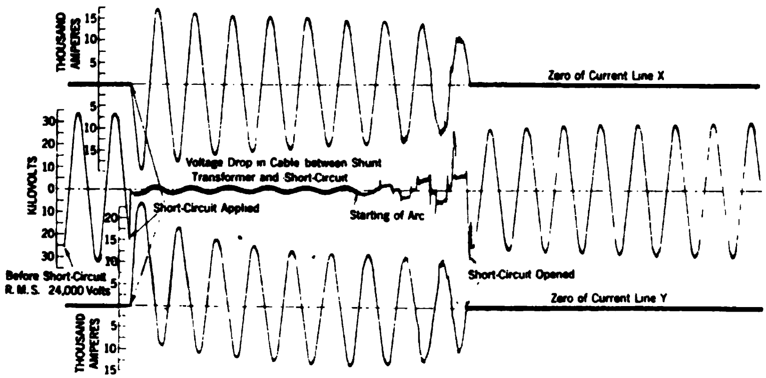


FIG. 1—60-CYCLE, THREE-PHASE SHORT CIRCUIT—142,620 KV-A. SYNCHRONOUS CONNECTED LOAD

to determine in advance exactly how heavy a short circuit it is possible to get at a given point on a transmission system, but from the view point of the manufacturer, it is simpler and better for him to make a definite guarantee as to just what service his breaker can accomplish, allowing the operating or designing engineer to determine whether such a breaker will meet the actual short-circuit conditions that may occur on any point of his system.

It is a well known fact that formerly the opportunities of testing the actual rupturing capacities of the largest capacity oil switches and breakers were almost nil and that the capacities assigned were really intelligent estimates based on the testing to destruction of small units and calculation as to the increase in rupturing capacity secured by greater volume of oil, greater head of oil, increase in strength of tanks, extra volume of expansion chamber and similar features, while this is still true in certain cases a large amount of valuable data have been collected in the last few years.

Among the more important tests on the rupturing capacity of oil circuit breakers may be mentioned those described in the papers presented in June 1911 before the Annual Convention of the A. I. E. E. in Chicago, by Messrs. Schweitzer and Schuchardt and Mr. E. B. Merriam. These were made on a 12,000-kv-a., 9000-volt, 25-cycle turbo generator of the Commonwealth Edison Co.

In February 1910 tests were made at the Long Island City power house of the Pennsylvania R. R. with two 5500-kv-a., 11,000-volt, 25-cycle turbo generators.

During 1910-1911 tests were made at the Cos Cob power house of the N. Y., N. H. and H. R. R. using 11,000-volt machines totalling 16,000 kv-a.

In the latter part of 1911 a series of tests under various conditions was made at the Hydraulic Power Co. plant at Niagara Falls where four 7500-kw., 12,000-volt machines were short-circuited. These were fully described by Mr. J. N. Mahoney in the *Electric Journal* September 1912.

A recent test shown on oscillogram, Fig. 1 was made with a total of 142,620 kv-a. in synchronous apparatus connected to 60-cycle 24,500-volt bus bars.

In this test there were successfully interrupted short circuits having a peak value of 950,000 kv-a. and root-mean-square value of 475,000 kv-a. at the time the contacts opened, both symmetrical values at 24,500 volts, representing the largest amount of power ever used on such a test. The unsymmetrical value of the initial wave of the short circuit was 50 per cent greater representing 1,425,000 kv-a. As shown by the oscillogram the short circuit continued for six cycles on a 60-cycle circuit before the circuit-breaker contacts parted and continued for three cycles through the arc. This breaker used the same oil and same arcing tips for all the tests. The only external effect was a small amount of oil forced out through a defective joint between the tanks and frame.

Other tests at various voltages have been made as the basis of circuit-breaker ratings, and although these have not been published the manufacturers guarantees are usually based on real data and can be accepted by operators as being fairly conservative.

Presented at the 327th meeting of the American Institute of Electrical Engineers, Boston Mass., December 8, 1916.

RATING OF OIL CIRCUIT BREAKERS

BY E. M. HEWLETT

ABSTRACT OF PAPER

Paper points out several difficulties, which are encountered in the rating of actual circuit breakers, but generally favors that these ratings be on the basis of the current to be opened in the arc at the operating voltage of the system.

THE VARIABLE factors entering into the problem of rating oil circuit breakers make its solution very difficult.

Up to certain capacities it has been possible to determine definitely what oil circuit breakers will open. The experience of many years, during which oil circuit breakers grew from a few thousand volts for a few kilowatts station capacity, to 10,000 volts, 40,000 volts and higher voltages, for many thousand kilowatts station capacity, coupled with the facility of testing various designs under actual emergency conditions, has crystalized the requirements of circuit breakers of this kind and the constructive features of commercial design.

However, the capacity of stations is always growing, the forces dealt with are ever increasing, and consequently, new types of circuit breakers must be constantly developed, ratings of which cannot be based on actual past service. To test such circuit breakers systematically would be beyond the scope of any testing units at the disposal of any manufacturing company and would require the use of power stations of enormously high capacity.

The possibility of utilizing such power stations for the testing of circuit breakers is very limited, as in order to carry their connected load the big operating companies must generally have constant and instantaneous control of all their apparatus.

Thus, new designs of high-duty circuit breakers must, for the present, be rated mainly upon judgment based on past broad experience. For the engineer, the ideal way of rating circuit breakers is on the basis of the current which is actually opened in the arc at the operating voltage of the system, as in the present A. I. E. E. ruling. (This current in the arc is not the peak value of the short-circuit current curve, but is that value which prevails at the moment when the circuit breaker opens, at the point where it is installed.) However, in a rational design of circuit breaker, other factors must be considered besides current to be ruptured, primarily the power factor at the time of the event and the voltage regulation of the system. In the smaller capacities, these factors could be disregarded, as with them it has always been possible to allow very liberal safety factors without sacrificing reasonable proportions. We are therefore rating at the present time oil circuit breakers by arc current and system voltage up to certain capacities. As the capacities of the system and circuit breakers increase, as spacings and clearances become important design factors, and as materials employed in the construction of the circuit breakers must be used more nearly to their limits, it becomes necessary to take all conditions into account.

Oil circuit breakers for small stations and industrial service are often used by men who should not be called upon to figure the current and voltage values, which is necessary for selecting the proper type circuit breaker for their service.

For these conditions the kilowatt rating is most convenient, *i.e.* the total generating capacity of the system, or its equivalent, at the point of disturbance. Generally the kilowatt rating is based on the assumption, that the disturbance takes place so close to the generating apparatus, that reactance and resistance of connections between generating apparatus and the place of disturbance need not be considered. A certain initial reactance of the generating apparatus and a certain diminution factor of the current started by the disturbance, dependent on the time required by the circuit breaker to open the circuit after the disturbance has started, are assumed.

If the oil circuit breaker is located at some other point in the system with considerable line or transformer impedance between the generating apparatus and circuit breaker, allowance must be made for the current-limiting effect of this additional impedance. Instead of the generated kilowatt capacity, an equivalent kilowatt capacity must be used, which refers to the actual location of the circuit breaker in the system and is lower than generated kilowatt capacity, by an amount dependent on the characteristics of the intervening conductors and circuits.

The physical dimensions of the conducting copper parts of the circuit breaker should always carefully be considered. Conducting parts must be of sufficient size to carry the rated current indefinitely without objectionable temperature rise, also be large and strong enough for the maximum current rushes between the instant of short circuit and the time of opening of the circuit.

The use of current-limiting reactors, or reactances in transformers and machines in connection with systems is increasing. The reactor may be in circuit permanently or only when the breaker is opening. Various means have been developed to insert reactors or resistance into the circuit as the circuit breaker opens. While such arrangements reduce the current which the circuit breaker opens, they cannot act quickly enough to reduce the instantaneous maximum current and the shock on the system which is the real point to be considered.

Finally, one man will require the circuit breaker to open the most severe short circuits without the slightest indication of distress. Another man may be well pleased if the circuit breaker protects his more costly machinery, even if the circuit breaker itself is destroyed in doing so. Some one else may expect the circuit breaker to open two or possibly three times without requiring inspection or repair.

It is thus evident that there is a wide range of opinion as to what constitutes satisfactory operation; but as experience and information accumulates, this situation will gradually improve and we will approach closer to, and it is hoped will ultimately reach, the solution of the problem.

To sum up—I am in favor of rating circuit breakers on the basis of current in the arc and operating voltage of the system. The term "current in the arc" implies, that in defining its value all factors have been considered, which are necessary to determine the actual work to be performed at the time when, and at the place where, the current is interrupted.

I am not in favor of giving ratings to circuit breakers, in transient peak values which do not exist at the time of opening the circuit

Discussion on "Rupturing Capacities of Oil Circuit Breakers" (Hayes), and "Rating of Oil Circuit Breakers" (Hewlett), Boston, Mass., December 8, 1916.

Chester Lichtenberg: The standardization of the rating of the interrupting capacity of an oil circuit breaker is fast becoming an economic necessity. Manufacturing companies have a wide variety of product to offer but operating companies have difficulty in choosing suitable devices therefrom, because the duty which they will perform is not published in standard form. Consequently, the rating suggestions made by Messrs. Hayes and Hewlett are timely and should encourage engineers to submit their ideas on this important topic in order that their knowledge may be utilized in arriving at suitable standards.

It seems desirable to rate circuit breakers on the basis of the current in the circuit during the time the arc persists in the breaker. There is, however, some question regarding the value of this current. It is described by Mr. Hayes as "the maximum peak of the current wave that occurs while the breaker is opening." It is defined by Mr. Hewlett as "that value which prevails at the moment when the circuit breaker opens." Neither of these seems quite clear nor comprehensive and in place thereof, it is suggested that, "the average of the r.m.s. values of the current peaks on the transient side of the true zero line as measured by an oscillograph, during the time that the arc persists," be taken as the current interrupted by the breaker, when interpreting test results.

Another question in considering the interrupting capacity of an oil circuit breaker is the pressure voltage of the circuit. Mr. Hayes proposes to use "the r.m.s. of the open-circuit voltage that occurs immediately after the breaker opens." This suggestion has much to commend it but unfortunately if it is adopted it may further complicate the rating, on account of the pressure variations which systems may exhibit. Mr. Hayes has mentioned some of these. Besides, during ordinary switching conditions, the circuit pressure may rise momentarily to about three times normal, and under unusual conditions, it may rise as high as seven times normal just after the breaker clears the circuit. It is quite important, therefore, that if the breaker rating is to be separated from its application, a value of the pressure should be adopted which is independent of system characteristics.

The calculation of the interrupting capacity of a breaker at pressures other than those for which tests are available, presents a difficult problem. One rule states that any change in the operating pressure from the listed pressure ratings will usually change the kv-a. rating in about the same percentage. An example of this method is given by Mr. Hayes. The data have been rearranged in Table No. 1 and there has been added the maximum safe rupturing capacity of the breaker and the interrupting capacity of the breaker in amperes, both calculated as outlined in the Hayes paper.

TABLE No. 1

Rated pressure	Operating pressure	Nominal rupturing capacity	Maximum safe rupturing capacity	Interrupting capacity at operating pressure
Volts	Volts	Kv-a.	Kv-a.	Amperes
22,000	22,000	10,000	62,500	1,700
22,000	16,500	12,000	75,000	2,600
22,000	13,200	13,000	81,250	3,600
22,000	7,500	17,000	106,000	8,200
22,000	4,500	19,000	118,750	15,000

An examination of the last column of this table indicates that, while current ratings at 13,200 volts and above are logical, those at 7500 volts and 4500 volts seem too high. Here it is obvious that the formula only holds to about 50 per cent of the maximum pressure listed. Consequently, in adopting rating standards, it will be necessary to consider the limitations through which the formulas will apply.

In considering the interrupting capacity of an oil circuit breaker, it is necessary to remember the duty to be performed by the device. It is called upon to open an electrical circuit which at any given instant has a definite amount of energy stored in the medium surrounding it. The process of opening the circuit causes a change in the energy storage. Under the usual a-c. circuit conditions, a portion of the stored energy must be dissipated when the breaker is opened, the dissipation taking place partly in the breaker and partly in the resistance of the electrical circuit. Besides, account must be taken of the energy stored in the rotating parts of synchronous machines connected to the circuit, and the energy supplied by the prime movers during the circuit interruption.

The usual method of rating oil circuit breakers, as well as those proposed, take into account only the steady current conditions of the circuit. They usually consider its normal pressure or sometimes the pressure just after the circuit is opened, and the current flowing through the breaker. These factors, however, do not completely account for the energy to be dissipated by the breaker. It is, therefore, necessary, in addition, to consider the condition of the circuit immediately preceding an attempt to to open it and the power factor of the circuit during the attempt. In other words, any definition of the duty to be performed by an oil circuit breaker or the rating of its interrupting capacity should include a statement of the power factor on which the rating is based, the point of the current wave at which the arc is started, and other essential factors. The worst conditions of power factor and point of the current wave at which the arc is started should always be understood or defined.

N. L. Pollard: In my opinion confusion will be avoided if all circuit breakers are given either a kv-a. or ampere-volt rating.

Mr. Hewlett stated that it might be necessary to rate a certain capacity of breaker, used a great deal in factories, in kilowatts, as this method of rating would be better understood by the users. If this is done, it may simplify matters for a certain class of users, but it certainly will complicate them for all others. Any purchaser knows the voltage of his system and what load in amperes he expects to carry, therefore he should have no difficulty in choosing the proper breaker. In case he is not satisfied with his own judgment, he should get in touch with some engineer who is competent to advise him.

I have known of cases where the manufacturer of breakers was advised by the purchaser that his load was such that he never would have more than a certain generator capacity connected to his lines at any time, and the manufacturer recommended a breaker which in his opinion would be adapted for the service. Some time later additional generator capacity was installed and several of the breakers failed. Cases like this will always exist unless all users of breakers become competent engineers.

In regard to just what a breaker should do, the question has been raised as to whether it should rupture the circuit only once or several times, with or without putting itself out of commission. There are not many central station men who care to see their station walls and floor splashed with oil or have the switch disabled to the extent that it becomes necessary to put the feeder out of service while repairs to the switch are being made.

In trying to analyze the proper rupturing capacity of a breaker, we come back to the question as to what is meant by "distress". It might be considered to be in distress when a small quantity of oil is thrown out or the contacts are slightly burned. These indications would show that the limit of its capacity had about been reached.

The capacity of the breaker should be great enough to rupture the circuit at least three times without any appreciable quantity of oil being thrown out and without any damage to the switch.

George A. Burnham: The Standards Committee on Switching Equipment had hoped at this meeting to remove one of the apparent obstacles in our way, namely, that of determining a satisfactory method of rating the rupturing capacity of oil switches and circuit breakers.

From the manufacturer's standpoint, it is evident that we are really getting closer to a common basis or rating.

Both Mr. Hayes and Mr. Hewlett are, evidently, in accord as to the method of rating circuit breakers, and this method, if I interpret it correctly, is exactly in accord with the method of rating oil circuit breakers which I presented to the Institute at the mid-winter convention in 1913.

The next important matter, it seems to me, is to select the proper terms to express the method. I do not, however, believe that it is for the best interests of all to include the word "arc" in the phrase which is to express the rupturing capacity of the switch or circuit breaker, for the reason that if we speak of the amperes at the arc it may lead one to believe that we are talking about the potential at the arc as well. Neither do I believe that we should speak of the voltage immediately after or during the time that circuit interruption takes place. For instance, suppose that we have a circuit breaker that is to interrupt a specific amount of current and that the working voltage of the circuit to which it is connected is 15,000 volts. Assume that at the instant the contacts part the voltage on the particular branch of the system which was short-circuited was caused to drop to 13,000 volts at the terminal of the circuit breaker. Now, how shall we rate the circuit breaker with reference to rupturing capacity, on 13,000 volts or on 15,000 volts? It is apparent that there is a possibility for a misunderstanding, which I do not believe should exist.

We all realize that the power factor as well as unsymmetrical current wave form, surges, etc., affect the rupturing capacity of the circuit breaker, but I do believe it would lead to needless confusion in bringing all these factors into consideration by attempting to express the duty of the circuit breaker under the average working condition.

It appears to me that the method of expressing rupturing capacity of a circuit breaker which is at the present time incorporated in the Standardization Rules is very clear and definite, in that it states amperes per phase at normal working voltage.

Mr. Hayes has very aptly put the question before us when he says it is a question of viewpoint. We know that at the present time we cannot say exactly what the switch will do under all possible conditions, but we can say that a circuit breaker is guaranteed to open, say, 6000 amperes at 2500 volts, based on actual test experience, and be assured that it will perform its function properly unless it is working under very special conditions.

There seems to be a difference of opinion as to what constitutes failure in an oil circuit breaker. I, personally, believe that a circuit breaker should be capable of going back into service after it has performed its function under its guaranteed limit. The question as to the number of times is worthy of consideration.

There is no reason but what more simple and direct terms may be used to express what we mean in reference to these matters, and the quicker we do away with the frills the quicker and easier will it be for us to get down to a more comprehensive basis, that we may all understand.

There is another matter which is, perhaps, trifling, but in working out the size of a breaker for a given system we usually arrive at the amount of current which the breaker is called upon to open under certain voltage conditions, and it would be very much easier to select the switch by consulting a table of the amperes per phase at normal working voltage which the various circuit breakers will satisfactorily open, than to attempt to select it from the ultimate kv-a. or bus-capacity basis.

John L. Harper: Our method of deciding on an oil switch at Niagara is to give the company that is used to building them a statement of our conditions, or get them to investigate for themselves; and then to install apparatus, that, when we put the plant back of it, will rupture properly under any duty put upon it.

However, there seems to be two classes of customers to consider—those who wish to get the switch that will just do the work and no more, and the other class, who are very desirous of getting a breaker that will always open and always be ready to go back into service, regardless of its cost and the possibility of having too large an instrument. Therefore, I would be in favor, in rating a circuit breaker, of using—referring to the illustration used by Mr. Burnham—15,000 volts as the maximum working pressure, and disregarding the lowering of the voltage at such time as the breaker may act, and in this way getting a breaker that will be sufficiently large to open under the very worst conditions, although possibly imposing a little upon the party who wishes to cut down the cost and the size of his breaker. I believe that that class of customers should be imposed upon by manufacturers, rather than those who desire and depend upon continuous and successful operation.

H. W. Buck: There was one point touched upon by Mr. Burnham that I should like to amplify, and that is the question of what determines the successful operation of an oil switch. I, myself, have seen oil switches operate under all kinds of conditions, and I never have yet seen one fail to open the circuit—but they have done so at times at the expense of their own existence—and that is the question. Does the rating of an oil switch mean that it is going to open the circuit successfully at that rating, or does it mean that it can only open it with resulting destruction to itself? Between those two limits, there are all degrees of operation.

An oil switch, to successfully operate, within its rating should certainly be able to open a short circuit in such a way that it can immediately go back into service. If it is going to open the circuit and clear a short on the line, and at the same time blow up its tank and throw oil all over the station, that certainly should not be considered to come within its rating. I think that the successful opening of a circuit should be more clearly defined than it is at the present time.

John B. Taylor: There is at least a tendency to come to some kind of an agreement on this question of rating, since both of the authors want to deal in current and voltage, though there seems to be unnecessary confusion as to what particular current is to be taken, and what particular voltage is to be taken. The principal difference is that Mr. Hayes wants to measure the voltage, not of the system before the trouble began, not of the system at some point while the trouble is on, but some final voltage which is not at all definitely defined. I hope that he will explain that a little more clearly. It is quite obvious from the oscillograph record exhibited, that there are a great many currents and a great many voltage values which may be picked off of the record between the time that the trouble begins and the time that the trouble is definitely over.

My own feeling on this question of rating is, that there is bound to be a great deal of difference of opinion and not much headway made, until the theory of the switch is discussed and a better agreement reached as to how the switch works. Now, while Mr. Hayes disclaims any intention of discussing the theory, scattered through the paper here and there, are various observations on how a switch is designed and the factors making one switch more effective than another. The reason why I feel that the theory of the switch is essential to progress, not only on rating, but for developing switches for more extreme service, comes from reviewing the discussions that have been held on this oil switch matter in the Institute papers for the last 10 or 15 years. Two men will think they are discussing the same point, when they are not discussing the same thing at all. The design of the switch—the designers' working theory as to what factors make a switch effective—appears to be in a very hazy state. On the one hand, we have men talking about a vacuum close to the point of the arc, due to the fact that a solid body has been drawn out of the oil leaving a space which the oil must fill; and at the same time the same man will be showing records of pressure up to 50 or 100 pounds to the square inch.

As Mr. Hewlett has pointed out in his paper, the test of switches under extreme duty is almost impossible today. The expense, the trouble and the danger from interrupting the service on large working systems make the opportunity for those tests so few and far between, that the best that any designer can expect to get out of them is a line on the particular switch that he had there. If he has an opportunity to make several short circuits he may be able to see which one is the better, but such tests cannot be done day after day. The minor details of design, that make the difference between success and failure, cannot be fully tried out. Of course, the proof of the pudding is in the eating, and if a switch has been produced that does the work, it may be more or less immaterial whether the details are worked out to the best advantage. In view of the limited opportunities for doing this work, I feel strongly that there is need of designers and investigators stating their ideas of just how a switch behaves and what factors in the design of one switch make it work better than another switch. After there is some semblance of an agreement on these points, the question of rating will be easier.

K. C. Randall: Some years ago transformers were built or designed by comparison, but they are now, built absolutely scientifically. That is, there is a limited amount of iron, a limited amount of copper, and a limited amount of insulation, which are necessary to the production of a certain performance. There is a mathematical calculation that takes care of it, and that is similarly true with induction motors, and more or less with other machinery. For circuit breakers, no such data are known. Circuit breakers are still comparatively built, and they are not designed on a technical basis.

We know how to build breakers that will perform a certain function; but it is possible, even probable, that the breakers that we are building today will be much more cumbersome, heavier, more expensive, than the breakers which we will build when we know something about breakers—I mean analytically. We know that an inductive circuit is more difficult to open than a like non-inductive circuit. But I don't know that any one will volunteer what the difference is? Whether a power factor of 60 per cent, 50 per cent or 10 per cent, bears a definite relation to the difficulty of the circuit-breaker problem. The technical analysis—the study—the real knowledge of the problem—has not been acquired at all.

Specifically, we don't know whether a tank that is 4 feet (121.9 cm.) deep, as against one that is 2 feet (60.9 cm.) deep, will handle twice as much current—will interrupt a circuit of twice the voltage—or will handle twice the kv-a.; nor do we know whether the diameter of the tank—holding the depth the same—if doubled, will double the capacity of the rupturing ability. Now, if these conditions prevail—and I think those who are confronted with applying circuit breakers and designing them and building them agree—then we are not quite ready to finally say just what a rating of a circuit breaker shall be in terms of power factor, current and voltage.

It might be well, then, to suggest that for the time being we should stick to the one question. For a long time we have gone along with a very hit or miss, perhaps antagonistic, lot of local and almost individual methods of rating. If we should agree now to rate breakers by the current, as Mr. Burnham said—not in the arc, but simply in the circuit; and the voltage of the circuit, the normal, operating potential—we will, I believe, obtain a practical working method which will be good for awhile, and will give an effective basis of comparison. Later on, when real knowledge of the problem has been acquired, we can, if desirable—and I frankly doubt whether it will be desirable—introduce the question of power factor.

It has already been said that probably the power factor, under the average condition of severe duty—say short circuit—may average fairly uniform; and if we build breakers which will deal with those fairly uniform conditions, we will solve the problem.

Then comes a matter that has been touched on several times, which I call the "*relation of freedom of distress to maximum rupturing ability or rating.*" A few of these points are: A function of safety; an indication of an available margin for additional duty; matter of appearance and orderliness; a source of security and confidence of the operators, where there is freedom from distress. Smoke and oil throwing are not necessarily proof of a near approach to the maximum rupturing capacity of the breaker; but, with all adjustments right, and with the operation as intended, such demonstrations should, at least, be rare.

Mr. Pollard, I believe, said that if you wanted to have an immaculate station—and I should think most operators would choose that, if it could be obtained at a reasonable expense—a larger unit could be purchased, which would withstand the duty, and not make a demonstration which a smaller and cheaper unit would manifest. So that, after all, whether the unit shall go back into operation clean, unsoiled and noiseless, or whether it shall go back limping, or perhaps having sacrificed itself and really not go back at all, is a matter for the purchaser. The manufacturer is glad to build whatever the purchaser chooses to buy, usually; but, as Mr. Pollard said, it is up to the purchaser, who does the applying to decide what he wants. He can buy a small breaker and blow it up, or he can buy a large one and not blow it up.

The choice of breaker equipment for freedom from demonstration demands the same foresight into the future methods of operation from the operator as he looks forward to his growing loads, that is exercised when he purchases additional generating equipment.

H. W. Buck: For a common kilowatt rating and a common power house capacity back of the arc, the oil switch of course may have to meet the condition either of large current and low voltage, or small current and high voltage.

The plant at Niagara Falls is particularly well equipped to make this direct comparison, in that it has a large plant, operating at 2200 volts, and also another large plant feeding a high-tension line, with the same amount of power back of the short circuits, operating at 60,000 volts. I would like to ask of Mr. Imlay, whether he considers rupturing the low voltage and large current more severe on oil switches than the same kilowatts output at high voltage on small current?

L. E. Imlay: We have very much less difficulty in rupturing the arcs on the high-voltage circuits than on the low voltage.

C. A. Adams: I should like to ask, then, why it is ordinarily considered that at the lower voltages the kv-a. rupturing capacity is larger than at the high voltages?

E. M. Hewlett: In this particular case, Mr. Imlay is not comparing the same switches. He is comparing the small low-voltage switch, which is insulated for a low voltage, with the large high-voltage switch which is insulated for a high voltage.

The low-voltage switch is relatively smaller because it is not necessary to make it larger, the striking distance is not the limiting feature. Hence the high-voltage switch has a great deal more oil in it, is a larger device, and has a higher rupturing capacity.

S. Q. Hayes: I think there is one other point which might be brought out right here. At the higher voltage there is probably more reactance in the circuit, and the amount of power at the arc is probably somewhat less at the higher voltage than at the lower voltage.

H. R. Summerhayes: It seems to me, on that same point, that there is another thing that should be considered. On the high-voltage switch you are not limited in space, and not so strictly limited in investment, as the low-voltage switch. If the manufacturer were allowed to build a low-voltage switch, using the same space and the same investment as is used for the high-voltage switch, he could probably build a switch which would show a very favorable and remarkable performance. The design of the low-voltage switch has been based on investment considerations and space considerations. The low-voltage stations—the large low-voltage stations—at first were always located in large cities, where real estate was expensive and the switches had to be confined to the least space. A great many switches required a great many feeders out of the stations, so that space was a limiting factor. The high-tension switches, on the other hand, are generally, nowadays, put out of doors, and there is no such objection to the large quantities of oil as was encountered in the original designs of low-voltage switches.

Mr. Hayes speaks of rating the switch on the circuit voltage immediately after the short circuit. The question of the meaning of the word *immediately* comes in. Of course we understand that if the field of the generator is under the control of an automatic regulator which pushes up the field excitation as soon as a short circuit comes, then the voltage may rise to a very high point after the short circuit, but that takes time. I can understand that the current is going up, possibly, during the short circuit, but it seems to me that the voltage would not rise until after the switch had opened. On this very point it has been observed that what we might call a sustained short circuit is more difficult to open than one in which the voltage is not sustained.

I am in favor of rating switches on the current which the switch opens and the system voltage. One reason for that is, that nearly all devices used on constant potential systems are rated at the system voltage, and it would be very convenient for engineers to observe the same custom in rating switches, rather than to rate them on a voltage which may be different for every short circuit.

Mr. Hayes speaks of short circuits not occurring closer together than two minutes, the breaker being capable of opening the short circuit ten times within the course of an hour. It occurs to me that such an arbitrary rating would be rather difficult for an operating engineer to take care of in his system. That is, it would be rather difficult to design a railway system, or any other system, in such a way that short circuits would come no closer than two minutes apart. They are not under control.

The point that a switch should be guaranteed to open the circuit, and then be in condition to be re-closed, is one which is well taken. There is very little doubt that most operating engineers prefer to have the switch capable of being reclosed at least once. That, I think, should be a standard. As to the number of times, there may be a difference of opinion, and more investment may be required.

The rating in which the kv-a. capacity goes up in greater proportion than the voltage goes down, is rather difficult to understand, and is rather difficult to reconcile with the other statement in the paper, that the rupturing capacity is a function of the tank dimensions.

There is another point that might be raised, and that is, that different designs of circuit breakers may require different formulas to be applied for the difference in rupturing capacity when the voltage is varied. I think some of them would act differently, on that point.

P. M. Lincoln: It seems to me that the main question under discussion here might be almost called one of the proper selection of a name by which to call our circuit breakers. At the present time, and during the past, if we wanted, for instance, to get a circuit breaker for a 1000-kw. machine, we took its ampere capacity from that of the machine and then selected our breaker on the basis of the short-circuit ampere capacity. Thus for various conditions we had to select various breakers, depending upon the conditions under which they were to be used.

A 1000-kw. machine, if built upon the old specifications when regulation was the thing which was desired in generators above everything else, might be capable of giving 15, 20, 30 times or perhaps even a higher percentage, of its normal current upon short circuit. Under modern conditions, however, particularly since the practise has arisen of using reactances, in series with generators, instead of giving 20, 30 or may be 40 times normal current, the modern generator may only give five to ten times normal full-load current on short circuits; so that, that condition introduces a decided factor in the selection of the breaker.

The question, therefore, is, in the future shall we select our breakers in regard to the normal current which they have to carry, or shall we select the breaker with regard to the maximum overloading—the worst condition that it must carry? I quite agree with both authors. Both authors take the position that the breaker should be selected, and it should be given a name with respect to the maximum short circuit that it has to interrupt. I quite agree with that view.

Some exception has been taken to the language of Mr. Hayes, when he speaks of the voltage to be interrupted. He calls the voltage that which exists immediately after the short circuit has been interrupted. I think Mr. Hayes used that language to give a picture of what the breaker has to do during the process rather than with a view of determining the voltage of the rating. I believe that the proper voltage to be used in getting at this rating is the normal voltage of the circuit.

It seems, therefore, that the main question that we have under discussion in this session is the proper name to apply to breakers, and I quite agree with both of these authors, in feeling that the proper name to give to them is the final rupturing capacity, rather than the normal ampere carrying capacity. Of course the breakers must have that normal ampere carrying capacity—that goes without saying. But the name to call them by should be their maximum rupturing capacity, rather than their normal ampere carrying capacity.

L. W. Chubb: The electromagnetic energy stored in a system when the breaker opens has to be dissipated either as heat in the breaker arc or stored as an electrostatic charge in the system, to be subsequently dissipated by oscillation and absorption in resistance. There are several different things to consider in the breaking of a circuit. The energy put in the breaker tank is a function of the power factor, the time of operation and the phase of the current at the first of the separation. If the breaker opens quickly at the zero point of current the breaker has no work to do and the energy will all go to increasing the voltage of the system. If the breaker takes a long time to open, the stored energy of the system and more coming from the generating station will be dissipated in the arc of the breaker. So that the time and speed of operation, the power factor, the ratio of line capacitance to inductance, and the kind of inductance are all things to be considered. It makes a difference whether the interruption and short circuit are at the far end of the line or near the station. A breaker in the station should handle a short circuit near the station, in which case there is the greatest current, lowest power factor, and lowest ratio of capacitance to inductance. With this low ratio of capacitance there is not the advantage of line elasticity, no place to store the energy, there is an almost instantaneous rise of voltage each time the current pauses at the zero point, which lights the arc repeatedly and the dynamic and stored energy must be taken care of in the arc under oil until the final break. Therefore it seems that to take care of the worst conditions, the rating of breakers should assume a zero power factor.

C. A. Adams: My interest in this subject is largely from the standpoint of standardization, to the end that the rating of an oil switch or circuit breaker may be definite, clear cut and determinable. In the early days of dynamo machinery, the maker's rating frequently differed from what we now understand as the continuous rating, by as much as 50 per cent. (usually in excess), due partly to crudeness in methods of design and calculation, partly to lack of digested experience, partly to lack of knowledge of the qualities of the materials employed, partly to the differing factors of safety employed by the various manufacturers, and partly to the differing allowances which the manufacturers made for the crudeness of the customer's estimate of the capacity required.

We are now in a somewhat similar stage of evolution as regards the rating of oil circuit breakers. The customer does not know exactly the work which the breaker will be called upon to do; the designer does not know how to design, with any reasonable degree of accuracy, a breaker to do just the work specified; and finally the manufacturer cannot easily reproduce the specified conditions of operation, to test his product.

Thus the task before us is two-fold: First, to reduce our knowledge of this whole subject to a more definite, computable and testable basis; and second, to agree upon certain definitions as to rating, etc., so that we will be talking the same language, so that both specifications and bids will be rational and comparable.

Out of the present discussion, one conclusion stands forth clearly in my mind, namely that the rating of an oil circuit breaker should be defined in terms of the work it can safely do, without reference to the nature or capacity of the system to which it may be connected by a particular customer. It is for the customer or his engineer to say what work it will be called upon to do, or to choose a standard breaker with a sufficient margin to cover his maximum requirement. If he wishes an unusually large factor of safety it is for him to specify the correspondingly larger standard rating, as he is the one to pay for this extra insurance.

Finally the task under discussion is not a small or unimportant one, and anyone who contributes even in part to its satisfactory completion deserves a large share of credit and appreciation from the profession at large.

S. Q. Hayes: Referring to Mr. Lichtenberg's discussion. My paper, as stated, is largely a series of disconnected notes. It really does not lay much claim to clearness of definition as to the proper method of this rating. I think probably the fourth line of the summary gives the gist of my idea in preparing this paper—that the main object was to open up a discussion; and I think we have opened up a pretty fair discussion on it. Mr. Lichtenberg I believe also brought out the question about the rating of the circuit breaker and the formula from which that is derived. That, as stated in the paper, is the rating assigned to it by the maker or the designer of that particular breaker. The makers have felt that the breaker which really has the 22,000-volt insulation, and the oil and the tanks suitable for that service, will actually open 1700 amperes at 22,000 volts, and will be reoperative after opening such a short circuit. They also claim that that same breaker will actually open 15,000 amperes at

4500 volts, and be immediately reoperative. They have made tests that prove that that particular breaker can fulfill that particular line of ratings. Whether that formula holds true for every particular line of breaker—as Mr. Summerhayes brings out—is another question. But the makers will guarantee that this particular breaker will meet the particular conditions stated.

Mr. Pollard and others brought out the question of rating in kv-a. or amperes and volts, and the question of the voltage immediately after opening the arc. Under normal conditions we actually rate a breaker at the service voltage. I wanted to point out the fact, however, that under the abnormal conditions met in certain cases, where you do have a very large rise in voltage, that the kv-a. rating should be based on the voltage that is practically available for maintaining that arc, namely, the voltage that exists just after the breaker has cleared the circuit.

H. R. Summerhayes: Don't you think it would be better, as a basis of rating, to use the system voltage?

S. Q. Hayes. I think, as a basis for rating, that the system voltage is probably the best way of doing it. This paper of mine is not any attempt to force this method of rating; but my idea was to put up a method of rating, largely as a target, so as to get the ideas of various people on this subject.

I notice that Mr. Pollard agrees with the recommendation, that the manufacturer should give the rating which he assigns to his oil circuit breaker, and the user should decide whether that breaker actually is satisfactory for his conditions.

The question of distress that Mr. Pollard brought out, really is a question for the operating engineers to settle, rather than for the designer to settle.

As Mr. Adams indicated, one thing necessary is to select the proper terms to be used in rating circuit breakers and the proper method of determining whether the circuit breakers have met their guarantees or not. This paper of mine suggests certain terms, not as being the best possible terms to describe what is intended, but as one method of describing them, in order, to give others a chance to suggest better means of expressing what I have attempted to express in this paper.

Now, that point about whether the breaker should be rated at 15,000 volts or 13,000 volts is, to a certain extent, answered by the recommendation of using the voltage that will exist immediately after the breaker has opened the circuit. That very difficulty is indicated on the curve. After opening, the circuit will undoubtedly have gone back to 15,000 volts, and may be a trifle higher.

Mr. Harper brought out the point that the practise of his company is practically to have the manufacturer send an engineer to investigate the particular conditions and then recommend a breaker that will meet those particular conditions. Now, in plants of the size of Mr. Harper's, that can usually be done; but the idea of this paper was to practically settle on a basis of rating that would take care of probably 90 per cent of the cases. There are undoubtedly other cases—maybe 10 per cent of the whole—where the operator will largely have to depend on the designing engineer—the manufacturing engineer—guaranteeing that he will actually furnish a breaker to meet the particular conditions.

Mr. Harper very aptly brought out the facts that there are two classes of customers. In making a note on Mr. Harper's statement, I called these people "minimum and maximum customers"—one who will be satisfied with the minimum, namely, the cheapest breaker, that will just get away with his service; and, the other one, who wants the best that can be purchased, irrespective of price. Now, naturally the manufacturer would like to see more of that latter class.

Mr. Buck brought out the point of what really was a successful operation; and various other people agreed with Mr. Buck that it was necessary to have repeat operation.

Now, on that oscillogram (referred to by Mr. Taylor), the point that I would take as to the maximum voltage just after opening is the point which is marked on the oscillogram "short circuit opened." You will notice that on this particular system, where this test was made, that point is just slightly above the normal station voltage.

Mr. Taylor brought out the point that testing under actual conditions is almost impossible. As a general rule, that statement is entirely correct. There are a certain number of tests that have been made on plants of comparatively large capacity, so that the operators know, or can know, that the manufacturers really have some actual data on which their apparatus is based.

Mr. Randall brought out the point that circuit breakers are what he called "comparatively built," and "comparatively designed," and that no real analysis has been made of a circuit-breaker design, and that no actual data have been obtained as to the effect of changes in dimensions. Now, those statements are entirely correct. No definite data have been secured as to the effect of increase in dimensions; but a certain amount of comparative data have been available. It is known that a certain type of breaker, with a tank of a certain diameter, will do a certain amount of work, and that the same general design of breaker, with a larger tank, will open a greater amount of power.

Mr. Randall also agreed with the statement made by various speakers, that the current of the circuit to be opened really should be the current at the normal voltage, and not the current that would exist after opening the arc. And he also brought out the various features that would occur at the time of rupture, which he spoke of as "demonstrations."

Mr. Imlay stated that he has found there is less difficulty opening a certain station capacity at 60,000 volts than at 2200 volts. In answering that point at that time I practically asked Mr. Imlay another question, and that was whether at 60,000 volts there really was not more reactance in his circuit, so that the power at the arc really was less on the 60,000 than on the 2200-volt circuit. Now, Mr. Summerhayes and Mr. Hewlett practically brought out, in answer to Mr. Imlay's point, that for the higher voltage, space and price were minor considerations. So that it is undoubtedly true that the high-voltage breakers, which Mr. Imlay has in his plant, open their circuits with less fuss than the low-voltage breaker.

Mr. Imlay I believe also brought out the question of the rating of the low-voltage breaker—the rating of a breaker being given greater for low voltage than for high voltage. I answered that question earlier, to the effect that those are the ratings which the manufacturer of that breaker guarantees the breaker will meet.

Mr. Summerhayes brought out the point that the space and the price of a low-voltage breaker, particularly when installed in city plants, where real estate was of vast importance, was one of the limiting features on the low-voltage breaker that was not met with in the high-voltage breaker; and that given more or less unlimited space and more or less unlimited price the low-voltage breaker could be made to open the circuit just as readily as the high-voltage breaker.

Mr. Summerhayes also stated that, it is his recommendation that the current rating should be on the system voltage. I practically agree with him; but I have brought out the point that for those particular conditions where we did have a high rise in voltage after an arc, that it will have to be watched rather carefully. Now, just on that point, there is one feature of circuit-breaker operation that some people lose sight of, and that is, that if you have a number of parallel connected circuits and one of them is opened due to a short circuit on that particular feeder, the duty is less on that breaker, because the system can discharge over the other circuits, than if that were the only circuit and it had to open all of the stored magnetic energy of the system.

Mr. Lincoln brought out the fact that the real feature was the proper selection of the name to be assigned to a circuit-breaker rating. And Mr. Lincoln stated correctly my viewpoint on that question of the open-circuit voltage that took place immediately after the breaker opened.

Mr. Chubb brought out the point of the energy to open and the storage of energy, and the point that I just made, about circuit breakers and parallel circuits, takes care of that point.

Mr. Adams felt that the rating of the breaker should be practically independent of the system; and, if it is possible to do so, I feel that that is the proper method of rating.

E. M. Hewlett: In reference to Mr. Pollard's point, and as Mr. Hayes stated, the manufacturer would like to have only one rating, and that rating for safety and service. Unfortunately, there are two classes of customers. Some want all they can get and others are content with just enough to squeeze through. You must consider both parties in the designing and the rating, so that you will need a rating that can be used both ways, or let a different safety factor be taken by the man who is willing to take the risk.

Mr. Randall is quite right in reference to our data. We have a great deal comparing different capacities and different dimensions, and the service that the switches have given will bear out the way we have used that data. I think that the manufacturers have selected ratings that have given on the average, very good service.

Mr. Lincoln spoke of using the rating—that is, the rupturing capacity rating—as the rating of the switch. I think, however, that a switch needs a first and a last name, as well as some other features, and that you have to give it not only a rupturing rating, but also a normal current carrying capacity at the station voltage.

Then, to take up the last point, the rupturing capacity should be stated in the actual current that the switch is called upon to open at the operating voltage. There are a great many factors, you can see, that have to be brought in; but we can use such a rating as this until such time as we find we have sufficient data to formulate a new rating.

P. Lindemann (by letter): It is quite evident that we will have as many types of circuit breakers as we have types of apparatus or systems to be protected.

Taking into consideration our present method of rating generators, transformers and motors, it seems most preferable that our oil switches or other protecting devices be treated with a like method of rating, so for a generator having a given name plate rating that a similar name plate rating be placed on the oil switch to signify the proper size of switch necessary.

By this method for a transmission line the proper oil switch would be one having a name plate rating equivalent to the current, voltage, frequency and power factor of the line which it is to protect.

Assuming the line connected to generator bus bars, a generator type of switch would be selected and if the switch was to be placed at the far end of the same line with no load taken off between them, the two oil switches should have the same ratings theoretically, their types however would be different.

It seems to me that the possible surges of voltage and current should not enter into its name plate rating, but rather that they be assumed in the design by the manufacturers.

In addition to the above an oil switch of such design as to take care of twelve interruptions of its maximum rating at two minute intervals before inspection is necessary, would be ideal practically.

STANDARDIZATION RULES

OF THE

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

HISTORY OF THE STANDARDIZATION RULES

The first step taken by the Institute toward the standardization of electrical apparatus and methods was a topical discussion on "The Standardization of Generators, Motors and Transformers," which took place simultaneously in New York and Chicago on the evening of January 26, 1898. The discussion appears in the Institute TRANSACTIONS, Vol. XV, pages 3 to 32. The opinions expressed were generally favorable to the scheme of standardization of electrical apparatus, although some members feared that difficulties might arise. As a result of this discussion, a Committee on Standardization was appointed by the Council of the Institute, consisting of the following members:

FRANCIS B. CROCKER, *Chairman.*

CARY T. HUTCHINSON	CHARLES P. STEINMETZ
ARTHUR E. KENNELLY	LEWIS B. STILLWELL
JOHN W. LIEB, JR.	ELIHU THOMSON

After a careful consideration of the matter and consultation with the members of the Institute and interested parties generally, a "Report of the Committee on Standardization," was presented and accepted by the Institute, June 26, 1899. Those original rules appeared in the Institute TRANSACTIONS, Vol. XVI, pages 255 to 268.

As a result of changes and developments in the electric art, it was subsequently found necessary to revise the original report, this work being carried out by the following Committe on Standardization:

FRANCIS B. CROCKER, *Chairman.*

ARTHUR E. KENNELLY	CHARLES P. STEINMETZ
JOHN W. LIEB, JR.	LEWIS B. STILLWELL
C. O. MAILLOUX	ELIHU THOMSON

This revised report was adopted at the 19th Annual Convention at Great Barrington, Mass., on June 20, 1902, and appears in the Institute TRANSACTIONS, Vol. XIX, pages 1075 to 1092.

In consequence of still further change and development in electrical apparatus and methods, it was decided in September, 1905, that a second revision was needed, and the following Committee was appointed to do this work.

FRANCIS B. CROCKER, *Chairman.*
ARTHUR E. KENNELLY, *Secretary.*

HENRY S. CARHART	CHARLES F. SCOTT
JOHN W. LIEB, JR.	CHARLES P. STEINMETZ
C. O. MAILLOUX	HENRY G. STOTT
ROBERT B. OWENS	S. W. STRATTON

This Committee held monthly meetings and carried on extensive correspondence with manufacturers, consulting and operating engineers and other interested parties, and as a result, presented its report at the 23d Annual Convention, held at Milwaukee, May 28–30, 1906. After considerable discussion the report was accepted and referred back to the Committee for amendment and rearrangement in form. It was then to be submitted to the Board of Directors for final adoption. In September, 1906, the following Standardization Committee was appointed:

FRANCIS B. CROCKER, *Chairman.*
ARTHUR E. KENNELLY, *Secretary.*

A. W. BERRESFORD	CHARLES F. SCOTT
DUGALD C. JACKSON	CHARLES P. STEINMETZ
C. O. MAILLOUX	HENRY G. STOTT
ROBERT B. OWENS	S. W. STRATTON

ELIHU THOMSON

This Committee held monthly meetings, also sub-committee meetings, and carefully referred the rules as a whole, and each part of them, to the members of the Institute. The rules were also entirely rearranged as to form, and put in shape to facilitate ready reference to them and enable future revisions to be made without breaking up the logical arrangement. Thus amended the rules were submitted to the Board of Directors and approved by it on June 21, 1907. The Board also directed that the rules should be presented, as accepted by the Board, at the Annual Convention held at Niagara Falls, June 24 to 27, 1907, which action was taken by President Sheldon on June 26, 1907. By the Constitution which went into effect on June 10, 1907, this Committee has been made a standing Committee with the title "Standards Committee," consisting of nine members.

On August 12, 1910, the Board of Directors increased the size of the committee from nine to twelve members; on October 14 from twelve to fourteen, and on March 10, 1911, from fourteen to sixteen. The committee thus constituted is given below.

COMFORT A. ADAMS, *Chairman.*
ARTHUR E. KENNELLY, *Secretary.*

H. W. BUCK	W. S. MOODY
GANO DUNN	R. A. PHILIP
H. W. FISHER	W. H. POWELL
H. B. GEAR	CHARLES ROBBINS
J. P. JACKSON	E. B. ROSA
W. L. MERRILL	CHARLES P. STEINMETZ
RALPH D. MERSHON	CALVERT TOWNLEY

This committee and several sub-committees held numerous meetings at which the general revision of the Standardization Rules of the Institute was considered. The complete Standardization Rules, as revised by this committee, were presented to and approved by the Board of Directors on June 27, 1911, at the Annual Convention held at Chicago, Ill.

During the following two years (1911-1913) the Standards Committee, somewhat modified and enlarged, undertook a radical revision of the Rules, particularly in connection with the important subject of Rating. In August 1913 the Committee was still further enlarged by the Board of Directors in order to permit of comprehensive sub-committees for the various parts of the work. The Committee thus constituted is given as follows:

A. E. Kennelly, *Chairman.*
Comfort A. Adams, *Secretary.*

SUB-COMMITTEE No. 1. ON RATING.

H. M. Hobart, *Chairman.*

James Burke	W. H. Powell
W. C. L. Eglin	Charles Robbins
B. G. Lamme	C. F. Scott
W. A. Layman	James M. Smith
W. L. Merrill	Charles P. Steinmetz
W. S. Moody	J. Franklin Stevens

Philip Torchio

SUB-COMMITTEE No. 2. ON TELEGRAPH AND TELEPHONE STANDARDS.

F. B. Jewett, *Chairman.*

H. W. Fisher	R. H. Marriott
F. F. Fowle	J. H. Morecroft

J. M. Smith

SUB-COMMITTEE No. 3. ON RAILWAY STANDARDS.

W. A. Del Mar, *Chairman.*

F. W. Carter*	William McClellan
Hugh Hazelton*	Harold Pender
E. R. Hill*	Martin Schreiber*
H. M. Hobart	N. W. Storer*

SUB-COMMITTEE No. 4. ON NOMENCLATURE AND SYMBOLS.

Comfort A. Adams, *Chairman.*

Louis Bell	H. Pender
Dugald C. Jackson	E. B. Rosa
M. G. Lloyd	A. S. McAllister

R. H. Marriott

SUB-COMMITTEE No. 5. ON WIRES AND CABLES.

H. W. Fisher, *Chairman.*

Wallace Clark	E. B. Rosa
W. A. Del Mar	C. E. Skinner
W. C. L. Eglin	S. W. Stratton

SUB-COMMITTEE NO. 6. ON RATING AND TESTING OF CONTROL APPARATUS.

L. T. Robinson, *Chairman.*

Morton Arendt	C. H. Sharp
N. A. Carle	P. H. Thomas

Philip Torchio

Sub-committee No. 1 had representation from the National Electric Light Association (Messrs. L. L. Elden, G. L. Knight, J. E. Kearns, and E. P. Dillon), from the Association of Edison Illuminating Companies (Mr. P. Torchio) and from the Electric Power Club (Messrs. James Burke and J. M. Smith).

Sub-committee No. 3, through Messrs. Schreiber and Del Mar, respectively, worked in collaboration with the Committees of the American Electric Railway Engineering Association, and the Association of Railway Electrical Engineers.

*Sub-committee No. 3 was a joint subcommittee of the Standards Committee and of the Railway Committee. The members opposite whose names occurs an asterisk, represented the latter committee.

The following members, although not appointed on the Standards Committee, have materially contributed to its work and have attended its meetings:

Carl J. Fechheimer, E. D. Priest, R. B. Williamson, K. A. Pauly, L. F. Blume, C. Renshaw, G. H. Hill, C. J. Hixson.

The radical revision begun in 1911 was completed by this Committee and approved by the Board of Directors at a special meeting held on July 10, 1914, subject to editorial revision by the Committee, and to go into force on Dec. 1, 1914.

The Committee of 1914-1915 which carried out the editorial revision, found it impossible to complete the work satisfactorily by Dec. 1st. The edition of July 1st, 1915, approved by the Board of Directors at its meeting of June 30, 1915, thus represents substantially the completion and clarification of the previous radical revision, although it includes a number of important additions. This Committee was constituted as follows:

A. E. KENNELLY, Chairman, Harvard University, Cambridge, Mass.
C. A. ADAMS, Secretary, Harvard University, Cambridge, Mass.

JAMES BURKE, Erie, Pa.
W. A. DEL MAR, New York.
H. W. FISHER, Perth Amboy, N. J.
G. L. KNIGHT, Brooklyn, N. Y.
H. M. HOBART, Schenectady, N. Y.
F. B. JEWETT, New York.
P. JUNKERSFELD, Chicago, Ill.
W. L. MERRILL, Schenectady, N. Y.
W. H. POWELL, Milwaukee, Wis.
CHARLES ROBBINS, East Pittsburgh, Pa.
L. T. ROBINSON, Schenectady, N. Y.
E. B. ROSA, Washington, D. C.
C. E. SKINNER, East Pittsburgh, Pa.
J. M. SMITH, New York.
H. G. STOTT, New York.
P. H. THOMAS, New York.

During 1915-16 a number of changes, deletions and additions were made. The 1915-16 Committee was constituted as follows:

C. A. ADAMS, Chairman, Harvard University, Cambridge, Mass.
HAROLD PENDER, Secretary, Univ. of Pennsylvania, Philadelphia, Pa.

FREDERICK BEDELL,
L. F. BLUME,
JAMES BURKE,
N. A. CARLE,
E. J. CHENEY,
FRANK P. COX,
W. A. DEL MAR,
W. F. DURAND,
H. W. FISHER,
H. M. HOBART,
F. B. JEWETT,
P. JUNKERSFELD.
A. E. KENNELLY,
G. L. KNIGHT,
A. S. McALLISTER,
W. M. McCONAHEY,
W. L. MERRILL,
R. B. OWENS,
CHARLES ROBBINS,
L. T. ROBINSON,
E. B. ROSA,
C. E. SKINNER,
H. G. STOTT.

In addition to the members of the Standards Committee, the following members of the Institute have served on one or more of the various sub-committees: J. R. C. Armstrong, H. S. Baldwin, Joseph Bijur, G. A. Burnham, W. S. Clark, L. W. Chubb, F. M. Farmer, G. M. W. Goettling, J. D. Harnden, R. E. Hellmund, C. T. Henderson, E. M. Hewlett, Guy Hill, H. D. James, Paul MacGahan, J. N. Mahoney, H. S. Osborne, K. A. Pauly, C. H. Sharp, T. H. Schoepf, P. H. Thomas, Philip Torchio, M. O. Troy, J. L. Woodbridge.

The following societies directly and through the committees named, have given helpful cooperation in the present revision of the Rules:

American Society for Testing Materials,
Committee B-1.

Association of Edison Illuminating Companies,
Committee on Meters.

Illuminating Engineering Society,
Committee on Nomenclature and Standards.

Electric Power Club,
Committee on Engineering Recommendations; Standardization Committee.

National Electric Light Association
Committee on Meters.
Committee on Apparatus.

Association of Railway Electrical Engineers
Committee on Wires and Cables.

American Electric Railway Engineering Association,
Committees on Equipment and Distribution.

Institute of Radio Engineers,
Committee on Standardization.

Society of Automobile Engineers,
Standards Committee

Of particular value in the present revision of the Rules has been the very cordial cooperation of the British Engineering Standards Committee, which was represented at the final meeting of the Standards Committee on May 15 and 16 by its Electrical Secretary, Mr. C. le Maistre, who came from London to New York for this express purpose. The British Engineering Standards Committee is supported by the following British Societies: The Institution of Civil Engineers, the Institution of Mechanical Engineers, The Institution of Naval Architects, The Iron and Steel Institute, The Institution of Electrical Engineers.

In order to crystalize the policy of the Standards Committee in its own activities, and in its relation to similar committees of other engineering societies, the 1915-16 Standards Committee formulated the by-laws given on the next page. These were approved by the Board of Directors June 28, 1916.

NOTE.

The Standards Committee takes this occasion to draw the attention of the membership to the value of suggestions based upon experience gained in the application of the Rules to general practise.

Any suggestions looking toward improvement in the Rules should be communicated to the Secretary of the Institute, for the guidance of the Standards Committee in the preparation of future editions.

BY-LAWS OF THE STANDARDS COMMITTEE OF THE A. I. E. E.

In Section 28 of the By-Laws the duties of the Standards Committee are stated as follows:

" The Standards Committee shall consider and investigate all matters relating to units and standards appertaining to or applicable in electrical engineering and in the allied arts and sciences. The Committee shall make reports and recommendations to the Board of Directors for action thereon."

The following by-laws are in accord with this section of the Constitution.

1 These by-laws, when approved by the Board of Directors, shall supersede all former resolutions governing the action and policy of the Standards Committee.

2 The minutes of each meeting, marked "Not for Publication," shall be sent by the Secretary to each member of the Committee. These minutes shall contain a summary of the reasons presented for and against any amendment or addition to the Standardization Rules which may be discussed at the meeting. An amendment or addition adopted by the Committee shall be marked in the minutes in a distinctive manner.

3 All amendments and additions adopted by the Committee during any fiscal year may be reconsidered by the Committee at any time, and shall be reviewed at its meeting held in May, and only those amendments and additions confirmed at this meeting shall be presented to the Board of Directors for their approval. Three-fourths of the votes of those present and voting shall be necessary for such confirmation. Any objection or change to be considered at this meeting shall be submitted in writing prior to the meeting and no action other than a vote for or against confirmation of any previous action of the Committee shall be taken at this meeting, except upon the unanimous vote of those present.

4 Amendments and additions to the Standardization Rules adopted by the Committee are not in force until approved by the Board of Directors, and may be reconsidered by the Committee at any time.

5 Cooperation is desirable between the Standards Committee of the Institute and other standards committees. To this end, a report, marked " Not For Publication," of the amendments and additions adopted at each meeting of the Committee shall be sent to those standards committees with which cooperation has been established.

6 An objection from a cooperating standards committee to an action taken by this Committee shall be considered at the next meeting of this Committee following the receipt of a written statement of this objection, provided such objection be submitted within thirty days of the date on which was mailed the report of the action to which objection is made.

A notice from another standards committee of a pending objection shall, however, suffice for an extension of time. In the case of foreign standards committees, the time allowed for an objection to be filed may be extended at the option of this Committee.

7 A cooperating standards committee which may submit an objection to a previous action of this Committee shall be invited to send a representative to the meeting or meetings of this Committee at which such objection is scheduled for consideration.

8 Whenever a new edition of the Rules is issued, old Rules in which changes other than typographical corrections have been made, and all additions and deletions, shall be distinctively indicated.

9 Amendments and additions to these By-Laws may be made by this Committee, subject to the approval of the Board of Directors.

OTHER APPROVED STANDARDIZATION RULES

At the April meeting the Standards Committee passed the following resolution, which was approved by the Board of Directors on April 14th:

" The Standards Committee, with the approval of the Board of Directors, recommends the use of the following rules and standards as adopted by other societies. These have been formally presented to the Standards Committee by the societies concerned and are found not to be incompatible with the Standardization Rules."

The Standards Committee will be pleased to receive from any of the engineering societies such standardization rules as they may care to have included in this list. Such rules will be included (by title only) if they are found not to be incompatible with the Standardization Rules of the A. I. E. E.

STANDARDIZATION RULES

OF THE

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

DEFINITIONS

NOTE. The following definitions are intended to be practically descriptive, rather than scientifically rigid.

CURRENT, E.M.F. and POWER.

(The definitions of currents given below apply also, in most cases, to electromotive force, potential difference, magnetic flux, etc.)

1 **Direct Current.** A unidirectional current. As ordinarily used, the term designates a practically non-pulsating current.

2 **Pulsating Current.** A current which pulsates regularly in magnitude. As ordinarily employed, the term refers to unidirectional current.

3 **Continuous Current.** A practically non-pulsating direct current.

4 **Alternating Current.** A current which alternates regularly in direction. Unless distinctly otherwise specified, the term "alternating current" refers to a periodic current with successive half waves of the same shape and area.

5 **Oscillating Current.** A periodic current whose frequency is determined by the constants of the circuit or circuits.

6 **Cycle.** One complete set of positive and negative values of an alternating current.

7 **Electrical Degree.** The 360th part of a cycle.

8 **Period.** The time required for the current to pass through one cycle.

9 **Frequency.** The number of cycles or periods per second. The product of 2π by the frequency is called the *angular velocity* of the current.

10 **Root-Mean-Square** or **Effective Value.** The square root of the mean of the squares of the instantaneous values for one complete cycle. It is usually abbreviated r.m.s. Unless otherwise specified, the numerical value of an alternating current refers to its r.m.s. value. The r.m.s. value of a sinusoidal wave is equal to its maximum, or crest value, divided by $\sqrt{2}$. The word "virtual" is sometimes used in place of r.m.s., particularly in Great Britain.

11 **Wave-Form** or **Wave-Shape.** The shape of the curve obtained when the instantaneous values of an alternating current are plotted against time in rectangular co-ordinates. The distance along the time axis corresponding to one complete cycle of values is taken as 2π radians, or 360 degrees. Two alternating quantities are said to have the same wave-form when their ordinates of corresponding phase (see § 13) bear a constant ratio to each other. The wave-shape, as thus understood, is therefore independent of the frequency of the current and of the scale to which the curve is plotted.

12 **Simple Alternating or Sinusoidal Current.** One whose wave-shape is sinusoidal.

Alternating-current calculations are commonly based upon the assumption of sinusoidal currents and voltages.

13 **Phase.** The distance, usually in angular measure, of the base of any ordinate of an alternating wave from any chosen point on the time axis, is called the phase of this ordinate with respect to this point. In the case of a sinusoidal alternating quantity, the phase at any instant may be represented by the corresponding position of a line or *vector* revolving about a point with such an angular velocity ($\omega = 2\pi f$), that its projection at each instant upon a convenient reference line is proportional to the value of the quantity at that instant.

14 **Non-Sinusoidal Quantities.** Quantities that cannot be represented by vectors of constant length in a plane. The following definitions of phase, active component, reactive component, etc., are not in general applicable thereto. Certain "equivalent" values, as defined below, may, however, be used in many instances, for the purpose of approximate representation and calculation.

15 **Crest-Factor or Peak-Factor.** The ratio of the crest or maximum value to the r.m.s. value. The crest factor of a sine-wave is $\sqrt{2}$.

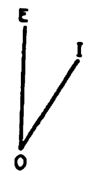
16 **Form Factor.** The ratio of the r.m.s. to the algebraic mean ordinate taken over a half-cycle beginning with the zero value. If the wave passes through zero more than twice during a single cycle, that zero shall be taken which gives the largest algebraic mean for the succeeding half-cycle. The form factor of a sine-wave is 1.11.

17 **The Distortion Factor of a wave.** The ratio of the r.m s. value of the first derivative of the wave with respect to time, to the r.m.s. value of the first derivative of the equivalent sine wave.

18 **Equivalent Sine Wave.** A sine wave which has the same frequency and the same r.m.s. value as the actual wave.

*19 **Phase Difference: Lead and Lag.** When corresponding cyclic values of two sinusoidal alternating quantities of the same frequency occur at different instants, the two quantities are said to differ in phase by the angle between their nearest corresponding values; *e.g.*, the phase angle between their nearest ascending zeros or between their nearest positive maxima. That quantity whose maximum value occurs first in time is said to lead the other, and the latter is said to lag behind the former.

*20 **Counter-Clockwise Convention.** It is recommended that in any vector diagram, the leading vector be drawn counter-clockwise with respect to the lagging vector, † as in the accompanying diagram, where OI represents the vector of a current in a simple alternating-current circuit, lagging behind the vector OE of impressed e.m.f.



*Note: Definitions 19, 20, 21, 22, 23, 24, 25 refer strictly only to cases where the voltage and current are both sinusoidal (see §11 and 12).

†See Publication of 12 the International Electrotechnical Commission (Report of Turin meeting, Sept. 1911, p. 78).

*21 **The Active or In-Phase Component** of the current in a circuit is that component which is in phase with the voltage across the circuit; similarly the active component of the voltage across a circuit is that component which is in phase with the current. The use of the term *energy component* for this quantity is disapproved.

*22 **Reactive or Quadrature Component** of the current in a circuit. That component which is in quadrature with the voltage across the circuit; similarly, the reactive component of the voltage across the circuit is that component which is in quadrature with the current. The use of the term *wattless component* for this quantity is disapproved.

*23 **Reactive Factor.** The sine of the angular phase difference between voltage and current; *i. e.*, the ratio of the reactive current or voltage to the total current or voltage.

*24 **Reactive Volt-Amperes.** The product of the reactive component of the voltage by the total current, or of the reactive component of the current by the total voltage.

*25 **Non-Inductive Load and Inductive Load.** A *non-inductive* load is a load in which the current is in phase with the voltage across the load. An *inductive* load is a load in which the current lags behind the voltage across the load. A *condensive* or *anti-inductive* load is one in which the current leads the voltage across the load.

26 **Power in an Alternating-Current Circuit.** The average value of the products of the coincident instantaneous values of the current and voltage for a complete cycle, as indicated by a wattmeter.

27 **Volt-Amperes or Apparent Power.** The product of the r.m.s. value of the voltage across a circuit by the r.m.s. value of the current in the circuit. This is ordinarily expressed in kv-a.

28 **Power Factor.** The ratio of the power (cyclic average as defined in §26) to the volt-amperes. In the case of sinusoidal current and voltage, the power factor is equal to the cosine of their difference in phase.

29 **Equivalent Phase Difference.** When the current and e.m.f. in a given circuit are non-sinusoidal, it is customary, for purposes of calculation, to take as the "equivalent" phase difference, the angle whose cosine is the power factor (see §28) of the circuit. There are cases, however, where this equivalent phase difference is misleading, since the presence of harmonics in the voltage wave, current wave, or in both, may reduce the power factor without producing a corresponding displacement of the two wave forms with respect to each other; *e.g.*, the case of an a-c. arc. In such cases, the components of the equivalent sine waves, the equivalent reactive factor and the equivalent reactive volt-amperes may have no physical significance.

30 **Single-Phase.** A term characterizing a circuit energized by a single alternating e.m.f. Such a circuit is usually supplied through

*Note: Definitions 19, 20, 21, 22, 23, 24, 25 refer strictly only to cases where the voltage and current are both sinusoidal (see §11 and 12).

two wires. The currents in these two wires, counted positively outwards from the source, differ in phase by 180 degrees or a half-cycle.

31 **Three-Phase.** A term characterizing the combination of three circuits energized by alternating e.m.f.'s. which differ in phase by one-third of a cycle; *i.e.*, 120 degrees.

32 **Quarter-Phase, also called Two-Phase.** A term characterizing the combination of two circuits energized by alternating e.m.f's. which differ in phase by a quarter of a cycle; *i.e.*, 90 degrees.

33 **Six-Phase.** A term characterizing the combination of six circuits energized by alternating e.m.f's. which differ in phase by one sixth of a cycle; *i.e.*, 60 degrees.

34 **Polyphase.** A general term applied to any system of more than a single phase. This term is ordinarily applied to symmetrical systems.

Per Cent Drop.

50 In electrical machinery, the ratio of the **internal resistance drop to** the terminal voltage, expressed in per cent, is called the "*per cent resistance drop.*"

51 Similarly the ratio of the **internal reactance drop** to the terminal voltage, expressed in per cent, is called the "*per cent reactance drop.*"

52 Similarly the ratio of the **internal impedance drop** to the terminal voltage, expressed in per cent, is called the "*per cent impedance drop.*"

Unless otherwise specified, these per cent drops shall be referred to rated load and rated power factor.

53 **In the case of transformers,** the per cent drop will be the sum of the primary drop (reduced to secondary turns) and the secondary drop, in per cent of secondary terminal voltage.

54 **In the case of induction motors,** it is advantageous to express the drops in per cent of the internally induced e.m.f.

55 **The Load Factor of a machine, plant or system.** The ratio of the average power to the maximum power during a certain period of time. The average power is taken over a certain period of time, such as a day, a month, or a year, and the maximum is taken as the average over a short interval of the maximum load within that period.

In each case, the interval of maximum load and the period over which the average is taken should be definitely specified, such as a "half-hour monthly" load-factor. The proper interval and period are usually dependent upon local conditions and upon the purpose for which the load factor is to be used.

56 **Plant Factor.** The ratio of the average load to the rated capacity of the power plant, *i.e.*, to the aggregate ratings of the generators.

57 **The Demand of an Installation or System** is the load which is drawn from the source of supply at the receiving terminals averaged over a suitable and specified interval of time. Demand is expressed in kilowatts, kilovolt-amperes, amperes, or other suitable units.

58 **The Maximum Demand of an Installation or System** is the greatest of all the demands which have occurred during a given period.

It is determined by measurement, according to specifications, over a prescribed time interval.

59 **Demand Factor.** The ratio of the maximum demand of any system or part of a system, to the total connected load of the system, or of the part of system under consideration.

60 **Diversity Factor.** The ratio of the sum of the maximum power demands of the subdivisions of any system or parts of a system to the maximum demand of the whole system or of the part of the system under consideration, measured at the point of supply.

61 **Connected Load.** The combined continuous rating of all the receiving apparatus on consumers' premises, connected to the system or part of the system under consideration.

62 **The Saturation Factor of a machine.** The ratio of a small percentage increase in field excitation to the corresponding percentage increase in voltage thereby produced. Unless otherwise specified, the saturation factor of a machine refers to the no-load excitation required at normal rated speed and voltage. It is determined from measurements of saturation made on open circuit at rated speed.

63 **The Percentage Saturation** of a machine at any excitation may be found from its saturation curve (generated voltage as ordinates, against excitation as abscissas), by drawing a tangent to the curve at the ordinate corresponding to the assigned excitation, and extending the tangent to intercept the axis of ordinates drawn through the origin. The ratio of the intercept on this axis to the ordinate at the assigned excitation, when expressed in percent, is the percentage saturation, and is independent of the scales selected for excitation and voltage. This ratio, as a fraction, is equal to the reciprocal of the saturation-factor at the same excitation, deducted from unity; or, if f be the saturation factor and p the percentage saturation,

$$p = 100\left(1 - \frac{1}{f}\right)$$

64 **Magnetic Degree.** The 360th part of the angle subtended, at the axis of a machine, by a pair of its field poles. One mechanical degree is thus equal to as many magnetic degrees as there are pairs of poles in the machine.

65 **The Variation in Prime Movers** which do not give an absolutely uniform rate of rotation or speed, as in reciprocating steam engines, is the maximum angular displacement in position of the revolving member expressed in degrees, from the position it would occupy with uniform rotation, and with one revolution taken as 360 degrees.

66 **The Variation in Alternators** or alternating-current circuits in general, is the maximum angular displacement, expressed in electrical degrees, (one cycle = 360 deg.) of corresponding ordinates of the voltage wave and of a wave of absolutely constant frequency equal to the average frequency of the alternator or circuit in question, and may be due to the variation of the prime mover.

67 **Relations of Variations in Prime Mover and Alternator.** If p is the number of pairs of poles, the variation of an alternator is p times the variation of its prime mover, if direct-connected, and pn times the variation of the prime mover if rigidly connected thereto in such a manner that the angular speed of the alternator is n times that of the prime mover.

68 **The Pulsation in a Prime Mover, or in the alternator connected thereto.** The ratio of the difference between the maximum and minimum velocities in an engine-cycle to the average velocity.

80 **Capacity.** The two different senses in which this word is used sometimes lead to ambiguity. It is therefore recommended that whenever such ambiguity is likely to arise, the descriptive term *power capacity* or *current capacity* be used, when referring to the power or current which a device can safely carry, and that the term "*Capacitance*" be used when referring to the electrostatic capacity of a device.

81 **Resistor.** A device, heretofore commonly known as a resistance, used for the operation, protection, or control of a circuit or circuits See **§ 740.**

82 **Reactor.** A coil, winding or conductor, heretofore commonly known as a reactance coil or choke coil, possessing inductance, the reactance of which is used for the operation, protection or control of a circuit or circuits. **See also § 214 and 736.**

83 **Efficiency.** The efficiency of an electrical machine or apparatus is the ratio of its useful output to its total input.

TABLE I.

90 **Symbols and Abbreviations.**

Name of Quantity.	Symbol for the Quantity.	Unit.	Abbreviation for the Unit.
Electromotive force, abbreviated e.m.f.	E, e	volt	....
Potential difference, abbreviated p.d.	V, v or E, e	"	....
Voltage	E, e or V, v	"	....
Current	I, i	ampere	....
Quantity of electricity	Q, q	coulomb, ampere-hour	....
Power	P, p	watt	....
Electrostatic flux	Ψ	....	....
Electrostatic flux density	D	....	....
Electrostatic field intensity	F		
Magnetic flux	Φ, φ	maxwell	....
Magnetic flux density	B, $\mathcal{B}$	gauss	....
Magnetic field intensity	H, $\mathcal{H}$	gilbert per centimeter or gauss†	gilbert per cm. ....

†The gauss is provisionally accepted for the present as the name of both the unit of field intensity and flux density, on the assumption that permeability is a simple numeric.

Magnetomotive force, abbreviated m.m.f.	$\mathfrak{F}$	gilbert*	....
Intensity of magnetization.	J	....	....
Susceptibility	$\kappa = J/H$	....	....
Permeability	$\mu = B/H$	....	....
Resistance	R, r	ohm	....
Reactance	X, x	"	....
Impedance	Z, z	"	....
Conductance	g	mho	....
Susceptance	b	"	....
Admittance	Y, y	"	....
Resistivity	ρ	† ohm-centimeter	ohm-cm.
Conductivity	γ	†mho per centimeter	mho per cm.
Dielectric constant	ϵ or k	....	....
Reluctance	$\mathfrak{R}$	....	....
Capacitance (Electrostatic capacity)	C	farad	....
Inductance (or coefficient of self induction)	L	henry	....
Mutual Inductance (or coefficient of mutual induction)	M	henry	....
Phase displacement	θ, φ	degree or radian	°
Frequency	f	cycle per second	~
Angular velocity	ω	radian per second	....
Velocity of rotation	n	revolution per second	rev. per sec.
Number of conductors or turns	N	convolution or turns of wire	
Temperature	T, t, θ	degree centigrade	C
Energy, in general	U or W	joule, watt-hour	....
Mechanical work	W or A	joule, watt-hour	....
Efficiency	η	per cent	....
Length	l	centimeter	cm.
Mass	m	gram	g.
Time	t	second	sec.

*An additional unit for m. m. f. is the "ampere-turn," for flux the "line," for magnetic flux-density "maxwells per sq. in."

†*Note.* The numerical values of these quantities are *ohms resistance* and *mhos conductance* between two opposite faces of a cm. cube of the material in question, but the correct names are as given, not ohms and mhos per cm. cube, as commonly stated

Acceleration due to gravity	g	centimeter per second per second	cm. per sec. per sec.
Standard acceleration due to gravity (at about 45 deg. latitude and sea level) equals 980.665†..................	g_o	centimeter per second per second	cm. per sec. per sec.

91 E_m, I_m and P_m should be used for maximum cyclic values, e, i and p for instantaneous values, E and I for r.m.s. values (see §10) and P for the average value of the power, or the active power. These distinctions are not necessary in dealing with continuous-current circuits. In print, vector quantities should be represented by bold-face capitals.

†This has been the accepted standard value for many years and was formerly considered to correspond accurately to 45° Latitude and sea level. Later researches, however, have shown that the most reliable value for 45° and sea-level is slightly different; but this does not affect the standard value given above.

CLASSIFICATION OF MACHINERY

100 The machinery under consideration in these rules may be classified in various ways, these various classifications overlapping or interlocking in considerable degree. Briefly, they are Direct-Current or Alternating-Current, Rotating or Stationary. Under Rotating Apparatus there are two principal classifications: *First,* according to the function of the machines; Motors, Generators. Boosters, Motor-Generators, Dynamotors, Double-Current Generators, Converters and Phase Advancers; *Second,* according to the type of construction or principle of operation; Commutating, Synchronous, Induction, Unipolar, Rectifying. Obviously, some of these machines could be rationally included in either classification, *e.g.*, Motor-Generators and Rectifying Machines.

In the following, self-evident definitions have for the most part, been omitted.

ROTATING MACHINES.

FUNCTIONAL CLASSIFICATION OF ROTATING MACHINES.

101 **Generator.** A machine which transforms mechanical power into electrical power.

102 **Motor.** A machine which transforms electrical power into mechanical power.

103 **Booster.** A generator inserted in series in a circuit to change its voltage. It may be driven by an electric motor (in which case it is termed a motor-booster) or otherwise.

104 **Motor-Generator Set.** A transforming device consisting of a motor mechanically coupled to one or more generators.

105 **Dynamotor.** A transforming device combining both motor and generator action in one magnetic field, either with two armatures, or with one armature having two separate windings and independent commutators.

106 A **Direct-Current Compensator** or **Balancer** comprises two or more similar direct-current machines (usually with shunt or compound excitation) directly coupled to each other and connected in series across the outer conductors of a multiple-wire system of distribution, for the purpose of maintaining the potentials of the intermediate wires of the system, which are connected to the junction points between the machines.

107 A **Double-Current Generator** supplies both direct and alternating currents from the same armature-winding.

108 A **Converter** is a machine employing mechanical rotation in changing electrical energy from one form into another. There are several types of converters as follow:

109 **A Direct-Current Converter** converts from a direct current to a direct current, usually with a change of voltage. Such a machine may be either a motor-generator set or a dynamotor.

110 **A Synchronous Converter** (sometimes called a Rotary Converter) converts from an alternating to a direct current, or vice-versa. It is a synchronous machine with a single closed-coil armature winding, a commutator and slip rings.

111 **A Cascade Converter,** also called a **Motor Converter,** is a combination of an induction motor with a synchronous converter, the secondary circuit of the former feeding directly into the armature of the latter; *i.e.*, it is a synchronous converter concatenated with an induction motor.

112 **A Frequency Converter** converts the power of an alternating-current system from one frequency to another, with or without a change in the number of phases, or in the voltage.

113 **A Rotary Phase-Converter** converts from an alternating-current system of one or more phases to an alternating-current system of a different number of phases, but of the same frequency.

114 **A Phase Advancer** is a machine which supplies reactive volt-amperes to the system to which it is connected. Phase advancers may be either synchronous or asynchronous.

115 **A Synchronous Condenser** or **Synchronous Phase Advancer** is a synchronous machine, running either idle or with load, the field excitation of which may be varied so as to modify the power-factor of the system, or through such modification to influence the load voltage.

CONSTRUCTIONAL CLASSIFICATION OF ROTATING MACHINES

Commutating Machines

130 **Direct-Current Commutating Machines** comprise a magnetic field of constant polarity, an armature, and a commutator connected therewith. These include: Direct-Current Generators; Direct-Current Motors; Direct-Current Boosters; Direct-Current Motor-Generator Sets and Dynamotors; Direct-Current Compensators or Balancers; and Arc Machines.

131 **Alternating-Current Commutating Machines*** comprise a magnetic field of alternating polarity, an armature, and commutator connected therewith.

132 **Synchronous Commutating Machines** include synchronous converters, cascade-converters, and double-current generators.

133 Synchronous **Machines** comprise a constant magnetic field and an armature receiving or delivering alternating-currents in

*A suggested classification of alternating-current commutator motors is given in the July 1916 PROCEEDINGS of the Institute synchronism with the motion of the machine; *i.e.*, having a frequency strictly proportional to the speed of the machine. They may be sub-divided as follow:

134 **An Alternator** is a synchronous alternating-current generator, either single-phase or polyphase.

135 **A Polyphase Alternator** is a polyphase synchronous alternating-current generator, as distinguished from **a single-phase alternator.**

136 **An Inductor Alternator** is an **Alternator** in which both field and armature windings are stationary, and in which masses of iron or inductors. by moving past the coils, alter the magnetic flux through them. It may be either single-phase or polyphase.

137 **A Synchronous Motor** is a machine structurally identical with an alternator, but operated as a motor.

138 **Induction Machines** include apparatus wherein primary and secondary windings rotate with respect to each other; *i.e.*, induction motors, induction generators, certain types of frequency converters and certain types of rotary phase-converters.

139 **An Induction Motor** is an alternating-current motor, either .singlephase or polyphase, comprising independent primary and secondary windings, one of which, usually the secondary, is on the rotating member. The secondary winding receives power from the primary by electromagnetic induction.

140 **An Induction Generator** is a machine structurally identical with an induction motor, but driven above synchronous speed as an alternating-current generator.

141 **Unipolar or Acyclic Machines** are direct-current machines, in which the voltage generated in the active conductors maintains the same direction with respect to those conductors.

SPEED CLASSIFICATION OF MOTORS.

150 **Motors** may, for convenience, be classified with reference to their speed characteristics as follow:

151 **Constant-Speed Motors,** whose speed is either constant or does not materially vary; such as synchronous motors, induction motors with small slip, and ordinary direct-current shunt motors.

152 **Multispeed Motors** (two-speed, three-speed, etc.), which can be operated at any one of several distinct speeds, these speeds being practically independent of the load; such as motors with two armature windings, or induction motors in which the number of poles is changed by external means.

153 **Adjustable-Speed Motors,** in which the speed can be varied gradually over a considerable range, but when once adjusted remains practically unaffected by the load; such as shunt motors designed for a considerable range of speed variation.

154 **Varying-Speed Motors,** or motors in which the speed varies with the load, ordinarily decreasing when the load increases; such as series motors, compound-wound motors, and series-shunt motors. As a sub-class of varying-speed motors, may be cited, **adjustable varying-speed motors,** or motors in which the speed can be varied over a considerable range at any given load, but when once adjusted, varies with the load; such as compound-wound motors arranged for adjustment of speed by varying the strength of the shunt field.

CLASSIFICATION OF ROTATING MACHINES RELATIVE TO THE DEGREE OF ENCLOSURE OR PROTECTION

160 The following types are recognized:

Open
Protected
Semi-enclosed
Enclosed
Separately ventilated
Water-cooled
Self-ventilated
Drip-proof
Moisture-resisting
Submersible
Explosion-proof
Explosion-proof slip-ring enclosure

161 An **"open" machine** is of either the pedestal-bearing or end-bracket type where there is no restriction to ventilation, other than that necessitated by good mechanical construction.

162 A **"protected" machine** is one in which the armature, field coils, and other live parts are protected mechanically from accidental or careless contact, while free ventilation is not materially obstructed.

163 A **"semi-enclosed" machine** is one in which the ventilating openings in the frame are protected with wire screen, expanded metal, or other suitable perforated covers, having apertures not exceeding ½ of a square inch (3.2 sq. cm.) in area.

164 An **" enclosed " machine** is so completely enclosed by integral or auxiliary covers as to prevent a circulation of air between the inside and outside of its case, but not sufficiently to be termed air-tight.

165 A **" separately ventilated " machine** has its ventilating air supplied by an independent fan or blower external to the machine.

166 A **" water-cooled " machine** is one which mainly depends on water circulation for the removal of its heat.

167 A **" self-ventilated " machine** differs from a separately ventilated machine only in having its ventilating air circulated by a fan, blower, or centrifugal device integral with the machine.

If the heated air expelled from the machine is conveyed away through a pipe attached to the machine, this should be so stated.

168 A **"drip-proof" machine** is one so protected as to exclude falling moisture or dirt. A "drip proof" machine may be either "open" or "semi-enclosed", if it is provided with suitable protection integral with the machine, or so enclosed as to exclude effectively falling solid or liquid material.

169 A **moisture-resisting machine** is one in which all parts are treated with moisture-resisting material. Such a machine shall be capable of operating continuously or intermittently in a very humid atmosphere, such as in mines, evaporating rooms, etc.

170 A **"submersible" machine** is a machine capable of withstanding complete submersion, in fresh water or sea water, as may be specified, for four hours without injury.

171 An **"explosion-proof" machine** is a machine in which the enclosing case can withstand, without injury, any explosion of gas that may occur within it, and will not transmit the flame to any inflammable gas outside it.

172 An induction motor in which the slip rings and brushes alone are included within an explosion-proof case should not be described as an explosion-proof machine, but as a machine **"with explosion-proof slip-ring enclosure."**

STATIONARY INDUCTION APPARATUS

200 **Stationary Induction Apparatus** changes electric energy to electric energy, through the medium of magnetic energy, without mechanical motion. It comprises several forms, distinguished as follow:

201 **Transformers**, in which the primary and secondary windings are ordinarily insulated one from another.

202 The terms **"high-voltage"** and **"low-voltage"** are used to distinguish the winding having the greater from that having the lesser number of turns. The terms **"primary"** and **"secondary"** serve to distinguish the windings in regard to energy flow, the primary being that which receives the energy from the supply circuit, and the secondary that which receives the energy by induction from the primary.

203 The **rated current of a constant-potential transformer** is that secondary current which, multiplied by the rated-load secondary voltage, gives the kv-a. rated output. That is, a transformer of given kv-a. rating must be capable of delivering the rated output at rated secondary voltage, while the primary impressed voltage is increased to whatever value is necessary to give rated secondary voltage.

The **Rated Primary Voltage** of a constant-potential transformer is the rated secondary voltage multiplied by the turn ratio.

204 The **ratio of a transformer,** unless otherwise specified, shall be the ratio of the number of turns in the high-voltage winding to that in the low-voltage winding; *i.e.*, the **"turn-ratio"**

205 The **voltage ratio** of a transformer is the ratio of the r.m.s. primary terminal voltage to the r.m.s. secondary terminal voltage, under specified conditions of load.

206 The "**current ratio**" of a current-transformer is the ratio of r.m.s. primary current to r.m.s. secondary current, under specified conditions of load.

207 The "**marked ratio**" of an instrument transformer is the ratio which the apparatus is designed to give under average conditions of use. When a precise ratio is required, it is necessary to specify the voltage, frequency, load and power factor of the load.

208 **Volt-Ampere Ratio of Transformers.**

The volt-ampere ratio, which should not be confused with real efficiency, is the ratio of the volt-ampere output to the volt-ampere input of a transformer, at any given power factor.

209 **Auto-transformers** have a part of their turns common to both primary and secondary circuits.

210 **Voltage Regulators** have turns in shunt and turns in series with the circuit, so arranged that the voltage ratio of the transformation or the phase relation between the circuit-voltages is variable at will They are of the following three classes:

211 **Contact Voltage Regulators,** in which the number of turns in one or both of the coils is adjustable.

212 **Induction Voltage Regulators,** in which the relative positions of the primary and secondary coils are adjustable.

213 **Magneto Voltage Regulators,** in which the direction of the magnetic flux with respect to the coils is adjustable.

214 **Reactors,** heretofore commonly called **Reactance Coils,** also called **Choke Coils**; a form of stationary induction apparatus used to supply reactance or to produce phase displacement. **See also §82 and 736.**

METERS AND INSTRUMENTS

225 Although the terms **Instruments** and **Meters** are frequently used synonymously in referring to electrical measuring devices, the meter departments of manufacturing and operating companies commonly use the word "meters" in the collective sense to designate only those devices which register the total energy or quantity of electricity consumed in or supplied to a circuit, and reserve the term "instruments," in the collective sense, for all other electrical measuring or indicating devices.

226 In general, the names of meters and instruments are self-defining, particularly when considered in connection with existing definitions. The following terms are preferred to other terms sometimes used for the same devices: **Reactive-Factor Meter, Power-Factor Meter, Watt-hour Meter,** etc.

227 **Crest Voltmeter.** A voltmeter depending for its indications upon the crest, that is the maximum value of the voltage of the system to which it is connected. These instruments are so calibrated that they indicate the r. m. s. value of the sinusoidal voltage having the same crest value.

228 **Synchronoscope** (also called a Synchroscope or Synchronism Indicator). A device which in addition to indicating synchronism between two machines, shows whether the speed of the incoming machine is fast or slow.

229 **Reactive-Volt-Ammeter** (also called a Reactive-Volt-Ampere Indicator). An instrument which indicates the reactive volt-amperes of the circuit to which it is connected.

230 **Line Drop Voltmeter Compensator.** A device used in connection with a voltmeter which causes it to indicate the voltage at some distant point of the circuit.

231 **Recording Ammeters, Voltmeters, Wattmeters, etc.,** are instruments which record graphically upon time-charts the values of the quantities they measure.

232 A **Demand Meter** is a device which indicates or records the demand or maximum demand (See §§**57** and **58**). In practice two types are recognized:

233 An **Integrated-Demand Meter** is one which indicates or records the maximum demand obtained through integration.

234 A **Lagged-Demand Meter** is one in which the indication of maximum demand is subject to a characteristic time lag.

235 **Errors of Indicating Instruments.** In specifying the accuracy of an indicating instrument, the error at any point on the scale shall be expressed as a percentage of the full scale reading.

236 **Torque** of meters and instruments shall be expressed in millimeter-grams.

STANDARDS FOR ELECTRICAL MACHINERY

250 *The expressions " machinery " and " machines " are here employed in a general sense, in order to obviate the constant repetition of the words " machinery or induction apparatus."*

251 *All temperatures are to be understood as centigrade.*

252 *The expression " capacity " is to be understood as indicating " capability ", except where specifically qualified, as, for instance, in the case of allusions to electrostatic capacity, i. e., capacitance.*

253 *Wherever special rules are given for any particular type of machinery or apparatus (such as switches, railway motors, railway substation machinery, etc., these special rules shall be followed, notwithstanding any apparent conflict with the provisions of the more general sections. In the absence of special rules on any particular point, the general rules on this point shall be followed.*

260 **Objects of Standardization.** To ensure satisfactory results, electrical machinery should be specified to conform to the Institute Standardization Rules, in order that it shall comply, in operation, with approved limitations in the following respects, so far as they are applicable.

Operating temperature
Mechanical strength
Commutation
Dielectric strength
Insulation resistance
Efficiency
Power factor
Wave shape
Regulation

261 **Capacity or Available Output of an Electrical Machine.** So far as relates to the purposes of these Standardization Rules, the Institute defines the Capacity of an Electrical Machine as the load which it is capable of carrying for a specified time (or continuously), without exceeding in any respect the limitations herein set forth.

Except where otherwise specified, the capacity of an electrical machine shall be expressed in terms of its available *output.* For exceptions see **§277** and **302.**

262 **Rating of an Electrical Machine.** Capacity should be distinguished from Rating. The Rating of a machine is the output marked on the Rating Plate, and shall be based on, but shall not exceed, the maximum* load which can be taken from the machine under prescribed conditions of test. This is also called the rated output.

*The term "maximum Load" does not refer to loads applied solely for mechanical commutation, or similar tests.

263 **The Principle upon which Machine Ratings** are based, so far as relates to thermal characteristics, is that the rated load, applied continuously or for a stated period, shall produce a temperature rise which, superimposed upon a standard ambient temperature, will not exceed the maximum safe operating temperature of the insulation.

264 **A. I. E. E. and I. E. C. Ratings.** When the prescribed conditions of test are those of the A. I. E. E. Standardization Rules, the rating of the machine is the Institute Rating. (See **§620**). When the prescribed conditions of the test are those of the I. E. C.† Rules, the rating of the machine is the I. E. C. rating. A machine so rated in either case may bear a distinctive sign upon its rating plate.

265 **Standard Temperature and Barometric Pressure for Institute Rating.** The Institute Rating (See §262) of a machine shall be its capacity when operating with a cooling medium of the ambient temperature of reference (40° for air or 25° for water, see **§305** and **309**) and with barometric conditions within the range given in §308. See §§**305A**, **307**, **320** and **321**.

266 **The Temperature Rises Specified in these Rules** apply to all ambient temperatures up to and including, but not exceeding, 40°C. for air and 25°C. for water. (For definition of ambient temperature see **§303**.)

267 **Any Machinery Destined for Use with Higher Ambient** temperatures of cooling mediums, and also any machinery for operation at altitudes for which no provision is made in **§308**, should be the subject of special guarantee by the manufacturer. The methods of test and performance set forth in these Rules will, however, afford guidance in such cases.

UNITS IN WHICH RATING SHALL BE EXPRESSED

274 The rating of **Direct-Current Generators**, shall be expressed in kilowatts (kw.) available at the terminals at a specified voltage.

275 The rating of **Alternators** and **Transformers**, shall be expressed in kilovolt-amperes (kv-a.) available at the output terminals, at a specified voltage and power factor.

276 It is strongly recommended that the **rating of motors** shall be expressed in kilowatts* (kw.) available at the shaft. (An ex-

†I.E.C. stands for "International Electrotechnical Commission. This rating has not yet been established.

*Since the input of machinery of this class is measured in electrical units and since the output has a definite relation to the input, it is logical and desirable to measure the delivered power in the same units as are employed for the received power. Therefore, the output of motors should be expressed in kilowatts instead of in horse power. However, on account of the hitherto prevailing practice of expressing mechanical output in horse power, it is recommended that for machinery of this class the rating should, for the present, be expressed both in kilowatts and in horse power; as follows:

kw.———— approx. equiv. h.p.————

For the purposes of these Rules the horse-power shall be taken as 746.0 watts. In order to lay stress upon the preferred future basis, it is desirable that on Rating plates, the Rating in kilowatts shall be shown in larger and more prominent characters than the rating in horse power.

ception to this rule is made in the case of Railway motors, which, for some purposes, are also rated by their *input*, see **§802.**)

277 **Auxiliary machinery,** such as regulators, resistors, reactors, balancer sets, stationary and synchronous condensers, etc., shall have their ratings appropriately expressed. It is essential to specify also the voltage (and frequency, if a-c.,), of the circuits on which the machinery may appropriately be used.

KINDS OF RATING

There are various kinds of rating such as:

281 **Continuous Rating.** A machine rated for continuous service shall be able to operate continuously at its rated output, without exceeding any of the limitations referred to in **§260.**

282 **Short-Time Rating.** A machine rated for short-time service; (*i.e.* service including runs alternating with stops of sufficient duration to ensure substantial cooling), shall be able to operate at its rated output during a limited period, to be specified in each case, without exceeding any of the limitations referred to in **§260.** Such a rating is a **short-time rating.**

283 **Nominal Ratings.** For railway motors and sometimes for railway substation machinery, certain nominal ratings are employed. See **§§765** and **800.** Nominal ratings for automobile propulsion motors and generators are not recommended; see **§837.**

284 **Duty-Cycle Operation.** Many machines are operated on a cycle of duty which repeats itself with more or less regularity. For purposes of rating, either a continuous or a short-time equivalent load, may be selected, which shall simulate as nearly as possible the thermal conditions of the actual duty cycle.

285 **Standard durations of equivalent tests** shall be for machines operating under specified duty-cycles as follow (see also **§836**):

5 minutes
10 "
15 "
30 "
60 "
120 "
and continuous.

Of these the first six are short-time ratings, selected as being thermally equivalent to the specified duty cycle.

When, for example, a short-time rating of 10 minutes duration is adopted, and the thermally equivalent load is 25 kw. for that period, then such a machine shall be stated to have a 10-minute rating of 25 kw.

286 In every case the equivalent short-time test shall commence only when the windings and other parts of the machine are **within 5°C of the ambient temperature** at the time of starting the test.

287 In the absence of any specification as to the kind of rating, the continuous rating shall be understood.*

*An exception is made in the case of motors for railway service, where in the absence of any specification as to the kind of rating, the "**nominal rating**" as defined in §319 and 415 shall be understood.

288 Machines marked in accordance with **§264** shall be understood to have a continuous rating, unless otherwise marked in accordance with **§285**.

HEATING AND TEMPERATURE

300 **Temperature Limitations of the Capacity of Electrical Machinery.** The capacity, so far as relates to temperature, is usually limited by the maximum temperature at which the materials in the machine, especially those employed for insulation, may be operated for long periods without deterioration. When the safe limits are exceeded, deterioration is rapid. The insulating material becomes permanently damaged by excessive temperature, the damage increasing with the length of time that the excessive temperature is maintained, and with the amount of excess temperature, until finally the insulation breaks down.

301 The result of operating at temperatures in excess of the safe limit is to shorten the life of the insulating material. This shortening of life is, in certain special cases, warranted, when necessary for obtaining some other desirable result, as, for example, in some instances of railway and other motors for propelling vehicles, in providing greater power within a limited space. See **§304**. Further instances may also be noted in the cases of contactors, controllers, induction-starters, arc-lamp-magnet windings, etc., designed and constructed for operation at relatively high temperatures.

302 There does not appear to be any advantage in operating at lower temperatures than the safe limits, so far as the life of the insulation is concerned. Insulation may break down from various causes, and when these breakdowns occur, it is not usually due to the temperature at which the insulation has been operated, provided the safe limits have not been exceeded.

303 **The Ambient Temperature** is the temperature of the air or water which, coming into contact with the heated parts of a machine, carries off its heat. See **§§309, 310** and **314.**

304 **The cooling fluid may** either be led to the machine through ducts, or through pipes, or merely surround the machine freely. In the former case the ambient temperature is to be measured at the intake of the machine itself. In the latter case see **§314.**

305 **Ambient Temperature of Reference for Air.** The standard ambient temperature of reference, when the cooling medium is air, shall be 40°C.

305A. **Whatever may be the Ambient Temperature** when the machine is in service, the limits of the maximum observable temperature or of temperature rise specified in the rules should not be exceeded in service; for, if the maximum temperature be exceeded, the insulation may be endangered, and if the rise be exceeded, the excess load may lead to injury, by exceeding limits other than those of temperature; such as commutation, stalling load and mechanical strength. For similar reasons, loads in excess of the rating should not be taken from a machine.

306 The permissible rises in temperature given in column 2 of table III page 38 have been calculated on the basis of the standard ambient temperature of reference, by subtracting 40° from the highest temperatures permissible, which are given in column 1 of the same table.

307 A machine may be tested at any convenient ambient temperature, preferably not below 15°C., but *whatever be the value of this ambient temperature, the permissible rises of temperature must not exceed those given in column 2 of table III page* 38.

308 **Altitude.** Increased altitude has the effect of increasing the temperature rise of some types of machinery. In the absence of information in regard to the height above sea level at which a machine is intended to work in ordinary service, this height is assumed not to exceed 1000 meters (3300 feet.) For machinery operating at an altitude of 1000 meters or less, a test at any altitude less than 1000 meters is satisfactory, and no correction shall be applied to the observed temperatures. Machines intended for operation at higher altitudes shall be regarded as special. See **§267.** It is recommended that when a machine is intended for service at altitudes above 1000 meters (3300 ft.) the permissible temperature rise at sea level, until more nearly accurate information is available, shall be reduced by 1 per cent for each 100 meters (330 ft.) by which the altitude exceeds 1000 meters. Water cooled oil transformers are exempt from this reduction.

309 **Ambient Temperature of Reference for Water-Cooled Machinery.** For water-cooled machinery, the standard temperature of reference for incoming cooling water shall be 25° C, measured at the intake of the machine.

310 **In the testing of water-cooled transformers,** it is not necessary to take into account the surrounding-air temperature, except where the cooling effect of the air is 15 per cent or more of the total cooling effect, referred to the standard ambient temperature of reference of 25°C. for water and 40°C. for air. When the effect of the cooling air is 15 per cent. or more of the total, the temperature of the cooling water should be maintained within 5°C. of the surrounding air. Where this is impractical, the ambient temperature should be determined from the change in the resistance of the windings, using a disconnected transformer, supplied with the normal amount of cooling water, until the temperature of the windings has become constant.

311 **In the case of rotating machines,** cooled by forced draught, a conventional weighted mean shall be employed, a weight of four being given to the temperature of the circulating air supplied through ducts (see **§304**), and a weight of one to the surrounding room air. **In the case of air-cooled transformers,** see "exception" **§321.**

312 **Machines Cooled by Other Means.** Machines cooled by means other than air or water shall receive special consideration.

313 **Outdoor Machinery Exposed to Sun's Rays.** Outdoor machinery not protected from the sun's rays at times of heavy load, shall receive special consideration.

314 **Measurement of the Ambient Temperature During Tests of Machinery.** The ambient temperature is to be measured by means of several thermometers placed at diffe ent points around and half-way up the machine, at a distance of 1 to 2 meters (3 to 6 feet), and protected from **drafts**, and abnormal heat radiation, preferably as in **§316**.

315 The value to be adopted for the ambient temperature during a test, is the mean of the readings of the thermometers (placed as above), taken at equal intervals of time during the last quarter of the duration of the test.

316 Inorder to avoid **errors due to the time lag** between the temperature of large machines and the variations in the ambient air, all reasonable precautions must be taken to reduce these variations and the errors arising therefrom. Thus, the thermometer for determining the ambient temperature shall be immersed in a suitable liquid, such as oil, in a suitable heavy metal cup. This can be made to respond to various rates of change, by proportioning the amount of oil to the metal in the containing cup. A convenient form for such an oil-cup consists of a massive metal cylinder, with a hole drilled partly through it. This hole is filled with oil and the thermometer is placed therein with its bulb well immersed. The larger the machine under test, the larger should be the metal cylinder employed as an oil-cup in the determination of the ambient temperature. The smallest size of oil cup employed in any case shall consist of a metal cylinder 25 mm. in diameter and 50 mm. high (1 in. in diameter and 2 in. high).

317 **Thermometers used for taking temperatures of Machinery** shall be covered by felt pads 3 mm. (⅛ inch) thick and 4 x 5 cm. wide (1½"x 2"), cemented on; oil putty may be used for stationary and small apparatus.

318 **In Transformer Testing,** and sometimes in testing other machines, it may be desirable to avoid errors due to time lag in temperature changes, by employing an idle unit of the same size and subjected to the same conditions of cooling as the unit under test, for obtaining the ambient temperature as described in **§310**.

319 Where **machines are partly below the floor line** in pits, the temperature of the rotor shall be referred to a weighted mean of the pit and room temperatures, the weight of each being based on the relative proportions of the rotor in and above the pit. Parts of the stator constantly in the pit shall be referred to the ambient temperature in the pit.

320 **Correction for the Deviation of the Ambient Temperature of the Cooling Medium, at the Time of the Heat Test, from the Standard Ambient Temperature of Reference.** Numerous experiments have shown that deviation of the temperature of the cooling medium from that of the standard of reference, at the time of the heat run, has a negligible effect upon the temperature rise of the apparatus; therefore, no correction shall be applied for this deviation. It is, however, desirable that tests should be conducted at ambient temperatures not lower than 15°C.

321 *Exception*—**A Correction shall be applied** to the observed temperature rise of the windings of *Air-blast transformers*, due to difference in resistance, when the temperature of the ingoing cooling air differs from that of the standard of reference. This correction shall be the ratio of the inferred absolute ambient temperature of reference to the inferred absolute temperature of the ingoing cooling air, *i. e.* the ratio $274.5/(234.5 + t)$; where t is the ingoing cooling-air temperature.

Thus, a cooling-air room temperature of 30°C. would correspond to an inferred absolute temperature of 264.5° on the scale of copper resistivity, and the correction to 40°C. (274.5° inferred absolute temperature) would be $274.5 \ / \ 264.5 = 1.04$, making the correction factor 1.04; so that an observed temperature rise of say 50°C. at the testing ambient temperature of 30°C. would be corrected to $50 \times 1.04 = 52$°C. this being the temperature rise which would have occurred had the test been made with the standard ingoing cooling-air temperature of 40°C.

322 **Duration of Temperature Test of Machine for Continuous Service.** The temperature test shall be continued until sufficient evidence is available to show that the maximum temperature and temperature rise would not exceed the requirements of the rules, if the test were prolonged until a steady final temperature was reached.

323 **Duration of Temperature Test of Machine with a Short-Time Rating.** The duration of the temperature test of a machine with a short-time rating shall be the time required by the rating. (See **§285** and **286**).

324 **Duration of Temperature Test for Machine having more than One Rating.** The duration of the temperature test for a machine with more than one rating shall be the time required by that rating which produces the greatest temperature rise. In cases where this cannot be determined beforehand, the machine shall be tested separately under each rating.

325 **Temperature Measurements during Heat Run.** Temperature measurements, when possible, shall be taken during operation, as well as when the machine is stopped. The highest figures thus obtained shall be adopted. In order to abridge the long heating period, in the case of large machines, reasonable overloads of current, during the preliminary period, are suggested for them.

TEMPERATURE MEASUREMENTS

340 **The Life of the Insulation of a Machine** depends in great measure upon the actual temperatures attained by the different parts, rather than on the rises of temperature in those parts.

341 **The Temperatures in the Different Parts of a Machine** which it would be desirable to ascertain, are the maximum temperatures reached in those parts.

343 **As it is Usually Impossible to Determine the Maximum Temperature** attained in insulated windings, it is convenient to apply a correction to the observable temperature, which approximates the difference between the actual maximum temperature and the observable temperature by the method used. This correction, or margin of security, is provided to cover the errors due to fallibility in the location of the measuring devices, as well as inherent inaccuracies in measurement and methods.

344 **In Determining the Temperature of Different Parts of a Machine** three methods are provided.

345 **Method No 1. Thermometer Method.**
This method consists in the determination of the temperature, by mercury or alcohol thermometers, by resistance thermometers, or by thermocouples, any of these instruments being applied to the hottest accessible part of the *completed* machine, as distinguished from the thermocouples or resistance coils embedded in the machine as described under Method No. 3.

346 **When Method No. 1 is Used,** the hottest-spot temperature for windings shall be estimated by adding a hottest-spot correction of 15°C to the highest temperature observed, in order to allow for the practical impossibility of locating any of the thermometers at the hottest spot.

347 *Exception.* When the thermometers are applied directly to the surfaces of bare windings, such as an edgewise strip conductor, or a cast copper winding, a hottest-spot correction of 5°C, instead of 15°C, shall be made. For commutators, collector rings, bare metallic surfaces not forming part of a winding, or for oil in which apparatus is immersed, no correction is to be applied.

348 **Method No. 2. Resistance Method.**
This method consists in the measurement of the temperature of windings by their increase in resistance, corrected* to the instant of shut-down when necessary. In the application of this method, *thermometer measurements shall also be made* whenever practicable without disassembling the machine† in order to increase the probability of revealing the highest observable temperature. Whichever measurement yields the higher temperature, that temperature

*Whenever a sufficient time has elapsed between the instant of shut-down and the time of the final temperature measurement to permit the temperature to fall, suitable corrections shall be applied, so as to obtain as nearly as practicable the temperature at the instant of shut-down. This can sometimes be approximately effected by plotting a curve, with temperature readings as ordinates and times as abscissas, and extrapolating back to the instant of shut-down. In other instances, acceptable correction factors can be applied. In transformers of 200 kv-a. and less the measured temperature shall be increased one degree for every minute between the instant of shut-down and the time of the final temperature measurement, provided this time does not exceed three minutes.

In cases where successive measurements show *increasing* temperatures after shutdown, the highest value shall be taken.

†As one of the few instances in which the thermometer check cannot be applied in Method No. 2, the rotor of a turbo-alternator may be cited.

shall be taken as the " highest observable " temperature and a hot-test-spot correction of 10°C added thereto.

349 **The Temperature Coefficient of Copper** shall be deduced from the formula $1/(234.5 + t)$. Thus, at an initial temperature $t = 40°C.$, the temperature co-efficient of increase in resistance per degree centigrade rise, is $1/(274.5) = 0.00364$. The following table, deduced from the formula, is given for convenience of reference.

TABLE II.

Temperature Coefficients of Copper Resistance.

Temperature of the winding, in degrees C. at which the initial resistance is measured.	Increase in resistance of copper per °C., per ohm of initial resistance.
0	0.00 427
5	0.00 418
10	0.00 409
15	0.00 401
20	0.00 393
25	0.00 385
30	0.00 378
35	0.00 371
40	0.00 364

350 **In Circuits of Low Resistance,** other than transformer windings (see **§351**), where joints and connections form a considerable part of the total resistance, the measurement of temperature by the resistance method shall not be used.

351 **The Temperature of the Windings of Transformers** is always to be ascertained by Method 2. In the case of air-blast transformers, it is especially important to place thermometers on the coils near the air outlet. See **§348.**

352 **Method No. 3. Embedded Temperature-Detector Method.**

This method consists in the use of thermo-couples or resistance temperature detectors, located as nearly as possible at the estimated hottest spot. When method No. 3 is used, it shall, when required, be checked by method No. 2; the hottest spot shall then be taken to be the highest value by either method, the required correction factors (**§348** and **§356**) being applied in each case.

353 **By Building into the Machine** suitably placed temperature detectors, a temperature not much less than that of the hottest spot will probably be disclosed. When these devices are adopted for such

temperature determinations, a liberal number shall be employed, and all reasonable efforts, consistent with safety, shall be made to locate them at the various places where the highest temperatures are likely to occur.

354 **Temperature-Detectors** should be placed in at least two sets of locations. One of these should be between a coil-side* and the core and one between the top and bottom coil-sides where two coil-sides per slot are used. Where only one coil-side per slot is used, one set of detectors shall be placed between coil-side and core, and one set between coil-side and wedge.

355 Method No. 3 should be applied to all stators of machines with cores having a width of 50 cm. (20 in.) and over. It should also be applied to all machines of 5000 volts and over, if of over 500 kv-a., regardless of core width. This method is not required for induction-regulators, which shall be tested as transformers.

356 **Correction Factor for Method No. 3.**—In the case of two-layer windings, with detectors between coil-sides, and between coil-side and core, add 5° C to the highest reading. In single-layer windings, with detectors between coil-side and core and between coil-side and wedge, add to the highest reading 10° C. plus 1° C. per 1000 volts above 5000 volts of terminal pressure.

TEMPERATURE LIMITS

375 Table III, page 38, gives the limits for the hottest-spot temperatures of insulations. The permissible limits are indicated in column 1 of the Table. The limits of temperature rise permitted under rated-load conditions are given in column 2, and are found by subtracting 40° C. from the figures in column 1. Whatever be the ambient temperature at the time of the test, the rise of temperature must never exceed the limits in column 2 of the table. The highest temperatures, and temperature rises, attained in any machine at the output for which it is rated, must not exceed the values indicated in the Table and clauses following.

376 **Permissible Temperatures and Temperature Rises For Insulating Materials.** Table III (see next page) gives the highest temperatures and temperature rises to which various classes of insulating materials may be subjected, based on a standard ambient temperature of reference of 40°C.

377 NOTE. The Institute recognizes the ability of manufacturers to employ Class B insulation successfully at maximum temperatures of 150° C. and even higher. However, as sufficient data covering experience over a period of years at such temperatures are at present unavailable, the Institute adopts 125° C as a conservative limit for this class of insulation, and any increase above this figure should be the subject of special guarantee by the manufacturer.

*A coil side is one of the two active sides of the coil lying in a slot.

TABLE III.

Permissible Temperatures and Temperature Rises for Insulating Materials.

Class	Description of Material	1 Maximum Temperature to which the material may be subjected	2 Maximum Temperature Rise
A.	Cotton, silk, paper and similar materials, when so treated or impregnated as to increase the thermal limit, or when permanently immersed in oil; also enamelled wire*	105°C	65°C
B.	Mica, asbestos and other materials capable of resisting high temperatures, in which any Class A. material or binder is used for structural purposes only, and may be destroyed without impairing† the insulating or mechanical qualities of the insulation	125°C	85°C
C.	Fireproof and refractory materials, such as pure mica, porcelain, quartz, etc.	No limits specified.	

*For cotton, silk, paper and similar materials, when neither treated, impregnated nor immersed in oil, the highest temperatures and temperature rises shall be 10°C below the limits fixed for Class A, in Table III.

†The word impair is here used in the sense of causing any change which would disqualify the insulation for continuous service.

378 When a lower-temperature class material is comprised in a completed product to such an extent, or in such ways, that its subjection to the temperature limits allowed for the higher-temperature class material, with which it is associated, would affect the integrity of the insulation either mechanically or electrically, the permissible temperature shall be fixed at such a value as shall afford ample assurance that no part of the lower-temperature class material shall be subjected to temperatures higher than those approved by the Institute and set forth above.

379

TABLE IV

Permissible Hottest Spot Temperatures and Limiting Observable Temperature Rises in Other than Water-Cooled Machinery

Method		Class	A*	B
		Permissible Hottest-Spot Temperature....	105°	125°
METHOD I Thermometer only See §345 to 347		Hottest Spot Correction..................	15°	15°
		Limiting Observable Temperature.........	90°	110°
		Limiting Observable Temperature Rise	50°	70°
METHOD II Resistance See §348		Hottest Spot Correction..................	10°	10°
		Limiting Observable Temperature.........	95°	115°
		Limiting Observable Temperature Rise	55°	75°
METHOD III Embedded Temperature Detectors See § 352 to §356	Double-Layer Windings. For all Voltages	Hottest Spot Correction.......	5°	5°
		Limiting Observable Temperature..................	100°	120°
		Limiting Observable Temperature Rise........	60°	80°
	Single-Layer Windings. For 5000 volts or less	Hottest Spot Correction.......	10°	10°
		Limiting Observable Temperature..................	95°	115°
		Limiting Observable Temperature Rise....	55°	75°
	Single-Layer Windings. For more than 5000 Volts	Hottest Spot Correction	10° + (*E*−5) †	10° + (*E*−5)
		Limiting Observable Temperature..................	95° − (*E*−5)	115° − (*E*−5)
		Limiting Observable Temperature Rise	55° − (*E*−5)	75° − (*E*−5)

*For cotton, silk, paper and similar materials, when neither treated, impregnated nor immersed in oil, the highest temperatures and temperature rises shall be 10°C. below the limits fixed for class A.

†In these formulas, *E* represents the rated pressure between terminals in kilovolts. Thus for a three-phase machine with single-layer winding, and with 11 kilovolts between terminals, the hottest-spot correction to be added to the maximum observable temperature will be 16°C.

Special Cases of Temperature limits.

385 **Temperature of Oil.** The oil in which apparatus is permanently immersed shall in no part have a temperature, observable by thermometer, in excess of 90°C.

386 **Water-Cooled Transformers.** In these the hottest-spot temperature shall not exceed 90°C.

386A **Enclosed Motors and Generators.** In an enclosed machine (see §**164**) the limiting observable temperature and the limiting observable temperature rise shall be taken as 5°C. higher than in Table IV. This is not to be interpreted as an increase in the permissible hottest spot temperature, but is in recognition of the lesser difference between the hottest spot temperature and the observable temperature within an enclosed machine. This rule does not apply to those types of machines defined in §§**163, 165** and **167**.

387 **Railway Motor Temperature Limits, see §804** and **805**.

387A. **Automobile Propulsion Motors and Generators, see §838.**

388 **Squirrel-Cage and Amortisseur Windings.** In many cases the insulation of such windings is largely for the purpose of making the conductors fit tightly in their slots, and the slightest effective insulation is ample. In other cases, there is practically no insulating material on the windings. Consequently, the temperature rise may be of any value such as will not occasion mechanical injury to the machine.

389 **Collector Rings.** The temperature of collector rings shall not be permitted to exceed the " hottest-spot " values set forth in §**376** and **379** for the insulations employed either in the collector rings themselves, or in adjacent insulations whose life would be affected by the heat from the collector rings.

390 **Commutators.** The observable temperature shall in no case be permitted to exceed the values given in §**376** and **379** for the insulation employed, either in the commutator or in any insulation whose life would be affected by the heat of the commutator. These temperature limits are intended only to protect the insulation of the commutator and of the adjacent parts, and are not intended as a criterion of successful commutation. See §**402**.

391 **Cores.** The temperature of those parts of the iron core in contact with insulating materials must not be such as to occasion in those insulating materials temperatures or temperature rises in excess of those set forth in §**376** and **379**.

392 **Other parts,** (such as brush-holders, brushes, bearings, pole-tips, cores, etc.) All parts of electrical machinery other than those whose temperature affects the temperature of the insulating material, may be operated at such temperatures as shall not be injurious in any other respect.

METHODS OF LOADING TRANSFORMERS FOR TEMPERATURE TESTS

393 Whenever practicable, transformers should be tested under conditions that will give losses approximating as nearly as possible to those obtained under normal or specified load conditions, maintained for the required time (See §**322** to **324**). The maximum temperature rises measured during this test should be considered as the observable temperature rises for the given load.

An approved method of making these tests is the "**loading-back**" method. The principal variations of this method are:

394 **With duplicate single-phase transformers.**

Duplicate single-phase transformers may be tested in banks of two, with both primary and secondary windings connected in parallel. Normal magnetizing voltage should then be applied and the required current circulated from an auxiliary source. One transformer can be held under normal voltage and current conditions, while the other may be operating under slightly abnormal conditions.

395 **With one three-phase transformer.**

One three-phase transformer may be tested in a manner similar to §**394** provided the primary and secondary windings are each connected in delta for the test. Normal three-phase magnetizing voltage should be applied and the required current circulated from an auxiliary single-phase source.

396 **With three single-phase transformers.**

Duplicate single-phase transformers may be tested in banks of three, in a manner similar to §**395** by connecting both primary and secondary windings in delta, and applying normal three-phase magnetizing voltage and circulating the required current from an auxiliary single-phase source.

397 NOTE:— Among other methods that have a limited application and can be used only under special conditions may be mentioned—

(1) Applying dead load by means of some form of rheostat.

(2) Running alternately for certain short intervals of time on open circuit and then on short circuit, alternating in this way until the transformer reaches steady temperature. In this test, the voltage for the open-circuit interval and the current for the short-circuit interval shall be such as to give the same integrated core loss, and the same integrated copper loss, as in normal operation.

ADDITIONAL REQUIREMENTS

398 **Short-Circuit Stresses.**

The Institute recognizes the self-destructibility, both mechanical and thermal, of certain sizes and types of machines, when subjected to severe short-circuits, and recommends that ample protection be provided in such cases, external to the machine if necessary.

Over-Speeds.

399 **All Types of Rotating Machines** shall be so constructed that they will safely withstand an over-speed of 25 per cent, except in the case of steam turbines, which, when equipped with emergency governors, shall be constructed to withstand 20 per cent over-speed.

400 **In the case of Series Motors,** it is impracticable to specify percentage values for the guaranteed over-speed, on account of the varying service conditions.

401 **Water-wheel Generators** shall be constructed for the maximum runaway speed which can be attained by the combined unit.

Momentary Loads.

402 **Continuously Rated Machines** shall be required to carry momentary loads of 150 per cent of the amperes corresponding to the continuous rating, keeping the rheostat set for rated load excitation, (See §**281**, **764** and **803**.) and commutating machinery shall commutate successfully under this condition. Successful commutation is such that neither brushes nor commutator are injured by the test. In the case of direct-connected generators, this clause is not to be interpreted as requiring the prime mover to drive the generator at this overload.

403 **Machines for duty-cycle operation** shall be rated according to their equivalent load, either on the short-time or continuous basis, but if intended for operation with widely fluctuating loads, shall commutate successfully under their specified operating conditions. See § **284**, **285**.

404 **Stalling Torque of Motors**

Motors for continuous service shall, except when otherwise specified, be required to develop a running torque at least 175 per cent of that corresponding to the running torque at their rated load, without stalling.

Obviously, duty-cycle machines must carry their peak loads without stalling.

WAVE FORM

405 The **Sine Wave** shall be considered as standard, except where deviation therefrom is inherent in the operation of the system of which the machine forms a part.

406 **The deviation of wave form** from the sinusoidal is determined by superposing upon the actual wave, (as determined by oscillograph), the equivalent sine wave of equal length, in such a manner as to give the least difference between ordinates, and then dividing the maximum difference between corresponding ordinates by the maximum value of the equivalent sine wave. A maximum deviation of the terminal voltage wave on open circuit from sinusoidal shape not exceeding 10 per cent is permissible, except when otherwise specified.

EFFICIENCY AND LOSSES

420 **Machine Efficiency** is the ratio of the power delivered by the machine to the power received by it.

421 **Plant or System Efficiency** is the ratio of the energy delivered from the plant or system to the energy received by it in a specified period of time.* In calculating plant or system efficiency it may be desirable to calculate the losses in each individual machine or part of the system at the actual temperature of that machine or part during the specified interval. These losses may be appreciably different from the losses at 75°C., which latter shall be the standard temperature of reference for all efficiency guarantees. See §**432**.

422 **In the Case of Machinery two Efficiencies are Recognized,** conventional efficiency (see §**423**) and directly measured efficiency. Unless otherwise specified, the conventional efficiency is to be employed. When the efficiency of a machine is stated without specific reference to the load conditions, rated load is always to be understood whether the efficiency be the conventional or directly measured efficiency.

423 **Conventional Efficiency** of machinery is the ratio of the output to the sum of the output and the losses; or of the input minus the losses to the input; when, in either case, conventional values are assigned to one or more of these losses. The need for assigning conventional values to certain losses, arises from the fact that some of the losses in electrical machinery are practically indeterminable, and must, in many cases, either be approximated by an approved method of test. or else values recommended by the Institute and designated " conventional" values shall be employed for them in arriving at the "conventional efficiency."

425 **Directly-Measured Efficiency.** Input and output determinations of efficiency may be made directly, measuring the output by brake, or equivalent, where applicable. Within the limits of practical application, the circulating-power method, sometimes described as the Hopkinson or " loading-back" method, may be used.

426 **Values of the Indeterminate Losses** may also be obtained by brake or other direct test, and used in estimating actual efficiencies of similar machines, by the separate-loss method.

427 **Normal Conditions.** The efficiency shall correspond to, or be corrected to, the normal conditions herein set forth, which shall be regarded as standard. These conditions include voltage, current, power-factor, frequency, wave-shape, speed, temperature, or such of them as may apply in each particular case.

428 **Measurement of Efficiency.** Electric power shall be measured at the terminals of the apparatus. In polyphase machines, sufficient measurements shall be made on all phases to avoid errors of unbalance.

429 **Point at Which Mechanical Power Shall be Measured.** Mechanical power delivered by machines, shall be measured at the pulley,

*An exception should be noted in the case of the efficiency of storage batteries.

gearing, or coupling, on the rotor shaft, thus excluding the loss of power in the belt or gear friction. See, however, an exception in **§800.**

430 **The Efficiency Specified for Alternators and Transformers** shall be of the ratio of the kilowatt output to the kilowatt input at the rated kv-a. and power factor.

431 **Efficiency of Alternating-Current Machinery in regard to WaveShape.** In determining the efficiency of alternating-current machinery, the sine wave is to be considered as standard, unless a different wave form is inherent in the operation of the system. See **§405.**

432 **Temperature of Reference for Machine Efficiency.** The efficiency, at all loads, of all apparatus, shall be corrected to a reference temperature of 75°C, but tests may be made at any convenient ambient temperature, preferably not less than 15°C. See §§**348** and **445.**

433 **The losses in constant-potential machinery,** either of the stationary type, or of the constant-speed rotary type, are of two classes; namely, those which remain substantially constant at all loads, and those which vary with the load. The former include iron losses, windage and friction, also I^2R losses in any shunt windings. The latter include I^2R losses in series windings. The constant losses may be determined by measuring the power required to operate the machine at no load, deducting any series I^2R losses. The variable loss at any load may be computed from the measured resistance of the series windings and the given load current.

434 **Stray Load Losses.** The above simple method of determining the losses and hence the efficiency is only approximate, since the losses which are assumed to be constant do actually vary to some extent with the load, and also because the actual loss in the copper windings is sometimes appreciably greater than the calculated I^2R loss. The difference between the approximate losses, as above determined, and the actual losses, is termed the " stray load losses "*. These latter are due to distortions in electric or magnetic fluxes from their no-load distributions or values, brought about by the load current. They are usually only approximately measurable, or may be indeterminable.

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*In Table V, the stray load losses include f, h, i, k, l and m; but do not include increased core losses due to increased excitation for compensating internal drop under load.

TABLE V

Classification of Losses in Machinery

435 Losses in machinery may be classified as follows:

Accurately Measurable or Determinable	*Approximately Measurable or Determinable*	*Indeterminable*
a. No-Load Core Losses including eddy-current losses in conductors at no-load	*c*. Brush Friction Loss	*h*. Iron Loss due to flux distortion.
b. Load I^2R losses in windings No-Load I^2R losses in windings	*d*. Brush-Contact Loss	*i*. Eddy-Current losses in conductors due to transverse fluxes occasioned by the load currents.
	e. Losses due to windage and to bearing friction	*k*. Eddy-Current losses in conductors due to tooth saturation resulting from distortion of the main flux.
	f. Extra copper loss in transformer windings, due to stray fluxes caused by load currents	*l*. Tooth-frequency losses due to flux distortion under load.
	g. Dielectric Losses.	*m*. Short-Circuit Loss of Commutation.

436 **Evaluation of Losses.** The larger individual losses are either accurately or approximately determinable, but certain of the indeterminable losses reach values in various kinds of machinery which require that they should be taken into account.

LOSSES TO BE TAKEN INTO ACCOUNT IN VARIOUS TYPES OF MACHINES

440 **Direct-Current Commutating Motors and Generators.**

Core losses. See §452.

I^2R loss in all windings.

Brush contact I^2R loss. Unless otherwise specified, use the Institute Standard of 1 volt for contact drop per brush; *i. e.*, 2 volts for total brush drop, either carbon or graphite brushes. (See §§454 and 819). In the case of low voltage automobile propulsion motors and generators this loss should be determined experimentally; see §839.

Friction of bearings and windage.

Rheostat losses, when present.

Brush friction.

All indeterminable load losses (including stray-load iron losses) which may be important, which vary with the design, and for which no satisfactory method of determination has been found, shall be included as zero per cent in estimating conventional efficiency.

441 **Synchronous Motors and Generators.**

Core losses. See **§452.**

I^2R loss in all windings, based upon rated k-va. and power factor.

Stray load-losses. In approximating these losses, the method described in **§458** shall be employed.

Friction of bearings and windage.

Brush friction and brush-contact loss is negligible, except in the case of revolving armature machines.

Rheostat losses, when present, corresponding to rated kv-a. and power factor.

442 **Induction Machines.**

Core losses. See **§452.**

I^2R losses in all windings.

Stray load-losses. In approximating these losses, the method described in **§459** shall be employed

Brush friction when collector rings are present.

Brush-contact loss. Unless otherwise specified, use the Institute Standard of 1 volt for contact drop per brush, for either carbon or graphite brushes. See **§454.**

Friction of bearings and windage.

443 **Commutating A-C. Machines**

Core losses. See **§452.**

I^2R losses in all windings.

Brush friction.

Brush-contact loss. Unless otherwise specified, use the Institute Standard of 1 volt for contact drop per brush, for either carbon or graphite brushes. See **§454** and **819.**

Friction of bearings and windage.

Short-circuit loss of commutation. Iron loss due to flux distortion. Eddy-current losses due to fluxes varying with load and saturation.	The Institute is not at this time prepared to make recommendations for approximating these losses.

444 **Synchronous Converters.**

Core losses. See **§452.**

I^2R losses in all windings, based on rated kw. and unity power factor. The I^2R losses in the armature winding shall be derived from those corresponding to its use as a direct-current generator, by using suitable factors.

Brush friction.

Rheostat losses when present, corresponding to rated kw. and unity power factor.

Brush-contact loss. Unless otherwise specified, use the Institute Standard of 1 volt for contact drop per brush, for either carbon or graphite brushes. See **§454.**

Short-circuit loss of commutation. Iron loss due to flux distortion when present. Eddy-current losses due to fluxes varying with load and saturation.	These losses, while usually of low magnitude, are erratic, and the Institute is not at this time prepared to make recommendations for approximating them.

Friction of bearings and windage.

For the booster type of synchronous converter, where the booster forms an integral part of the unit, its losses shall be included in the total converter losses in estimating the efficiency.

445 Transformers

No-load losses. These include the core loss, and the I^2R loss due to the exciting current, also the dielectric loss in the insulation. (See **§470**).

Load losses. These include I^2R losses, and stray load-losses due to eddy currents caused by fluxes varying with load. (See **§471**).

DETERMINATION OR APPROXIMATION OF LOSSES IN ROTATING MACHINERY

450 Bearing Friction and Windage may be determined as follows. Drive the machine from an independent motor, the output of which shall be suitably determined. The machine under test shall have its brushes removed and shall not be excited. This output represents the bearing friction and windage of the machine under test.

The bearing friction and windage of induction motors may be measured by running motors free at the lowest voltage at which they will rotate continuously at approximately rated speed; the watts input, minus I^2R loss, under these conditions being taken as the friction and windage.

In the case of engine-type generators, the windage and bearing friction loss is ordinarily very small,amounting to a fraction of one per cent of the output. In these rules this loss is neglected owing to its small value and the difficulty of measuring it.

451 Brush Friction of Commutator and Collector Rings. Follow the test of **§450,** taking an additional reading with the brushes in contact with the commutator or collector rings. The difference between the output obtained in the test in **§450** and this output shall be taken as the brush friction. Note: The surfaces of the commutator and brushes should already be smooth and glazed from running when this test is made.

452 Core Loss. Follow the test of **§451** with an additional reading taken in a similar manner, except that the machine is to be excited so as to produce at the terminals a voltage corresponding to the calculated internal voltage for the load under consideration. The difference between the output obtained by this test and that obtained by test under Sec. **451** shall be taken as the core loss.

For Synchronous Machines, the internal voltage shall be determined by correcting the terminal voltage for the resistance drop only.

The Core Loss of Induction Motors may be determined by measuring the watts input to the motor when running free at rated voltage and frequency and subtracting therefrom the no-load copper loss, bearing friction and windage.

454 **The Brush-Contact I^2R Loss** depends largely upon the material of which the brush is composed. As indicating the range of variation the following table will be of interest:

TABLE VI.

Brush-Contact Drop.

Grade of Brush	Volts drop across one brush-contact. (Average of positive and negative brushes)
Hard Carbon	1.1
Soft Carbon	0.9
Graphite	0.5 to 0.8
Metal-Graphite types	0.15 to 0.5 (The former for largest proportion of metal)

One volt drop per brush shall be considered as the Institute Standard drop corresponding to the I^2R brush-contact loss, for carbon and graphite brushes. Metal-graphite brushes shall be considered as special. See **§819**.

455 **Field-Rheostat Losses** shall be included in the generator losses where there is a field rheostat in series with the field magnets of the generator, even when the machine is separately excited.

456 **Ventilating Blower.** When a blower is supplied as part of a machine set, the power required to drive it shall be charged against the complete unit; but not against the machine alone.

457 **Losses in Other Auxiliary Apparatus.** Auxiliary apparatus, such as a separate exciter for a generator or motor, shall have its losses charged against the plant of which the generator and exciter are a part, and not against the generator. An exception should be noted in the case of turbo-generator sets with direct-connected exciters, in which case the losses in the exciter shall be charged against the generator. The actual energy of excitation and the field-rheostat losses, if any, (see §455) shall be charged against the generator.

458 **Stray Load-Losses in Synchronous Generators and Motors.** These include iron losses, and eddy-current losses in the copper, due to fluxes varying with load and also to saturation.

Stray load-losses are to be determined by operating the machine on short circuit and at rated-load current. This, after deducting the windage and friction and I^2R loss, gives the stray load-loss for polyphase generators and motors. These losses in single-phase machines are large; but the Institute is not yet prepared to specify a method for measuring them.

459 **Stray Load-Losses in Induction Machines.**

These include eddy-current losses in the stator copper, and other eddy-current losses due to fluxes varying with the load. In windings consisting of relatively small conductors, these eddy-current losses are usually negligible.

With rotor removed, measure the power input to the stator with different values of current at the rated frequency. The curve plotted with these values gives the combined I^2R and stray load-losses due to eddy currents in the stator copper. Deduct the I^2R loss determined from the resistance, and the difference will represent the stray load-losses corresponding to the various currents. While this method is not accurate for some types of motors it usually represents a sufficiently good approximation.

460 **Polyphase Induction-Motor Rotor I^2R Loss.** This should be determined from the slip, whenever the latter is accurately determinable, using the following equation:

$$\text{Rotor } I^2R \text{ loss} = \frac{\text{Output} \times \text{slip}}{1 - \text{slip}}$$

In large slip-ring motors, in which the slip cannot be directly measured by loading, the rotor I^2R loss shall be determined by direct resistance measurement; the rotor full-load current to be calculated by the following equation:

$$\text{Current per ring} = \frac{\text{watts output}}{\text{rotor voltage at stand-still} \times \sqrt{3} \times K}$$

This equation applies to three-phase rotors. For rotors wound for two phase, use 2 instead of the $\sqrt{3}$. K may be taken as 0.95 for motors of 150 kw. or larger. The factor K usually decreases as the size of motor is reduced, but no specific value can be stated for smaller sizes.

DETERMINATION OR APPROXIMATION OF LOSSES IN TRANSFORMERS

470 **No-Load Losses.** These shall be measured with open secondary circuit at the rated frequency, and with an applied primary voltage

giving the rated secondary voltage plus the IR drop which occurs in the secondary under rated load conditions.

471 **Load Losses.** These include I^2R and stray load-losses. They shall be measured by applying a primary voltage, preferably at rated frequency, sufficient to produce rated load current in the windings, with the secondary windings short circuited.

DIELECTRIC STRENGTH TESTS OF MACHINERY

480 **Basis for Determining Test Voltages.** The test voltage which shall be applied to determine the suitability of insulation for commercial operation is dependent upon the kind and size of the machinery, and its normal operating voltage, upon the nature of the service in which it is to be used, and upon the severity of the mechanical and electrical stresses to which it may be subjected. The voltages and other conditions of test which are recommended, have been determined as reasonable and proper for the great majority of cases, and are proposed for general adoption, except when specific reasons make a modification desirable.

481 **Condition of Machinery to be Tested.** Commercial tests shall, in general, be made with the completely assembled machinery and not with individual parts. The machinery shall be in good condition, and high-voltage tests, unless otherwise specified, shall be applied before the machine is put into commercial service, and shall not be applied when the insulation resistance is low owing to dirt or moisture. High-voltage tests shall be made at the temperature assumed under normal operation or at the temperature attained under the conditions of commercial testing. High-voltage tests to determine whether specifications are fulfilled, are admissible on new machines only. Unless otherwise agreed upon, high-voltage tests of a machine shall be understood as being made at the factory.

482 **Points of Application of Voltage.** The test voltage shall be successively applied between each electric circuit and all other electric circuits and metal parts grounded.

483 **Interconnected Polyphase Windings** are considered as one circuit. All windings of a machine except that under test, shall be connected to ground.

484 **Frequency, Wave Form and Test Voltage.** The frequency of the testing circuit shall not be less than the rated frequency of the apparatus tested. A sine-wave form is recommended. See **§405.** The test shall be made with alternating voltage having a crest value equal to $\sqrt{2}$ times the specified test voltage. In d.c. machines, and in the general commercial application of a.c. machines, the testing frequency of 60 cycles per second is recommended.

485 **Duration of Application of Test Voltage.** The testing voltage for all classes of apparatus shall be applied continuously for a period of 60 seconds. See exception, **485A.**

485A *Exception*—**For All Standard Devices Produced in Large Quantities** and with á standard test pressure of 2500 volts or less, a test pressure applied for one second 20 per cent higher than the one-minute test pressure will be satisfactory.

486 **Apparatus for Use on Single-Phase, 3-Phase-Delta or 3-Phase-Star Circuits.** Apparatus, such as transformers, which may be used in star connection on three-phase circuits, shall have the delta voltage of the circuits on which they may be used indicated on the rating plate and the test shall be based on such delta voltage.

VALUES OF A-C. TEST VOLTAGES

500 **The Standard Test for All Classes of Apparatus, Except as Otherwise Specified, Shall be Twice the Normal Voltage of the Circuit to Which the Apparatus is Connected, Plus 1000 Volts.**

501 *Exception*—**Alternating-Current Apparatus connected to Permanently Grounded Single-Phase Systems, for use on Permanently Grounded Circuits of more than 300 Volts,** shall be tested with 2.73 times the voltage of the circuit to ground + 1000 volts. This does not refer to three-phase apparatus with grounded star neutral.

502 *Exception*—**Distributing Transformers.** Transformers for primary pressures from 550 to 5000 volts, the secondaries of which are directly connected to consumers' circuits and commonly known as distributing transformers, shall be tested with 10,000 volts from primary to core and secondary combined. The secondary windings shall be tested with twice their normal voltage plus 1000 volts.

503 *Exception*—**Auto-Transformers** used for starting purposes, shall be tested with the same voltage as the test voltage of the apparatus to which they are connected

504 *Exception*—**Household Devices.** Apparatus taking not over 660 watts† and intended solely for operation on supply circuits not exceeding 250 volts, shall be tested with 900 volts, except in the case of heating devices which shall be tested with 500 volts at operating temperature.

505 *Exception*—**Apparatus for use on Circuits of 25 Volts or Lower,** such as bell-ringing apparatus,* electrical apparatus used in automobiles, apparatus used on low-voltage battery circuits, etc., shall be tested with 500 volts.

506 *Exception*—**Field Windings of Alternating-Current Generators** shall be tested with 10 times the exciter voltage, but in no case with less than 1500 volts nor more than 3500 volts.

507 *Exception*—Field Windings‡ of Synchronous Machines, including motors and converters which are to be started from alternating-current circuits, shall be tested as follows:

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†The present National Electric Code power limit for a single outlet.

*This rule does not include bell-ringing transformers of ratio 125 to 6 volts. See National Electric Code.

‡Series field coils should be regarded as part of the armature circuit and tested as such.

a. When machines are started with fields short-circuited they shall be tested as specified in §506.

b. When machines are started with fields open-circuited and sectionalized while starting, they shall be tested with 5000 volts.

c. When machines are started with fields open-circuited and connected all in series while starting, they shall be tested with 5000 volts for less than 275-volt excitation and 8000 volts for excitation of 275 volts to 750 volts.

508 *Exception*. **Phase-Wound Rotors of Induction Motors.** The secondary windings of wound rotors of induction motors shall be tested with twice their normal induced voltage, plus 1000 volts. By normal induced voltage is here meant the voltage between slip rings on open circuit at standstill with normal voltage impressed on the primary.

When induction motors with phase-wound rotors are reversed, while running at approximately normal speed, by reversing the primary connections, the test shall be four times the normal induced voltage, plus 1000 volts.

509 *Exception*—**Switches and Circuit Control Apparatus above 600** volts, shall be tested with 2½ times rated voltage, plus 2000 volts. See §720 to 741.

510 *Exception*—**Assembled Apparatus.** Where a number of pieces of apparatus are assembled together and tested as an electrical unit, they shall be tested with 15 per cent lower voltage than the lowest required on any of the individual pieces of apparatus.

510A *Exception*. **Meters and Instruments.** The Institute is not at present in a position to make a recommendation in regard to the dielectric tests of meters and instruments.

511 **Testing Transformers by Induced Voltage.** Under certain conditions it is permissible to test transformers by inducing the required voltage in their windings, in place of using a separate testing transformer. By "required voltage", is meant a voltage such that the line end of the windings shall receive a test to ground equal to that required by the general rules.

512 **Transformers with Graded Insulation** shall be so marked. They shall be tested by inducing the required test-voltage in the transformer and connecting the successive line leads to ground.

Transformer windings permanently grounded within the transformer shall be tested by inducing the required test voltage in such windings. (See §500).

MEASUREMENT OF VOLTAGE IN DIELECTRIC TESTS OF MACHINERY

530 **Use of Voltmeters and Spark-Gaps in Insulation Tests.** When making insulation tests on electrical machinery. every

precaution must be taken against the occurrence of any spark-gap discharges in the circuits from which the machinery is being tested. A non-inductive resistance of about one ohm per volt shall be inserted in series with one terminal of the spark gap. If the test is made with one electrode grounded, this resistance shall be inserted directly in series with the non-grounded electrode. If neither terminal is grounded, one-half shall be inserted directly in series with each electrode. In any case this resistance shall be as near the measuring gap as possible and not in series with the tested apparatus. The resistance will damp high-frequency oscillations at the time of breakdown and limit the current which will flow. A water tube is the most reliable form of resistor. Carbon resistors should not be used because their resistance may become very low at high voltages.

531 **For Machinery of Low Capacitance.** When the machinery under test does not require sufficient charging current to distort the high-voltage wave shape, or change the ratio of transformation, the spark gap should be set for the required test voltage and the testing apparatus adjusted to give a voltage at which this spark gap just breaks down. This adjustment should be made with the apparatus under test disconnected. The apparatus should then be connected, and with the spark gap about 20 per cent longer, the testing apparatus is again adjusted to give the voltage of the former breakdown, which is the assumed voltage of test. This voltage is to be maintained for the required interval.

532 **For Machinery of High Capacitance.** When the charging current of the machinery under test may appreciably distort the voltage wave or change the effective ratio of the testing transformer, the first adjustment of voltage with the gap set for the test voltage should be made with the apparatus under test connected to the circuit and in parallel with the spark gap.

When making arc-over tests of large insulators, leads, etc. partial arc-over of the tested apparatus may produce oscillations which will cause the measuring gap to discharge prematurely. The measured voltage will then appear too high. In such tests the " equivalent " ratio " of the testing transformer should be measured by gap to within 20% of the arc-over voltage of the tested apparatus with the tested apparatus in circuit. The measuring gap should then be greatly lengthened out and the voltage increased until the tested apparatus arcs over. This arc-over voltage should then be determined by multiplying the voltmeter reading by the equivalent ratio found above. Direct measurement of the spark-over voltage over one gap by another gap should always be avoided.

533 **Measurements with Voltmeter.** In measuring the voltage with a voltmeter, the instrument should preferably derive its voltage from the high-tension circuit, either directly, or by means of a voltmeter coil placed in the testing transformer, or through an auxiliary *ratio transformer*. It is permissible to measure the voltage at other places, such as the transformer primary provided cor-

rections can be made for the variations in ratio caused by the charging current of the machinery under test, or provided there is no material variation of this ratio. In any case, when the capacitance of the apparatus to be tested is such as to cause wave distortion, the testing voltage must be checked by a spark gap as set forth in §538, or by a crest voltage meter. If the crest-voltage meter is calibrated in crest volts, its readings must be reduced to the corresponding r. m. s. sinusoidal value by dividing with $\sqrt{2}$.

534 **Measurements with Spark Gaps.** If proper precautions are observed, spark gaps may be used to advantage in checking the calibration of voltmeters when set up for the purposes of high-voltage tests of the insulation of machinery.

535 **Ranges of Voltages.** For the calibrating purposes set forth in §534 the sphere-gap shall be used for voltages above 50 kv., and is to be preferred down to 30 kv. The needle spark-gap may, however, be used for voltages from 10 to 50 kv.

536 **The Needle Spark Gap.** The needle spark gap shall consist of new sewing needles, supported axially at the ends of linear conductors which are at least twice the length of the gap. There must be a clear space around the gap for a radius of at least twice the gap length.

537 The sparking distances in air between No. 00 sewing needle points for various root-mean-square sinusoidal voltages are as follows:

TABLE VII.

Needle-Gap Spark-Over Voltages

(At 25°C and 760 mm. barometer).

R.M.S. Kilovolts	Millimeters	R.M.S. Kilovolts	Millimeters
10	11.9	35	51
15	18.4	40	62
20	25.4	45	75
25	33	50	90
30	41		

The above values refer to a relative humidity of 80 per cent. Variations from this humidity may involve appreciable variations in the sparking distance.

538 **The Sphere Spark-Gap.** The standard sphere spark-gap shall consist of two suitably mounted metal spheres. When used as specified below, the accuracy obtainable should be approximately 2 per cent.

No extraneous body, or external part of the circuit, shall be nearer the gap than twice the diameter of the spheres. By the "gap" is meant the shortest path between the two spheres.

The shanks should not be greater in diameter than 1/5th the sphere diameter. Metal collars, etc., through which the shanks extend, should be as small as practicable and should not, during any measurement, come closer to the sphere than the maximum gap length used in that measurement.

The sphere diameter should not vary more than 0.1 per cent and the curvature, measured by a spherometer, should not vary more than 1 per cent from that of a true sphere of the required diameter.

539 **In using the spherometer** to measure the curvature, the distance between the points of contact of the spherometer feet should be within the following limits:

TABLE VIII

Spherometer Specifications

Diameter of Sphere in m.m.	Distance between contact points in mm.	
	Maximum	Minimum
62.5	35	25
125	45	35
250	65	45
500	100	65

539A **In using Sphere Gaps** constructed as above, it is assumed that the apparatus will be set up for use in a space comparatively free from external dielectric fields. Care should be taken that conducting bodies forming part of the circuit, or at circuit potential, are not so located with reference to the gap that their dielectric fields are superposed on the gap; *e.g.*, the protecting resistance should not be arranged so as to present large masses or surfaces near the gap, even at a distance of two sphere diameters.

In case the sphere is grounded, the spark point of the grounded sphere should be approximately five diameters above the floor or ground.

540 **The sparking distances between different spheres** for various r.m.s sinusoidal voltages shall be assumed to be as follows:

TABLE IX.

Sphere-Gap Spark-Over Voltages

(At 25°C and 760 mm. barometric pressure)

Kilo-volts	Sparking Distance in Millimeters.							
	62.5 mm. spheres		125 mm. spheres		250 mm. spheres		500 mm. spheres	
	One sphere grounded	Both spheres insulated	One sphere grounded	Both spheres insulated	One sphere grounded	Both spheres insulated	One sphere grounded	Both spheres insulated
10	4.2	4.2	..	..	..	..	..	..
20	8.6	8.6	..	..	..	..	..	..
30	14.1	14.1	14.1	14.1	..	..	..	..
40	19.2	19.2	19.1	19.1	..	..	..	..
50	25.5	25.0	24.4	24.4	..	..	..	..
60	34.5	32.0	30.	30.	29	29	..	..
70	46.0	39.5	36	36	35	35	..	..
80	62.0	49.0	42	42	41	41	41	41
90		60.5	49	49	46	45	46	45
100			56	55	52	51	52	51
120			79.7	71	64	63	63	62
140			108	88	78	77	74	73
160			150	110	92	90	85	83
180				138	109	106	97	95
200					128	123	108	106
220					150	141	120	117
240					177	160	133	130
260					210	180	148	144
280					250	203	163	158
300						231	177	171
320						265	194	187
340							214	204
360							234	221
380							255	239
400							276	257

The sphere gap is more sensitive than the needle gap to momentary rises of voltage and the voltage required to spark over the gap should be obtained by slowly closing the gap under constant voltage, or by slowly raising the voltage with a fixed setting of the gap. Open arcs should not be permitted in proximity to the gap during its operation, as they may affect its calibration.

AIR-DENSITY CORRECTION-FACTORS FOR SPHERE GAPS

541 **The Spark-Over Voltage,** for a given gap, decreases with decreasing barometric pressure and increasing temperature. This correction may be considerable at high altitudes.

The spacing at which it is necessary to set a gap to spark over at some required voltage, is found as follows: Divide the required voltage by the correction factor given below in Table X. A new voltage is thus obtained. The spacing on the standard curves obtained from Table IX, corresponding to this new voltage, is the required spacing.

The voltage at which a given gap sparks over is found by taking the voltage corresponding to the spacing from the standard curves of Table IX, and multiplying by the correction factor.

When the variation from sea level is not great, the relative air density may be used as the correction factor; when the variation is great, or greater accuracy is desired, the correction factor corresponding to the relative air density should be taken from Table X below, in which

$$\text{Relative air density} = \frac{0.392\, b}{273 + t}$$

b = barometric pressure in mm.
t = temperature in deg. C.

Corrected curves may be plotted for any given altitude, if desired.

Values of relative air density and corresponding values of the correction factor are tabulated below. It will be seen that for values above .9, the correction factor does not differ greatly from the relative air density.

TABLE X.

Air-Density Correction Factors for Sphere Gaps

Relative air density	Diameter of standard spheres in mm.			
	62.5	125	250	500
0.50	0.547	0.535	0.527	0.519
0.55	0.594	0.583	0.575	0.567
0.60	0.640	0.630	0.623	0.615
0.65	0.686	0.677	0.670	0.663
0.70	0.732	0.724	0.718	0.711
0.75	0.777	0.771	0.766	0.759
0.80	0.821	0.816	0.812	0.807
0.85	0.866	0.862	0.859	0.855
0.90	0.910	0.908	0.906	0.904
0.95	0.956	0.955	0.954	0.952
1.00	1.000	1.000	1.000	1.000
1.05	1.044	1.045	1.046	1.048
1.10	1.090	1.092	1.094	1.096

INSULATION RESISTANCE OF MACHINERY

550 **The insulation resistance of a machine** at its operating temperature shall be not less than that given by the following formula:

$$\text{Insulation Resistance in megohms} = \frac{\text{voltage at terminals}}{\text{rated capacity in kv-a.} + 1000}$$

The formula only applies to dry apparatus. Such high values are not attainable in oil-immersed apparatus.

Insulation resistance tests shall, if possible, be made at a d.c. pressure of 500 volts. Since the insulation resistance varies with the pressure, it is necessary that, if a pressure other than 500 volts is to be employed in any case, this other pressure shall be clearly specified.

The order of magnitude of the values obtained by this rule is shown in the following table:

TABLE XI.

Insulation Resistance of Machinery

Rated Voltage of machine	Megohms		
	100 kv-a.	1000 kv-a.	10,000 kv-a.
100	0.001	0.05	—
1,000	0.01	0.50	0.001
10,000	0.1	5.0	0.01
100,000	—	50	0.1

551 It should be noted that the insulation resistance of machinery is of doubtful significance by comparison with the dielectric strength. The insulation resistance is subject to wide variation with temperature humidity and cleanliness of the parts. When the insulation resistance falls below that corresponding to the above rule, it can, in most cases of good design and where no defect exists, be brought up to the required standard by cleaning and drying out the machine. The insulation-resistance test may therefore afford a useful indication as to whether the machine is in suitable condition for the application of the dielectric test.

REGULATION

DEFINITIONS

560 **Regulation.** The regulation of a machine in regard to some characteristic quantity (such as terminal voltage or speed) is the change in that quantity occurring between any two loads. Unless otherwise specified, the two loads considered shall be zero load and rated load, and at the temperature attained under normal operation. The regulation may be expressed by stating the numerical values of the quantity at the two loads, or it may be ex-

pressed by the "percentage regulation", which is the percentage ratio of the change in the quantity occurring between the two loads, to the value of the quantity at either one or the other load, taken as the normal value. It is assumed that all parts of the machine affecting the regulation maintain constant temperature between the two loads, and where the influence of temperature is of consequence, a reference temperature of 75°C shall be considered as standard. If change of temperature should occur during the tests, the results shall be corrected to the reference temperature of 75°C.

The normal value may be either the no-load value, as the no-load speed of induction motors; or it may be the rated-load value, as in the voltage of a.c. generators.

It is usual to state the regulation of d-c. generators by giving the numerical values of the voltage at no load and rated load, and in some cases it is advisable to state regulation at intermediate loads.

561 The **Regulation of d-c. Generators** refers to changes in voltage corresponding to gradual changes in load and does not relate to the comparatively large momentary fluctuations in voltage that frequently accompany instantaneous changes in load.

In determining the regulation of a compound-wound d-c. generator, two tests shall be made, one bringing the load down and the other bringing the load up, between no-load and rated load. These may differ somewhat, owing to residual magnetism. The mean of the two results shall be used.

562 In **constant-potential a-c. generators,** the regulation is the rise in voltage (when the specified load at specified power factor is reduced to zero) expressed in per cent of normal rated-load voltage.

563 In **constant-current machines,** the regulation is the ratio of the maximum difference of current from the rated-load value (occurring in the range from rated-load to short-circuit, or minimum limit of operation), to the rated-load current.

564 In **constant-speed direct-current motors,** and induction motors, the regulation is the ratio of the difference between full-load and no-load speeds to the no-load speed.

565 In **constant-potential transformers,** the regulation is the difference between the no-load and rated-load values of the secondary terminal voltage, at the specified power factor (with constant primary impressed terminal voltage) expressed in per cent of the rated-load secondary voltage, the primary voltage being adjusted to such a value that the apparatus delivers rated output at rated secondary voltage.

566 In **converters, dynamotors, motor-generators and frequency converters,** the regulation is the change in the terminal voltage of the output side between the two specified loads. This may be expressed by giving the numerical values, or as the percentage of the terminal voltage at rated load.

567 In **transmission lines, feeders etc.,** the regulation is the change in the voltage at the receiving and between rated non-inductive load and no load, with constant impressed voltage upon the sending

end. The percentage regulation is the percentage change in voltage to the normal rated voltage at the receiving end.

568 In **steam engines, steam turbines and internal combustion engines,** the percentage speed regulation is usually expressed as the percentage ratio of the maximum variation of speed, to the rated-load speed in passing slowly from rated load to no load (with constant conditions at the supply.)

569 If the test is made by passing suddenly from rated load to no load, the immediate percentage speed regulation so derived shall be termed the **fluctuation**.

570 In a **hydraulic turbine,** or other water motor, the percentage speed regulation is expressed as the percentage ratio of the maximum variation in speed in passing slowly from rated load to no load (at constant head of water), to the rated-load speed.

571 In a **generator unit,** consisting of a generator combined with a prime mover, the speed or voltage regulation should be determined at constant conditions of the prime mover; *i.e.* constant steam-pressure, head, etc. It includes the inherent speed variations of the prime mover. For this reason, the regulation of a generator unit is to be distinguished from the regulation of either the prime mover, or of the generator combined with it, when taken separately.

CONDITIONS FOR TESTS OF REGULATION

580 **Speed and Frequency.** The regulation of generators is to be determined at constant speed, and of alternating-current apparatus at constant frequency.

581 **Power Factor.** In apparatus generating, transforming or transmitting alternating currents, the power factor of the load to which the regulation refers should be specified. Unless otherwise specified, it shall be understood as referring to non-inductive load, that is to a load in which the current is in phase with the *e.m f.* at the output side of the apparatus.

582 **Wave Form.** In the regulation of alternating-current machinery receiving electric power, a sine wave of voltage is assumed, except where expressly specified otherwise. See **§405.**

583 **Excitation.** In commutating machines, rectifying machines, and synchronous machines, such as direct-current generators and motors, as well as in alternating-current generators, the regulation is to be determined under such conditions as to maintain the field adjustment constant at that which gives rated-load voltage at rated-load current, as follows:

(1) In the case of separately-excited field magnets—constant excitation.

(2) In the case of shunt machines, constant resistance in the shunt-field circuit.

(3) In the case of series or compound machines, constant resistance shunting the series-field windings.

584 **Tests and Computation of Regulation of A-C. Generators.**

Any one of the three following methods may be used. They are given in the order of preference.

Method a.

The regulation can be measured directly, by loading the generator at the specified load and power factor, then reducing the load to zero, and measuring the terminal voltage, with speed and excitation adjusted to the same values as before the change. This method is not generally applicable for shop tests, particularly on large generators, and it becomes necessary to determine the regulation from such other tests as can be readily made.

585 **Method b.**

This consists in computing the regulation from experimental data of the open-circuit saturation curve and the zero-power-factor saturation curve. The latter curve, or one approximat-

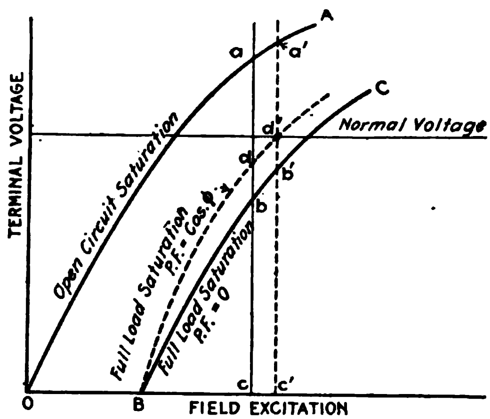


Fig. 1

ing very closely to it, can be obtained by running the generator with over excitation on a load of idle-running under-excited synchronous motors. The power factor under these conditions is very low and the load saturation curve approximates very closely the zero power factor saturation curve. From this curve and the open circuit curve, points for the load saturation curve, for any power factor, can be obtained by means of vector diagrams.

To apply Method b, it is necessary to obtain from test, the open-circuit saturation curve *OA*, Fig. 1, and the saturation curve *BC* at zero power factor and rated-load current. At any given excitation *Oc*, the voltage that would be induced on open circuit is *ac*, the terminal voltage at zero power factor is *bc*, and the apparent internal drop is *ab*. The terminal voltage *dc* at any other power factor can then be found by drawing an e.m.f. diagram* as in Fig. 2, where ϕ is

*Method b, for deducing the load saturation curve, at any assigned power factor, from no-load and zero power-factor saturation curves obtained by test must be regarded as empirical. Its value depends upon the fact that experience has demonstrated the reasonable correctness of the results obtained by it.

an angle such that *cos* ϕ is the power factor of the load, *be* the resistance drop (IR) in the stator winding, *ba* the total internal drop, and *ac* the total induced voltage; *ba* and *ac* being laid off to correspond with the values obtained from Fig. 1. The terminal voltage at power factor *cos* ϕ, is then *cb* of Fig. 2, which, laid off in Fig. 1, gives point *d*. By finding a number of such points, the curve *Bdd'* for power factor *cos* ϕ is obtained and the regulation at this power factor (expressed in per cent) is $\frac{100 \times a'd'}{d'c'}$, since $a'd'$ is the rise in voltage when the load at power factor *cos* ϕ is thrown off at normal voltage $c'd'$.

Generally, the ohmic drop can be neglected, as it has very little influence on the regulation, except in very low-speed machines where the armature resistance is relatively high, or in some cases where regulation at unity power factor is being estimated. For low power factors, its effect is negligible in practically all cases. If

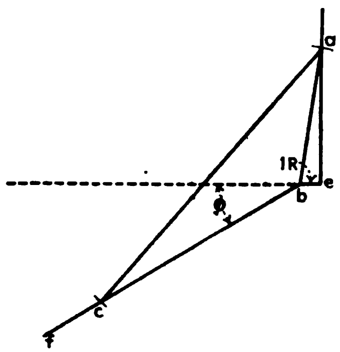


Fig. 2

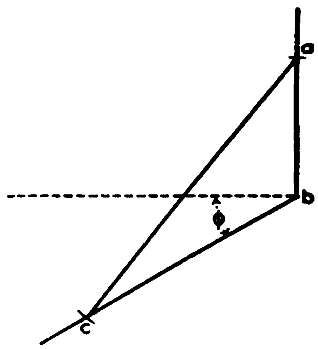


Fig. 3

resistance is neglected, the simpler e.m.f. diagram, Fig. 3, may be used to obtain points on the load saturation curve for the power factor under consideration.

586 **Method c.**

Where it is not possible to obtain by test a zero-power-factor saturation curve as in Method b, this curve can be estimated closely from open-circuit and short-circuit curves, by reference to tests at zero power factor on other machines of similar magnetic circuit. Having obtained the estimated zero-power-factor curve, the load saturation for any other power factor is obtained as in method b.

Thus Method c is the same as Method b; except that the zero-power-factor curve must be estimated. This may be done as follows. In Fig. 4, *OA* is the open-circuit saturation curve and *OE* the short-circuit line as shown by test. The zero-power-factor curve corresponding to any given current *BF* will start from point *B*, and for machines designed with low saturation and low reactance, will follow parallel to *OA*, as shown by the dotted curve *BD*, which is *OA* shifted horizontally parallel to itself by the distance *OB*. In high-speed machines, or in others having low reactance and a low degree of saturation in the magnetic circuit, the zero-power-factor curve will lie quite close to *BD*, particularly in those parts that are used for determining the regulation. This is the case with many turbo-generators and high-speed water-wheel generators. In many cases, however, the zero-power-factor curve will deviate from *BD*, as shown by *BC*, and the deviation will be most pronounced in machines of high reactance, high saturation, and large magnetic leakage. The position of the actual curve *BC* with relation to *BD*, can be approximated with sufficient exactness by investigating the corresponding relation as obtained by test at zero power factor on machines of similar characteristics and magnetic circuit. Or curve *BC* can be calculated by methods based on the results of tests at zero power factor. After *BC* has been obtained, the saturation curve and regulation for any other power factor can be derived as in Method (b).

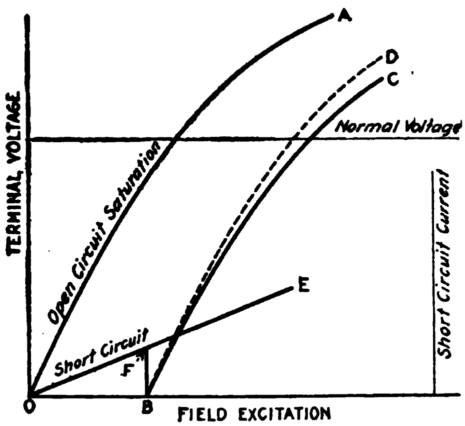


FIG. 4

587 Tests and Computation of Regulation for Constant-Potential Transformers.

The regulation can be determined by loading the transformer and measuring the change in voltage with change in load, at the specified power factor. This method is not generally applicable for shop tests, particularly on large transformers.

The regulation for any specified load and power factor can be computed from the measured impedance watts and impedance volts, as follows:

Let:

P = impedance watts, as measured in the short-circuit test and corrected to 75°C.

E_z = impedance volts, as measured in the short-circuit test.

IX = Reactance Drop in Volts.

I = Rated Primary Current.

E = Rated Primary Voltage.

q_r = percent drop in phase with current.
q_x = percent drop in quadrature with current.

$$IX = \sqrt{E_s^2 - \left(\frac{P}{I}\right)^2}$$

$$q_r = 100\frac{P}{EI}$$

$$q_x = 100\frac{IX}{E}$$

588 Then—

1. For **unity power factor**, we have approximately:-

$$\text{Per cent regulation} = q_r + \frac{q_x^2}{200}$$

589 2. For **inductive loads** of power-factor m and reactive-factor n,

$$\text{Per cent regulation} = mq_r + nq_x + \frac{(mq_x - nq_r)^2}{200}$$

TRANSFORMER CONNECTIONS*

(These rules do not apply to auto transformers.)

600 **Diagrammatic Sketch of Connections.** The manufacturer shall furnish with each transformer a complete diagrammatic sketch of the internal connections, and all terminals and taps of the transformer shall be marked to correspond with letters and numbers in the sketch. This sketch should preferably be on a metal plate on the transformer case.

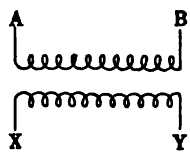
SINGLE-PHASE TRANSFORMERS

601 **Marking of Leads.** The leads of single-phase transformers shall be distinguished from each other by marking the high-voltage leads with the letters A and B, and the low-voltage leads with the letters X and Y.

The terminals (by terminals is meant the ends of the windings) shall be so marked that the potential difference in all windings at any instant shall have the same sign, that is, the potential difference between A and B shall have the same sign at any instant as the potential difference between X and Y.**

602 In accordance with the above rule, the terminals of single-phase transformers shall be marked as follows:

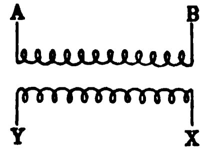
(1) High- and Low-Voltage Windings in Phase:



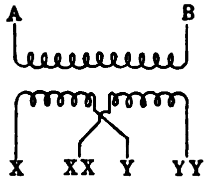
*Sections 601 to 611, relative to a specific scheme of marking the leads, are tentative only, subject to the adoption of a comprehensive scheme of marking the terminals of all classes of apparatus.

**To test the correctness of single-phase markings, connect A to X and apply voltage to the high voltage winding A-B. Voltage B-Y must be numerically less than voltage A-B.

603 (2) High- and Low-Voltage Windings 180 deg. Apart in Phase:

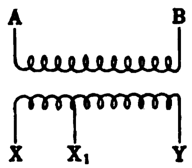


604 **Single-Phase Transformers with More than Two Windings.** Transformers with three or more windings (each being provided with separate outgoing leads) shall have the leads of two of their windings lettered in accordance with the preceding paragraph. The remaining leads shall be designated AA BB. etc. in the case of high-voltage leads and XX, YY, etc. in the case of low-voltage leads. For example, transformers having four secondary leads from two distinct, similar windings shall be lettered as follows:



This indicates that the low-voltage winding consists of two disconnected parts, one part having terminals X, Y and the other part having terminals XX, YY. For multiple connection, X and XX are to be connected and Y and YY are to be connected. For series operation, Y is to be connected to XX.

605 **Tap Connections.** All tap connections which are not brought outside the transformer case shall be marked serially with numerals only. Where tap leads are brought out of the transformer case they shall be given the letter designation together with a subscript indicating the relative position of the tap, as in the following diagram.



606 **Neutral Lead.** Where a neutral lead is brought outside the transformer case, it shall be lettered N.

607 **Parallel Operation.** Transformers marked as above may be operated in parallel, by connecting similarly marked terminals provided their ratios, voltages resistances and reactances are such as to permit parallel operation.

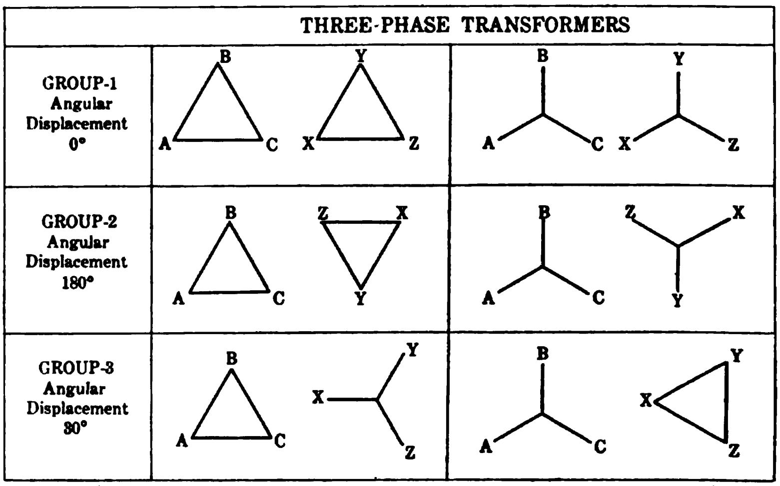
THREE-PHASE TRANSFORMERS

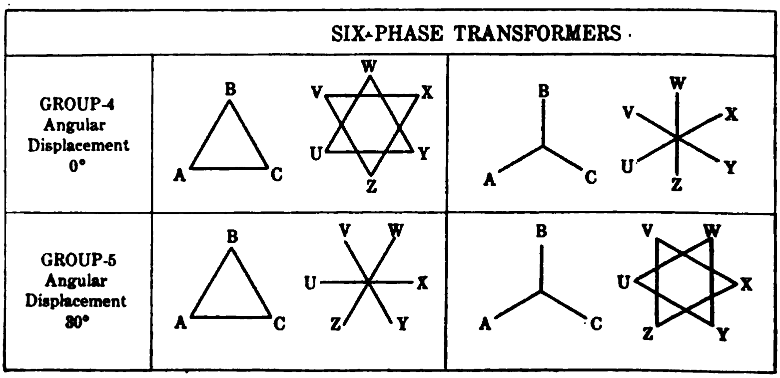
608 **Marking of Leads.** Three-phase transformers ordinarily have three or four leads for high-voltage and three or four leads for low-

voltage windings. To distinguish the various leads from each other, and also to distinguish between the various phase relations obtainable, the three high-voltage leads should be lettered A, B and C and the three low-voltage leads X, Y and Z.

For transformers having six-phase secondaries the primary leads should be lettered A, B and C as above, and the secondary leads U, V, W, X, Y and Z.

The letters shall be so applied to the transformer terminals that if the phase sequence of voltage on the high-voltage side is in the order of A to B to C, it is in the order of X to Y to Z, etc., on the low-voltage side. This arrangement is represented by the diagrams below, which show the various common angular displacements between high- and low-voltage windings of standard transformers. In addition it should be distinctly stated, preferably on the rating plate, in which of the groups given in the following diagrams the transformer belongs.





609 The rules given above for single-phase transformers in regard to the neutral tap (see **§606**), and also in regard to internal connections (see **§§601** to **605**), are applicable to three-phase transformers and six-phase transformers.

610 **Angular Displacement.** The angular displacement between high- and low-voltage windings, is the angle in the diagram in **§608** between the lines passing from the neutral point through *A* and *X* respectively for three-phase transformers and through *A* and *U* for six-phase transformers. Thus, in Group 1, the angular displacement is zero degrees; in Group 2, the angular displacement is 180° and in Group 3, the angular displacement is 30°.

611 **Parallel Operation.** Three-phase and six-phase transformers marked as above may be operated in parallel, by connecting similarly marked terminals together, provided their ratios, voltages, resistances, reactances and angular displacements are such as to permit parallel operation.

INFORMATION ON THE RATING PLATE OF A MACHINE

620 It is recommended that the rating plate of machines which comply with the Institute rules shall carry a distinctive special sign, such as "A.I.E.E. 1916 Rating" or "A16" Rating.

621 The absence of any statement to the contrary on the rating plate of a machine implies that it is intended for continuous service and for the standard altitude and ambient temperature of reference. See **§§287, 305, 308** and **309.**

622 The rating plate of a machine intended to work under various kinds of rating must carry the necessary information in regard to those kinds of ratings.

STANDARDS FOR WIRES AND CABLES

TERMINOLOGY*

635 **Wire.**—A slender rod or filament of drawn metal.

The definition restricts the term to what would ordinarily be understood by the term "solid wire." In the definition, the word "slender" is used in the sense that the length is great in comparison with the diameter. If a wire is covered with insulation, it is properly called an insulated wire; while primarily the term "wire" refers to the metal, nevertheless when the context shows that the wire is insulated, the term "wire" will be understood to include the insulation.

636 **Conductor.**—A wire or combination of wires not insulated from one another, suitable for carrying a single electric current.

The term "conductor" is not to include a combination of conductors insulated from one another, which would be suitable for carrying several different electric currents.

Rolled conductors (such as busbars) are, of course, conductors, but are not considered under the terminology here given.

637 **Stranded Conductor.**—A conductor composed of a group of wires, or of any combination of groups of wires.

The wires in a stranded conductor are usually twisted or braided together.

638 **Cable.**—(1) A stranded conductor (single-conductor cable); or (2) a combination of conductors insulated from one another (multiple-conductor cable).

The component conductors of the second kind of cable may be either solid or stranded, and this kind of cable may or may not have a common insulating covering. The first kind of cable is a single conductor, while the second kind is a group of several conductors. The term "cable" is applied by some manufacturers to a solid wire heavily insulated and lead-covered; this usage arises from the manner of the insulation, but such a conductor is not included under this definition of "cable." The term "cable" is a general one, and, in practise, it is usually applied only to the larger sizes. A small cable is called a "stranded wire" or a "cord," both of which are defined below. Cables may be bare or insulated, and the latter may be armored with lead, or with steel wires or bands.

639 **Strand.**—One of the wires, or groups of wires, of any stranded conductor.

640 **Stranded Wire.**—A group of small wires, used as a single wire.

A wire has been defined as a slender rod or filament of drawn metal. If such a filament is subdivided into several smaller filaments or strands, and is used as a single wire, it is called a "stranded wire." There is no sharp dividing line of size between a "stranded wire" and a "cable." If used as a wire, for example in winding inductance coils or magnets, it is called a stranded wire and not a cable. If it is substantially insulated, it is called a "cord," defined below.

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*From Circular No. 37 of the Bureau of Standards.

641 **Cord.**—A small cable, very flexible and substantially insulated to withstand wear.

There is no sharp dividing line in respect to size between a "cord" and a "cable," and likewise no sharp dividing line in respect to the character of insulation between a "cord" and a "stranded wire." Rubber is used as the insulating material for many classes of cords.

642 **Concentric Strand.**—A strand composed of a central core surrounded by one or more layers of helically-laid wires or groups of wires.

643 **Concentric-Lay Cable.**—A single-conductor cable composed of a central core surrounded by one or more layers of helically-laid wires.

644 **Rope-Lay Cable.**—A single-conductor cable composed of a central core surrounded by one or more layers of helically-laid groups of wires.

This kind of cable differs from the preceding in that the main strands are themselves stranded.

645 **N-Conductor Cable.**—A combination of N conductors insulated from one another.

It is not intended that the name as here given be actually used. One would instead speak of a "3-conductor cable," a "12-conductor cable" etc. In referring to the general case, one may speak of a "multiple-conductor cable" (as in definition §638 above.)

646 **N-Conductor Concentric Cable.**—A cable composed of an insulated central conducting core with (N − 1) tubular stranded conductors laid over it concentrically and separated by layers of insulation.

This kind of cable usually has only two or three conductors. Such cables are used in carrying alternating currents. The remark on the expression "N-conductor" given for the preceding definition applies here also.

647 **Duplex Cable.**—Two insulated single-conductor cables, twisted together.

They may or may not have a common insulating covering.

648 **Twin Cable.**—Two insulated single-conductor cables laid parallel, having a common covering.

649 **Triplex Cable.**—Three insulated single-conductor cables twisted together.

They may or may not have a common insulating covering.

650 **Twisted Pair.**—Two small insulated conductors, twisted together, without a common covering.

The two conductors of a "twisted pair" are usually substantially insulated, so that the combination is a special case of a "cord."

651 **Twin Wire.**—Two small insulated conductors laid parallel, having a common covering.

SPECIFICATION OF SIZES OF CONDUCTORS

652 **The sizes of solid wires shall be stated by their diameter in mils, the American Wire Gage (Brown and Sharpe) sizes being taken as standard. The sizes of stranded conductors shall be stated by their cross-sectional area in circular mils. For brevity, in cases where the most**

careful specification is not required, the sizes of solid wires may be stated by the gage number in the American Wire Gage, and the sizes of stranded conductors smaller than 250,000 circular mils (*i.e.*, No. 0000 A.W.G. or smaller) may likewise be stated by means of the gage number in the American Wire Gage of a solid wire having the same cross-sectional area. Futhermore, an exception is made in the case of " Flexible Stranded Conductors," for which see §655 below. In stating large cross-sections, it is sometimes convenient to use a circular inch (507 sq. mm.) instead of 1,000,000 circular mils.

STRANDING

653 Cables not requiring special flexibility shall be stranded in accordance with the following table.

TABLE XII

Standard Stranding of Concentric Lay-Cables

SIZE (See note 1.)	Number of Wires (See note 2) A — Bare, insulated or weatherproof cables for aerial use.	Number of Wires (See note 2) B — Insulated cables for other than aerial use.
2.0 Cir. Inches	91	127
1.5 "	61	91
1.0 "	61	61
0.6 "	37	61
0.5 "	37	37
0.4 "	19	37
0000 A. W. G.	19 or 7 (See note 3.)	19
00 "	7	19
2 "	7	7
7 and smaller	..	7

1. For intermediate sizes, use stranding for next larger size.
2. Conductors of 0000 A. W. G. and smaller are often made solid and this table of stranding should not be interpreted as excluding this practice.
3. Class A cable, sizes 0000 and 000 A. W. G., is usually made of 7 strands when bare and 19 strands when insulated or weatherproof.

654 Sectional Area of Cables. The cross-sectional area of a cable shall be considered to be the sum of the cross-sectional areas of its component wires, when measured perpendicular to their axes.

655 **Flexible Stranding.** Conductors of special flexibility should ordinarily be made with wires of regular A.W.G. sizes,* the number of wires and size being given. The approximate gage number or approximate circular mils of such flexible stranded conductors may be stated. The stranding of standard flexible cables is given in Table XIII and a tentative stranding for apparatus cable in Table XIII-A.

TABLE XIII

Proposed Standard Stranding of Flexible Cables

Nearest A.W.G. size (see Note 1)	Circular mils (see Note 3)	Diam. of cable. Mils	No. of wires	Size of each wire A.W.G.	Diam. Mils	Make-up (see Note 2)
	2039000	1836.	703	15.5	53.9	37 × 19
..	1816000	1778.	"	16.0	50.8	"
..	1617000	1680.	"	16.5	48.0	"
..	1440000	1586.	"	17.0	45.3	"
..	1282000	1495.	"	17.5	42.7	"
..	1103000	1372.	427	16.0	50.8	61 × 7
..	874500	1223.	"	17.0	45.3	"
..	693400	1088.	"	18.0	40.3	"
..	550000	969.	"	19.0	35.9	"
..	436400	864.	"	20.0	32.0	"
..	345900	770.	"	21.0	28.5	"
..	274300	686.	"	22.0	25.4	"
..	264700	672.	259	20.0	32.0	37 × 7
0000	209800	599.	"	21.0	28.5	"
000	171300	539.	133	19.0	35.9	19 × 7
00	135900	480.	"	20.0	32.0	"
0	107700	428.	"	21.0	28.5	"
1	82780	332.	91	20.5	30.2	Concentric
2	65660	296.	"	21.5	26.9	"
3	58460	279.	"	22.0	25.4	"
4	39190	229.	61	22.0	25.4	"
5	31080	203.	"	23.0	22.6	"
6	24650	181.	"	24.0	20.1	"
8	17400	152.	"	25.5	16.9	"
10	10560	118.	37	25.5	16.9	"
12	6442	94.	"	27.5	13.4	"
14	4177	74.	"	29.5	10.6	"
Smaller	....	....	To equal Required Size	30.0	....	Bunched

Note 1. The A.W.G. sizes except for 61 strands are approximated within 2 per cent. In the case of 61 strand cables the approximation is 6 per cent.

Note 2. "61 × 7" signifies a rope-lay cable composed of 61 strands of 7 wires each.

Note 3. Circular mils are based on theoretical diameters of A.W.G. sizes which vary above or below values given in table by less than 0.1 mil.

*Where necessary to closely approximate a regular size cable, the strands may be made of half-size wires from No. 15 to No. 30 A. W. G.

TABLE XIII-A

Proposed Standard Stranding of Apparatus Cables

(This table is offered for consideration but will not be recommended for final adoption until ratified by other societies interested.)

Nearest A.W.G. size (see Note 1)	Circular mils (see Note 3)	Diameter of cable Mils	No. of wires	Size of each wire A.W.G	Diam. Mils	Make-up
..	2053000	1903.	2257	20.5	30.2	61 × 37
..	1829000	1796.	"	21.0	28.5	"
..	1629000	1695.	"	21.5	26.9	"
..	1450000	1600.	"	22.0	25.4	"
..	1291000	1506.	"	22.5	23.9	"
..	1150000	1424.	"	23.0	22.6	"
..	1054000	1359.	1159	20.5	30.2	61 × 19
..	938900	1283.	"	21.0	28.5	"
..	836200	1211.	"	21.5	26.9	"
..	744500	1143.	"	22.0	25.4	"
..	663000	1076.	"	22.5	23.9	"
..	590500	1017.	"	23.0	22.6	"
..	525800	958.	"	23.5	21.3	"
..	451600	889.	703	22.0	25.4	37 × 19
..	402200	836.	"	22.5	23.9	"
..	358200	791.	"	23.0	22.6	"
..	319000	745.	"	23.5	21.3	"
..	284000	703.	"	24.0	20.1	"
..	253000	665.	"	24.5	19.0	"
0000	217600	610.	427	23.0	22.6	61 × 7
000	172500	543.	"	24.0	20.1	"
00	136800	483.	"	25.0	17.9	"
0	104600	422.	259	24.0	20.1	37 × 7
1	82980	376.	"	25.0	17.9	"
2	65810	334.	"	26.0	15.9	"
3	52190	298.	"	27.0	14.2	"
4	42610	268.	133	25.0	17.9	19 × 7
5	33800	238.	"	26.0	15.9	"
6	26800	213.	"	27.0	14.2	"
see Note 2.						

NOTE 1. The A.W.G. sizes are approximated within 3 per cent.
NOTE 2. For sizes smaller than No. 6 see table XIII.
NOTE 3. Circular mils are based on theoretical diameters of A.W.G. sizes, which vary above or below values given in table by less than 0.1 mil.

656 **Correction for Lay.** The resistance and mass of a stranded conductor are greater than in a solid conductor of the same cross-sectional area, depending on the lay (*i.e.*, the pitch of the twist of the wires). Two per cent shall be taken as the standard increment of resistance and of mass. In cases where the lay is definitely known, the increment should be calculated and not assumed.

The direction of lay is the lateral direction in which the strands of a cable run over the top of the cable as they recede from an observer looking along the axis of the cable.

657 The lay of any layer of wires of a cable or strand shall not exceed 15 times the pitch diameter of that layer. The lay of any layer of

strands of rope-lay cables shall not exceed 12 times the pitch diameter of the layer.

CONDUCTIVITY OF COPPER.

675 The following I. E. C. rules are adopted:*

The following shall be taken as normal values for standard annealed copper:

(1) At a temperature of 20°C., the resistance of a wire of standard annealed copper one meter in length and of a uniform section of 1 square millimeter is 1/58 ohm = 0.017241.... ohm.

(2) At a temperature of 20°C., the density of standard annealed copper is 8.89 grams per cubic centimeter.

(3) At a temperature of 20°C, the "constant mass" temperature coefficient of resistance of standard annealed copper, measured between two potential points rigidly fixed to the wire, is 0.00393 = 1/254.45.... per degree centigrade.

(4) As a consequence, it follows from (1) and (2) that, at a temperature of 20 °C. the resistance of a wire of standard annealed copper of uniform section, one meter in length and weighing one gram, is (1/58) × 8.89 = 0.15328...... ohm.†§

676 **Copper Wire Tables.** The copper-wire Tables published by the Bureau of Standards in Circular No. 31 are adopted. These Tables are based upon the I. E. C. rules stated in §675.

HEATING AND TEMPERATURE OF CABLES.

677 **Maximum Safe Limiting Temperatures.**

The maximum safe limiting temperature in degrees C. at the surface of the conductor in a cable shall be:—

For impregnated paper insulation	(85—E)
" varnished cambric	(75—E)
" rubber insulation	(60—0.25E)

where E represents the r.m.s. operating e.m.f. in kilovolts between conductors.

Thus, at a working pressure of 3.3 kv., the maximum safe limiting temperature at the surface of the conductor, or conductors, in a cable would be:—

For impregnated paper	81.7°C.
" varnished cambric	71.7°C.
" rubber insulation	59.2°C.

ELECTRICAL TESTS.

678 **Lengths Tested.** Electrical tests of insulation on wires and cables shall be made on the entire lengths to be shipped.

*See I. E. C. Publication No. 28 "International Standard of Resistance for Copper" March 1914.

†Paragraphs (1) and (4) of § 675 define what are sometimes called "volume resistivity," and "Mass resistivity" respectively. This may be expressed in other units as follows:—volume resistivity = 1.7241 microhms-cm. (or microhms in a cm. cube) at 20°C. = 0.67879 microhm-inch at 20°C., and mass resistivity = 875.20 ohms (mile, pound) at 20°C.

§For detailed specifications of commercial copper, see the "Standard Specifications" of the American Society for Testing Materials.

679 **Immersion in Water.** Electrical tests of insulated conductors not enclosed in a lead sheath, shall be made while immersed in water after an immersion of twelve (12) consecutive hours, if insulated with rubber compound, or if insulated with varnished cambric. It is not necessary to immerse in water insulated conductors enclosed in a lead sheath.

In multiple-conductor cables, without waterproof overall jacket of insulation, no immersion test should be made on finished cables, but only on the individual conductors before assembling.

680 **Dielectric-Strength Tests. Object of Tests.** Dielectric tests are intended to detect weak spots in the insulation and to determine whether the dielectric strength of the insulation is sufficient for enabling it to withstand the voltage to which it is likely to be subjected in service, with a suitable factor of assurance.

The initially-applied voltage must not be greater than the working voltage, and the rate of increase shall not be over 100 per cent in 10 seconds.

681 **Factor of Assurance.** The factor of assurance of wire or cable insulation shall be the ratio of the voltage at which it is tested to that at which it is used.

682 **Test Voltage.** The dielectric strength of wire and cable insulation shall be tested at the factory, by applying an alternating test voltage between the conductor and sheath or water.

683 **The Magnitude and Duration of the Test Voltage** should depend upon the dielectric strength and thickness of the insulation, the length and diameter of the wire or cable, and the assurance factor required, the latter in turn depending upon the importance of the service in which the wire or cable is employed.

684 **The following test voltages** shall apply unless a departure is considered necessary, in view of the above circumstances. Rubber covered wires or cable for voltages up to 7 kv. shall be tested in accordance with the National Electric Code. Standardization for higher voltages for rubber insulated cables is not considered possible at the present time.

Varnished cambric and impregnated paper insulated wires or cables shall be tested at the place of manufacture for five (5) minutes in accordance with the Table XIV below.

TABLE XIV

Recommended Test Kilovolts Corresponding to Operating Kilovolts

Operating kv.	Test kv.	Operating kv.	Test kv.
Below 0.5	2.5*	5	14
0.5	3	10	25
1	4	15	35
2	6.5	20	44
3	9	25	53
4	11.5		

*The minimum thickness of insulation shall be $\frac{1}{16}$ in. (1.6 mm.)

Different engineers specify different thickness of insulation for the same working voltages. Therefore, at the present time the test kv. corresponding to working kv. given in Table XIV are based on the **minimum** thickness of insulation specified by engineers and operating companies.†

685 **The Frequency of the Test Voltage** shall not exceed 100 cycles per second, and should approximate as closely as possible to a sine wave. The source of energy should be of ample capacity.

686 **Where Ultimate Break-Down Tests** are required, these shall be made on samples not more than 6 meters (20 ft.) long. The maximum allowable temperature at which the test is made for the particular type of insulation and the particular working pressure, shall not be greater than the temperature limits given in **§ 677**.

687 **Multiple-Conductor Cables.** Each conductor of a multiple-conductor cable shall be tested against the other conductors connected together with the sheath or water.

INSULATION RESISTANCE

688 **Definition.** The insulation resistance of an insulated conductor is the electrical resistance offered by its insulation, to an impressed voltage tending to produce a leakage of current through the same.

689 **Insulation Resistance** shall be expressed in megohms for a specified length (as for a kilometer, or a mile, or one thousand feet), and shall be corrected to a temperature of 15.5° C. using a temperature coefficient determined experimentally for the insulation under consideration.

690 **Linear Insulation Resistance,** or the insulation resistance of Unit Length, shall be expressed in terms of the megohm-kilometer, or the megohm-mile, or the megohm-thousand-feet.

691 **Megohms Constant.** The Megohms Constant of an insulated conductor shall be the factor " K " in the equation

$$R = K \log_{10} \frac{D}{d}$$

where R = The insulation resistance, in megohms, for a specified unit length.

D = Outside diameter of insulation.

d = Diameter of conductor.

Unless otherwise stated, K will be assumed to correspond to the mile unit of length.

692 **Test.** The apparent insulation resistance should be measured after the dielectric-strength test, measuring the leakage current after a one-minute electrification, with a continuous e.m.f. of from 100 to 500 volts, the conductor being maintained negative to the sheath or water.

†The Standards Committee does not commit itself to the principle of basing test voltages on working voltages, but it is not yet in possession of sufficient data to base them upon the dimensions and physical properties of the insulation.

693 **Multiple-Conductor Cables.** The insulation resistance of each conductor of a multiple-conductor cable shall be the insulation resistance measured from such conductor to all the other conductors in multiple with the sheath or water.

CAPACITANCE OR ELECTROSTATIC CAPACITY

694 **Capacitance** is ordinarily expressed in microfarads. Linear Capacitance, or Capacitance per unit length, shall be expressed in Microfarads per unit length (kilometer, or mile, or one thousand feet) and shall be corrected to a temperature of 15.5° C.

695 **Microfarads Constant.** The Microfarads Constant of an insulated conductor shall be the factor " K " in the equation

$$C = \frac{K}{\text{Log}_{10} \frac{D}{d}}$$

where C = the capacitance in microfarads per unit length.

D = the outside diameter of insulation.

d = the diameter of conductor.

Unless otherwise stated, K will be assumed to refer to the mile unit of length.

696 **Measurement of Capacitance.** The Capacitance of low-voltage cable, shall be measured by comparison with a standard condenser. For long lengths of high-voltage cables, where it is necessary to know the true capacitance, the measurement should be made at a frequency approximating the frequency of operation.

697 **Paired Cables.** The capacitance shall be measured between the two conductors of any pair, the other wires being connected to the sheath or ground.

698 **Electric Light and Power Cables.** The capacitance of low-voltage cables is generally of but little importance. The capacitance of high-voltage cables should be measured between the conductors, and also between each conductor and the other conductors connected to the lead sheath or ground.

699 **Multiple-Conductor Cables** (not paired). The capacitance of each conductor of a multiple-conductor cable shall be the capacitance measured from such conductor to all of the other conductors in multiple with the sheath or the ground.

STANDARDS FOR SWITCHES AND OTHER CIRCUIT-CONTROL APPARATUS*

SWITCHES

720 **The following Rules apply to Switches** of above 600 volts. (For 600 volts and below, see National Electric Code.†)

721 **Definition.** A switch is a device for making, breaking, or changing connections in an electric circuit.

722 **Rating.**

(a) By amperes to be carried with not more than 30 °C. rise on contacts and current-carrying parts.

(b) By normal voltage of circuit on which it may be used.

723 **Performance and Tests.**

(a) **Heating Test** with rated current applied continuously until temperature is constant; ambient temperature 40 °C.

(b) **Dielectric Test** at 2½ times rated voltage plus 2000. See **§509.**

CIRCUIT BREAKERS

724 **Definition.** A device designed to open a current-carrying circuit without injury to itself. A circuit breaker‡ may be:

(a) An automatic circuit-breaker, which is designed to trip automatically under any predetermined condition of the circuit, such as an underload or overload of current or voltage.

(b) A manually tripped circuit-breaker, which is designed to be tripped by hand.

Both types of operation may be combined in one and the same device.

725 **Rating.**

(a) By normal current-carrying capacity.

(b) By normal voltage.

(c) By amperes which it can interrupt at normal voltage of the circuit.

726 **Performance and Tests.** The heating test shall be made with normal current. In oil circuit breakers the same oil must be used for heating tests as for rupturing tests. The rise of temperature at the contacts shall not exceed 30 °C. The Rise on tripping solenoids and accessory parts not to exceed 50 °C. Ambient temperature of reference, 40 °C.

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*These rules do not apply to magnetically-operated or air-operated switches used for motor control.

†By the term "Code" is meant "National Electrical Code" as recommended by the National Fire Protection Association.

‡These rules refer only to circuit breakers of above 550 volts. For 550 volts and below, see the National Electric Code.

727 **Dielectric Test.** Same as §723.

728 **Rupturing Test** must be made with the current specified under §725 (c), and at normal voltage.

NOTE. Although circuit breakers should be considered as devices alone, no account being taken, in the rating, of the system on which they are to be used: yet in applying circuit breakers to any given service, it may be necessary to take into account the system on which they are to be used, with all its characteristics.

Allowances must be made for the reactance, resistance, etc., of the circuit to be controlled, as these have a direct bearing on the maximum current flow.

In some systems it has been found that the pressure rises so high during switching, that higher insulation tests than that specified in §723 should be given.

FUSES

(For circuits up to and including 600 volts, see National Electric Code)

729 **Definition.** A fuse is an element designed to melt or dissipate at a predetermined current value, and intended to protect against abnormal conditions of current.

NOTE. (The terminals, tubes, etc. which go with the fuse proper are included in the definition).

730 **Rating.** Fuses shall be rated at the maximum current which they are required to carry continuously, and at the normal voltage of the circuit on which they are designed to be used.

Fuses may be divided into two classes:

(1) Those designed to protect the circuit and apparatus both against short circuit and against definite amounts of overload (*e.g.* fuses of the National Electric Code which open on 25 per cent overload).

(2) Those designed to protect the system only against short circuits; (*e.g.* expulsion fuses, which blow at several times the current which they are designed to carry continuously). The line separating these two classes is not definitely fixed.

731 **Temperature.** Coils or windings (such as accompany fuses of the magnetic blow-out type) should not exceed the limits set for machine coils having the same character of insulation. (See §§376 to 379). The highest temperature for the fuse proper should not exceed the safe limit for the material employed (*e.g.* the temperature of the fibre tube of an enclosed fuse should not exceed the safe limit for this material, but an open-link metal fuse may be run at any temperature which will not injure the fuse material; except that no application of the above rule shall contravene the National Electric Code).

732 **Test.** For fuses intended for use on circuits of small capacity, or in protected positions on systems of large capacity, see Nation-

NOTE. Complete standardization of these fuses above 600 volts, according to the method of the National Electric Code, is not advisable at this time, but is expected to be accomplished by an eventual extension of the National Electric Code. Until such extension is made, the following definitions and ratings may be followed.

al Electric Code. For large power fuses intended for service similar to that required of circuit breakers, see **§724** to **728**, or the National Electric Code, as far as the latter applies.

LIGHTNING ARRESTERS

733 **Definition.** A lightning arrester is a device for protecting circuits and apparatus against lightning or other abnormal potential rises of short duration.

734 **Rating.** Arresters shall be rated by the voltage of the circuit on which they are to be used.

Lightning arresters may be divided into two classes:

(a) Those intended to discharge for a very short time.

(b) Those intended to discharge for a period of several minutes.

735 **Performance and Tests.** Dielectric Test same as **§723.**

The resistance of the arrester at double potential and also at normal potential, shall be determined by observing the discharge currents through the arrester.

(c) In the case of any arrester using a gap, a test shall be made of the spark potential on either direct-current or 60-cycle a-c. excitation.

(d) The equivalent sphere gap under disruptive discharge shall also be measured, using a considerable quantity of electricity.

(e) The endurance of the arrester to continuous surges shall be tested.

PROTECTIVE REACTORS

736 **Definition.** A reactor (See **§82** and **214**) is a device for protecting circuits by limiting the current flow and localizing the disturbance under short-circuit conditions.

737 **Rating.**

(a) In kilovolt-amperes absorbed by normal current.

(b) By the normal current, frequency and line (delta) voltage for which the reactor is designed.

(c) By the current which the device is required to stand under short-circuit conditions.

738 **Performance and Tests.**

The Heat Test shall be made with normal current and frequency applied until the temperature is constant. The temperature should not exceed the safe limits for the materials employed. See **§§376** to **379.**

739 **Dielectric Test.** 2½ times line voltage plus 2000, for one minute, from conductor to ground.

NOTE. The reactor shall be so designed as to be capable of withstanding, without mechanical injury, rated current at normal frequency, suddenly applied.

RESISTOR OR RHEOSTAT

740 **Definition.** Any device heretofore commonly known as a resistance, used for operation or control. (**§81**) See National Electric Code.

INSTRUMENT TRANSFORMERS

741 **Definition.** An instrument transformer is a transformer for use with measuring instruments, in which the conditions in the primary circuit as to current and voltage are represented with high numerical accuracy in the secondary circuit.

Under this heading and for more general use:

(a) A current transformer is a transformer designed for series connection in its primary circuit with the ratio of transformation appearing as a ratio of currents.

(b) A potential (voltage) transformer is a transformer designed for shunt or parallel connection in its primary circuit, with the ratio of transformation appearing as a ratio of potential differences (voltages)

For further definitions relative to instrument transformers, see **205-207.**

For the dielectric test of potential transformers, see **§500,** and for the dielectric test of current transformers, see **§509.**

Further standards concerning instrument transformers are still under discussion.

STANDARDS FOR ELECTRIC RAILWAYS

DEFINITIONS

760 **Transmission System:** When the current generated for an electric railway is changed in kind or voltage, between the generator and the cars or locomotives, that portion of the conductor system carrying current of a kind or voltage substantially different from that received by the cars or locomotives, constitutes the *transmission system.**

761 **Distribution System:** That portion of the conductor system of an electric railway which carries current of the kind and voltage received by the cars or locomotives, constitutes the *distribution system.**

762 **Substation:** A substation is a group of apparatus or machinery which receives current from a transmission system, changes its kind or voltage, and delivers it to a distribution system.

RATING OF RAILWAY SUBSTATION MACHINERY

763 **Continuous Rating.** The rating of a substation machine shall be the kv-a. output at a stated power factor input, which it will deliver continuously with temperatures or temperature rises not exceeding the limiting values given in Sections **376** and **379** and also fulfilling the other requirements set forth in these rules and summarized in Section **260.**

764 **Momentary Loads.** These machines should be capable of carrying a load of twice their rating for one minute, after a continuous run at rated load, without disqualifying them for continuous service.

765 **Nominal Rating.** Where the continuous rating is inconvenient, the following nominal rating may be used. The nominal rating of a substation machine shall be the kv-a. output at a stated power factor input, which, having produced a constant temperature in the machine may be increased 50 per cent for two hours, without producing temperatures or temperature rises exceeding by more than 5°C. the limiting values given in §**376** and **379.** These machines should be capable of carrying a load of twice their nominal rating for a period of one minute, without disqualifying them for continuous service. The name plate should be marked " nominal rating."

CONDUCTOR AND RAIL SYSTEMS.

766 **Contact Conductors.** That part of the distribution system other than the traffic rails, which is in immediate electrical contact with

*These definitions are identical in sense, although not in words, with those of the Interstate Commerce Commission, as given in their Classification of Accounts for Electric Railways.

the circuits of the cars or locomotives, constitutes the contact conductors.

767 **Contact Rail:** A rigid contact conductor.

768 OVERHEAD CONTACT RAIL: A contact rail above the elevation of the maximum equipment line.†

769 THIRD RAIL: A contact conductor placed at either side of the track, the contact surface of which is a few inches above the level of the top of the track rails.

770 CENTER CONTACT RAIL: A contact conductor placed between the track rails, having its contact surface above the ground level.

771 UNDERGROUND CONTACT RAIL: A contact conductor placed beneath the ground level.

772 GAGE OF THIRD RAIL: The distance, measured parallel to the plane of running rails, between the gage line of the nearer track rail and the inside gage line of the *contact surface* of the third rail.

773 ELEVATION OF THIRD RAIL: The elevation of the contact-surface of the third rail, with respect to the plane of the tops of running rails.

774 STANDARD GAGE OF THIRD RAILS: The gage of third rails shall be not less than 26 inches (66 cm.) and not more than 27 inches (68.6 cm.).

775 STANDARD ELEVATION OF THIRD RAILS: The elevation of third rails shall be not less than 2¾ inches (70 mm.), and not more than 3½ inches (89 mm.).

776 THIRD RAIL PROTECTION: A guard for the purpose of preventing accidental contact with the third rail.

777 **Trolley Wire:** A flexible contact conductor, customarily supported above the cars.

778 **Messenger Wire or Cable:** A wire or cable running along with and supporting other wires, cables or contact conductors.

A primary messenger is directly attached to the supporting system. A secondary messenger is intermediate between a primary messenger and the wires, cables or contact conductors.

779 **Classes of Construction:** Overhead trolley construction will be classed as *Direct Suspension* and *Messenger or Catenary Suspension*

780 DIRECT SUSPENSION: All forms of overhead trolley construction in which the trolley wires are attached, by insulating devices, directly to the main supporting system.

781 MESSENGER OR CATENARY SUSPENSION: All forms of overhead trolley construction in which the trolley wires are attached, by suitable devices, to one or more messenger cables, which in turn may be carried either in *Simple Catenary*, *i.e.*, by primary messengers, or in *Compound Catenary*, *i.e.*, by secondary messengers.

782 SUPPORTING SYSTEMS shall be classed as follows:

783 SIMPLE CROSS-SPAN SYSTEMS: Those systems having at each support a single flexible span across the track or tracks.

†The contour which embraces cross-sections of all rolling stock under all normal operating conditions.

784 MESSENGER CROSS-SPAN SYSTEMS: Those systems having at each support two or more flexible spans across the track or tracks, the upper span carrying part or all of the vertical load of the lower span.

785 BRACKET SYSTEMS: Those systems having at each support an arm or similar rigid member, supported at only one side of the track or tracks.

786 BRIDGE SYSTEMS: Those systems having at each support a rigid member, supported at both sides of the track or tracks.

787 STANDARD HEIGHT OF TROLLEY WIRE ON STREET AND INTERURBAN RAILWAYS: It is recommended that supporting structures shall be of such height that the lowest point of the trolley wire shall be at a height of 18 feet (5.5m.) above the top of rail under conditions of maximum sag, unless local conditions prevent. On trackage operating electric and steam road equipment and at crossings over steam roads, it is recommended that the trolley wire shall be not less than 21 feet (6.4m.) above the top of rail, under conditions of maximum sag.

RAILWAY MOTORS

RATING

800 **Nominal Rating:** The nominal rating of a railway motor shall be the mechanical output at the car or locomotive axle, measured in kilowatts, which causes a rise of temperature above the surrounding air, by thermometer, not exceeding 90 °C. at the commutator, and 75 °C. at any other normally accessible part after one hour's continuous run at its rated voltage (and frequency in the case of an alternating-current motor) on a stand with the motor covers arranged to secure maximum ventilation without external blower. The rise in temperature as measured by resistance, shall not exceed 100 °C.*

801 The statement of the nominal rating shall also include the corresponding voltage and armature speed.

802 **Continuous Rating:** The continuous ratings of a railway motor shall be the *inputs* in amperes at which it may be operated continuously at ½, ¾ and full voltage respectively, without exceeding the specified temperature rises (see §805), when operated on stand test with motor covers and cooling system, if any, arranged as in service. Inasmuch as the same motor may be operated under different conditions as regards ventilation, it will be necessary in each case to

* This definition differs from that in the 1911 edition of the Rules, principally by the substitution of a kilowatt rating for the horse-power rating and the omission of a reference to a room temperature of 25°C. For the purposes of these Rules the horse-power shall be taken as 746.0 watts. On account of the hitherto prevailing practise of expressing mechanical output in horse-power, it is recommended that, for the present the capacity be expressed both in kilowatts and in horse-power, a double rating, namely,

kw.———————approx. equiv. h.p.———————

In order to lay stress upon the preferred future basis, it is desirable that on rating plates, the rating in kilowatts shall be shown in larger and more prominent characters than the capacity in horse power.

define the system of ventilation which is used. In case motors are cooled by external blowers, the flow of air on which the rating is based shall be given.

803 **Maximum Input.** The subject of momentary loads for railway motors is under investigation.

TEMPERATURE LIMITATIONS

804 **The allowable temperature** in any part of a motor in service will be governed by the kind of material with which that part is insulated. In view of space limitations, and the cost of carrying dead weight on cars, it is considered good practice to operate railway motors for short periods at higher temperatures than would be advisable in stationary motors. The following temperatures are permissible:

TABLE XV

Operating Temperatures of Railway Motors

Class of Material See §376 to 379.	Maximum Observable Temperature of windings when in continuous service.	
	By Thermometer See §345	By Resistance
A	85	110
B	100	130

For infrequent occasions, due to extreme ambient temperatures, it is permissible to operate at 15° higher temperature.

805 With a view to not exceeding the above temperature limitations, the continuous ratings shall be based upon the **temperature rises** tabulated below:

TABLE XVI

Stand-Test Temperature Rises of Railway Motors*

Class of Material See §376 to 379	Temperature Rises of windings	
	By Thermo-meter See §345	By Resis-tance
A	65	85
B	80	105

*The temperature rise in service may be very different from that on stand test. See § 1104 for relation between stand test and service temperatures, as affected by ventilation.

806 **Field-Control Motors.** The nominal and continuous ratings of field-control motors shall relate to their performance with the operating field which gives the maximum motor rating. Each section of the field windings shall be adequate to perform the service required of it, without exceeding the specified temperature rises.

CHARACTERISTIC CURVES

810 **The Characteristic Curves** of railway motors shall be plotted with the current as abscissas and the tractive effort, speed and efficiency as ordinates. In the case of a-c. motors, the power factor shall also be plotted as ordinates.

811 **Characteristic curves of direct-current motors** shall be based upon full voltage, which shall be taken as 600 volts, or a multiple thereof.

812 **In the case of field-control motors,** characteristic curves shall be given for all operating field connections.

EFFICIENCY AND LOSSES

815 **The efficiency** of railway motors shall be deduced from a determination of the losses enumerated in §816 to 820. (See also § 1100 and 1101.)

816 **The copper loss** shall be determined from resistance measurements corrected to 75° C.

817 **The no-load core loss, brush friction, armature-bearing friction and windage** shall be determined as a total under the following conditions:

In making the test, the motor shall be run without gears. The kind of brushes and the brush pressure shall be the same as in commercial service. With the field separately excited, such a voltage shall be applied to the armature terminals as will give the same speed for any given field current as is obtained with that field current when operating at normal voltage under load. The sum of the losses above-mentioned, is equal to the product of the counter-electromotive force and the armature current.

818 The **core loss** in d-c. motors shall be separated from the friction and windage losses above described by measuring the power required to drive the motor at any given speed without gears, by running it as a series motor on low voltage and deducting this loss from the sum of the no-load losses at corresponding speed. (See §1101 for alternative method).

The friction and windage losses under load shall be assumed to be the same as without load, at the same speed.

The core loss under load shall be assumed as follows:

TABLE XVII

Core Loss in D-C. Railway Motors at Various Loads.

Per cent of Input at Nominal Rating	Loss as Per cent of No-load Core Loss
200	165
150	145
100	130
75	125
50	123
25 and under	122

Note:—With motors designed for field control the core losses shall be assumed as the same for both full and permanent field. It shall be the mean between the no-load losses at full and permanent field, increased by the percentages given in the above Table

819 **The brush-contact resistance loss** to be used in determining the efficiency, may be obtained by assuming that the sum of the drops at the contact surfaces of the positive and negative brushes is three volts.

820 The losses in gearing and axle bearings for single-reduction single-geared motors, varies with type, mechanical finish, age and lubrication The following values, based on accumulated tests, shall be used in the comparison of single-reduction single-geared motors.

TABLE XVIII

Losses in Axle Bearings and Single-Reduction Gearing of Railway Motors.

Per Cent of Input at Nominal Rating	Losses as Per Cent of Input
200	3.5
150	3.0
125	2.7
100	2.5
75	2.5
60	2.7
50	3.2
40	4.4
30	6.7
25	8.5

Note:—Further investigation may indicate the desirability of giving separate values of the losses for full and tapped fields, or low- and high-speed motors.

ELECTRIC LOCOMOTIVES

830 **Rating.** Locomotives shall be rated in terms of the weight on drivers, nominal one-hour tractive effort, continuous tractive effort and corresponding speeds.

831 **Weight on Drivers.** The weight on drivers, expressed in pounds, shall be the sum of the weights carried by the drivers and of the drivers themselves.

832 **Nominal Tractive Effort:** The nominal tractive effort, expressed in pounds, shall be that exerted at the rims of the drivers, when the motors are operating at their nominal (one-hour) rating.

833 **Continuous Tractive Effort.** The continuous tractive effort, expressed in pounds, shall be that exerted at the rims of the drivers when the motors are operating at their full-voltage continuous rating, as indicated in **§802**.

In the case of locomotives operating on intermittent service, the continuous tractive effort may be given for ½ or ¾ voltage, but in such cases the voltage shall be clearly specified.

834 **Speed:** The rated speed, expressed in miles per hour, shall be that at which the continuous tractive effort is exerted.

See also Appendix II on Additional Standards for Railway Motors.

RATING OF AUTOMOBILE PROPULSION MOTORS AND GENERATORS

(ROAD VEHICLES)

835 **Continuous Rating.** Automobile propulsion motors and generators shall be given a continuous rating, expressed in kilowatts output available at the shaft at specified speed. The machines shall be able to operate continuously at their rated outputs without exceeding any of the limitations referred to in **§260**.

836 **Short-Time Rating.** Owing to the variety of services which road vehicles are called upon to perform, no single standard period for short-time ratings is recommended.

837 **Nominal Rating.** No special nominal rating is required for automobile propulsion motors or generators.

838 **Temperature Rises.** Owing to space limitations and the cost of carrying dead weight on automobiles, it is considered good practice to operate the propulsion machinery at higher temperatures than would be advisable in stationary machines. The rating of automobiles motors and generators shall be based upon temperature rise, on a stand test and with motor covers arranged as in service, fifteen degrees by thermometer or twenty-five degrees by resistance, above those of **§379**.

839 **Efficiency and Losses.** Unless otherwise specified the efficiency of automobile propulsion machines shall be based upon the output at the shaft, using conventional losses as tabulated in **§440**. When such machines are of low voltage, the great influence of brush-contact losses on the efficiency requires that these losses be determined experimentally for the type of brush used.

ILLUMINATION AND PHOTOMETRY

The following Sections, **850** to **895**, are abstracts from the rules of the Nomenclature and Standards Committee of the Illuminating Engineering Society. They are here included by permission.

850 **Luminous Flux** is radiant power evaluated according to its capacity to produce the sensation of light.

851 **The stimulus coefficient** K_λ for radiation of a particular wavelength, is the ratio of the luminous flux to the radiant power producing it.

852 **The mean value of the stimulus coefficient,** K_m, over any range of wave-lengths, or for the whole visible spectrum of any source, is the ratio of the total luminous flux (in lumens) to the total radiant power (in ergs per second, but more commonly in watts).

853 **The luminous intensity** of a point source of light is the solid angular density of the luminous flux emitted by the source in the direction considered; or it is the flux per unit solid angle from that source.

Defining equation:

Let I be the intensity, F the flux and ω the solid angle.

Then if the intensity is uniform,

$$I = \frac{F}{\omega},$$

854 **Illumination,** on a surface, is the luminous flux-density over that surface, or the flux per unit of intercepting area.

Defining equation:

Let E be the illumination and S the area of the intercepting surface.

Then when uniform,

$$E = \frac{F}{S},$$

855 **Candle,** the unit of luminous intensity maintained by the National Laboratories of France, Great Britain, and the United States.[1]

856 **Candle-power,** luminous intensity expressed in candles.

857 **Lumen,** the unit of luminous flux, equal to the flux emitted in a unit solid angle (steradian) by a point source of one candle-power.[2]

858 **Lux,** a unit of illumination equal to one lumen per square meter. The C. G. S. unit of illumination is one lumen per square centimeter. For this unit Blondel has proposed the name "Phot." One millilumen per square centimeter (milliphot) is a practical derivative of

1 This unit, which is used also by many other countries, is frequently referred to as the international candle.

the C. G. S. system. One foot-candle is one lumen per square foot[2] and is equal to 1.0764 milliphots.

860 **Specific luminous radiation,** the luminous flux-density emitted by a surface, or the flux emitted per unit of emissive area. It is expressed in lumens per square centimeter.

Defining equation:

Let E' be the specific luminous radiation.

For surfaces obeying Lambert's cosine law of emission.

$$E' = \pi b_0.$$

863 **The Lambert, the C. G. S. Unit of Brightness,** the brightness of a perfectly diffusing surface radiating or reflecting one lumen per square centimeter. This is equivalent to the brightness of a perfectly diffusing surface having a coefficient of reflection equal to unity and illuminated by one phot.

864 **For most purposes, the millilambert** (0.001 lambert) is the preferable practical unit. A perfectly diffusing surface emitting one lumen per square foot will have a brightness of 1.076 millilamberts.

865 **Brightness expressed in candles per square centimeter** may be reduced to Lamberts by multiplying by π.

Brightness expressed in candles per square inch may be reduced to foot-candle brightness, by multiplying by the factor $144\,\pi = 452$.

Brightness expressed in candles per square inch may be reduced to lamberts by multiplying by $\pi/6.45 = 0.4868$.

In practise, no surface obeys exactly Lambert's cosine law of emission; hence the brightness of a surface in lamberts is, in general not numerically equal to its specific luminous radiation in lumens per square centimeter.

866 **Coefficient of reflection,** the ratio of the total luminous flux reflected by a surface to the total luminous flux incident upon it. It is a simple numeric. The reflection from a surface may be regular, diffuse or mixed. In perfect regular reflection, all of the flux is reflected from the surface at an angle of reflection equal to the angle of incidence. In perfect diffuse reflection, the flux is reflected from the surface in all directions, in accordance with Lambert's cosine law. In most practical cases, there is a superposition of regular and diffuse reflection.

867 **Coefficient of regular reflection** is the ratio of the luminous flux reflected regularly to the total incident flux.

868 **Coefficient of diffuse reflection** is the ratio of the luminous flux reflected diffusely to the total incident flux.

Defining equation:

Let m be the coefficient of reflection (regular or diffuse).

Then, for any given portion of the surface,

$$m = \frac{E'}{E}$$

2 A uniform source of one candle emits 4π lumens.

869 **Lamp,** a generic term for an artificial source of light.

870 **Primary luminous standard,** a recognized standard luminous source reproducible from specifications.

871 **Representative luminous standard,** a standard of luminous intensity adopted as the authoritative custodian of the accepted value of the unit.

872 **Reference standard,** a standard calibrated in terms of the unit from either a primary or representative standard and used for the calibration of working standards.

873 **Working standard,** any standardized luminous source for daily use in photometry.

874 **Comparison lamp,** a lamp of constant but not necessarily known candle-power, against which a working standard and test lamps are successively compared in a photometer.

875 **Test lamp,** in a photometer,—a lamp to be tested.

876 **Performance curve,** a curve representing the behavior of a lamp in any particular (candle-power, consumption, etc.) at different periods during its life.

877 **Characteristic curve,** a curve expressing a relation between two variable properties of a luminous source, as candle-power and volts, candle-power and rate of fuel consumption, etc.

878 **Horizontal Distribution Curve.** A polar curve representing the luminous intensity of a lamp, or lighting unit, in a plane perpendicular to the axis of the unit, and with the unit at the origin.

879 **Vertical Distribution Curve.** A polar curve representing the luminous intensity of a lamp, or lighting unit, in a plane passing through the axis of the unit, and with the unit at the origin. Unless otherwise specified, a vertical distribution curve is assumed to be an *average* vertical distribution curve, such as may in many cases be obtained by rotating the unit about its axis and measuring the average intensities at the different elevations. It is recommended that in vertical distribution curves, angles of elevation shall be counted positively from the nadir as zero, to the zenith as 180 degrees. In the case of incandescent lamps, it is assumed that the vertical distribution curve is taken with the tip downward.

880 **Mean horizontal candle-power** of a lamp,—the average candle-power in the horizontal plane passing through the luminous center of the lamp.

It is here assumed that the lamp (or other light source) is mounted in the usual manner, or, as in the case of an incandescent lamp, with its axis of symmetry vertical.

881 **Mean spherical candle-power** of a lamp,—the average candle-power of a lamp in all directions in space. It is equal to the total luminous flux of the lamp, in lumens, divided by 4π.

882 **Mean hemispherical candle-power** of a lamp (upper or lower),—the average candle-power of a lamp in the hemisphere considered. It is equal to the total luminous flux emitted by the lamp, in that hemisphere, divided by 2π.

883 **Mean zonal candle-power** of a lamp,—the average candle-power of a lamp over the given zone. It is equal to the total luminous flux emitted by the lamp in that zone, divided by the solid angle of the zone.

884 **Spherical reduction factor** of a lamp,—the ratio of the mean spherical to the mean horizontal candle-power of the lamp.[3]

885 **Photometric Tests** in which the results are stated in candle-power should be made at such a distance from the source of light that the latter may be regarded as practically a point. Where tests are made in the measurement of lamps with reflectors, the results should always be given as "apparent candle-power" at the distance employed, which distance should always be specifically stated.

886 **The output of all illuminants** should be expressed in lumens.

887 **Illuminants should be rated** upon a lumen basis instead of a candle-power basis.

888 **The specific output of electric lamps** should be stated in lumens per watt; and the specific output of illuminants depending upon combustion should be stated in lumens per b.t.u. per hour. The use of the term "efficiency" in this connection should be discouraged.

When auxiliary devices are necessarily employed in circuit with a lamp, the input should be taken to include both that in the lamp and that in the auxiliary devices. For example, the watts lost in the ballast resistance of an arc lamp are properly chargeable to the lamp.

889 **The Specific Consumption** of an electric lamp is its watt consumption per lumen. "Watts per candle" is a term used commercially in connection with electric incandescent lamps, and denotes watts per mean horizontal candle-power.

890 **Life Tests. Electric Incandescent Lamps** of a given type may be assumed to operate under comparable conditions only when their lumens per watt consumed are the same. Life-test results, in order to be compared, must be either conducted under, or reduced to, comparable conditions of operation.

891 **In Comparing Different Luminous Sources**, not only should their candle-power be compared, but also their relative form, brightness, distribution of illumination and character of light.

892 **Lamp Accessories. A reflector** is an appliance, the chief use of which is to redirect the luminous flux of a lamp in a desired direction or directions.

893 **A Shade is** an appliance, the chief use of which is to diminish or to interrupt the flux of a lamp in certain directions, where such flux is not desirable. The function of a shade is commonly combined with that of a reflector.

894 **A Globe is** an enclosing appliance of clear or diffusing materials, the chief use of which is either to protect the lamp, or to diffuse its light.

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3 In the case of a uniform point-source, this factor would be unity, and for a straight cylindrical filament obeying the cosine law it would be $\pi/4$.

895

TABLE XIX.

Photometric Units and Abbreviations.

Photometric quantity	Name of unit	Abbreviations, Symbols and defining equations
1. Luminous flux	Lumen	$F. \Psi$
2. Luminous intensity	Candle	$I = \frac{dF}{d\omega}, \Gamma = \frac{d\Psi}{d\omega}$, cp.
3. Illumination	Phot., foot-candle, lux	$E = \frac{dF}{dS} = \frac{I}{r^2}\cos\theta.\beta$
4. Exposure	Phot-second	$t \quad E$
5. Brightness	Apparent candles per sq. cm. Apparent candles per sq. in.	$b = \frac{dI}{dS \cos\theta}$
	Lambert	$L = \frac{dF}{dS}$
6. Normal brightness	Candles per sq. cm. Candles per sq. in.	$b_0 = \frac{dI}{dS}$
7. Specific luminous radiation	Lumens per sq. cm. Lumens per sq. in.	$E' = \pi b_0 \beta'$
8. Coefficient of reflection	—	$m = \frac{E'}{E}$

9. Mean spherical candlepower	scp
10. Mean lower hemispherical candlepower	lcp
11. Mean upper hemispherical candlepower	ucp
12. Mean zonal candlepower	zcp

13. 1 lumen is emitted by 0.07958 spherical cp.
14. 1 spherical candlepower emits 12.57 lumens.
15. 1 lux = 1 lumen incident per square meter = 0,0001 phot = 0.1 milliphot.
16. 1 phot = 1 lumen incident per sq. cm. = 10.000 lux = 1000 milliphot.
17. 1 milliphot = 0.001 phot = 0.929 foot-candle.
18. 1 foot-candle = 1 lumen incident per square foot = 1.076 milliphot = 10.76 lux.
19. 1 lambert = 1 lumen emitted per square centimeter.*
20. 1 millilambert = 0.001 lambert.
21. 1 lumen, emitted, per square foot* = 1.076 millilambert.
22. 1 millilambert = 0.929 lumen, emitted, per square foot*.
23. 1 lambert = 0.3183 candle per sq. cm. = 2.054 candles per sq. in.
24. 1 candle per sq. cm. = 3.1416 lamberts.
25. 1 candle per sq. in. = 0.4868 lamberts = 486.8 millilamberts.

*Perfect diffusion assumed.

STANDARDS FOR TELEPHONY AND TELEGRAPHY

910 After careful consideration, it does not seem that the time is yet ripe for a formal standardization of terms and definitions used in telephony and telegraphy. Many of the terms commonly employed are used in more than a single way, and conversely, many pieces of apparatus and many constants which are essentially identical from a physical standpoint have been and are known by more than one designation.

911 **Damping of a Circuit.** The damping, at a given point, in a circuit from which the source of energy has been withdrawn, is the progressive diminution in the effective value of electromotive force and current at that point resulting from the withdrawal of electrical energy.

912 **Damping Constant.** The damping constant of a circuit depends upon the ratio of the dissipative to the reactive component of its impedance or admittance.

Applied to the admittance of a condenser or other simple circuit having capacity reactance, the damping constant for a harmonic electromotive force of given frequency is the ratio of the conductance of the condenser or simple circuit at that frequency, to twice the capacity of the condenser at the same frequency.

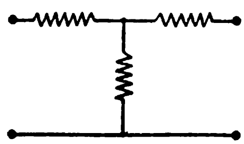
Applied to the reactance of a coil or other simple circuit having inductive reactance, the damping constant for a harmonic current of given frequency is the ratio of the resistance of the coil or circuit at that frequency, to twice the inductance at the same frequency.

913 **Equivalent Circuit.** An equivalent circuit is a simple network of series and shunt impedances, which, at a given frequency, is the approximate electrical equivalent of a complex network at the same frequency and under steady-state conditions.

Note: As ordinarily considered, the simple networks as defined are the electrical equivalents of complex networks only with respect to definite pairs of terminals, and only as to sending-end impedances, and total attenuation. A further requirement is that the only connections between the pairs of terminals are those through the network itself.

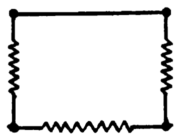
914 **" T " Equivalent Circuit.** A " T " equivalent circuit is a triple-star or " Y " connection of three impedances externally equivalent to a complex network.

Symbol:



915 **"U" Equivalent Circuit.** A "U" equivalent circuit is a delta connection of three impedances externally equivalent to a complex network. It is also called a "Π" equivalent circuit.

Symbol:



IMPEDANCE

916 **Mutual Impedance.** The mutual impedance, for alternating currents, between a pair of terminals and a second pair of terminals of a network, under any given condition, is the negative vector ratio of the electromotive force produced between either pair of terminals on open circuit, to the current flowing between the other pair of terminals.

917 **Self Impedance.** The self impedance between a pair of terminals of a network, under any given condition, is the vector ratio of the electromotive force applied across the terminals to the current produced between them.

LINE CHARACTERISTICS

918 **Characteristic Impedance.** The characteristic impedance of a line is the ratio of the applied electromotive force to the resulting steady-state current upon a line of infinite length and uniform structure, or of periodic recurrent structure.

NOTE: In telephone practice, the terms (1) line impedance, (2) surge impedance, (3) iterative impedance, (4) sending-end impedance, (5) initial sending-end impedance, (6) final sending-end impedance, (7) natural impedance and (8) free impedance, have apparently been more or less indefinitely and indiscriminately used as synonyms with what is here defined as "characteristic impedance."

919 **Sending-End Impedance.** The sending-end impedance of a line is the vector ratio of the applied electromotive force to the resulting steady-state current at the point where the electromotive force is applied.

NOTE: See note under "Characteristic Impedance." In case the line is of infinite length of uniform structure or of periodic recurrent structure, the sending-end impedance and the characteristic impedance are the same.

920 **Propagation Constant.** The propagation constant per unit length of a uniform line, or per section of a line of periodic recurrent structure, is the natural logarithm of the vector ratio of the steady-state currents at various points separated by unit length in a uniform line of infinite length, or at successive corresponding points in a line of recurrent structure of infinite length. The ratio is determined by dividing the value of the current at the point nearer the transmitting end by the value of the current at the point more remote.

921 **Attenuation Constant.** The attenuation constant is the real part of the propagation constant.

922 **Wave-Length Constant.** The wave-length constant is the imaginary part of the propagation constant.

LINE CIRCUITS

930 **Ground-Return Circuit.** A ground-return circuit is a circuit consisting of one or more metallic conductors in parallel, with the circuit completed through the earth.

931 **Metallic Circuit.** A metallic circuit is a circuit of which the earth forms no part.

932 **Two-Wire Circuit.** A two-wire circuit is a metallic circuit formed by two paralleling conductors insulated from each other.

933 **Superposed Circuit.** A superposed circuit is an additional circuit obtained from a circuit normally required for another service, and in such a manner that the two services can be given simultaneously without mutual interference.

934 **Phantom Circuit.** A phantom circuit is a superposed circuit, each side of which consists of the two conductors of a two-wire circuit in parallel.

935 **Side Circuit.** A side circuit is a two-wire circuit forming one side of a phantom circuit.

936 **Non-Phantomed Circuit.** A non-phantomed circuit is a two-wire circuit, which is not arranged for use as the side of a phantom circuit.

937 **Simplexed Circuit.** A simplexed circuit is a two-wire telephone circuit, arranged for the super-position of a single ground-return signalling circuit-operating over the wires in parallel.

Note: In view of the use of the term "Simplex Operation" in telegraph practice, it is felt that the designation "Simplexed Circuit" as applied to the arrangement described is not a happy one.

938 **Composited Circuit.** A composited circuit is a two-wire telephone circuit, arranged for the superposition on each of its component metallic conductors, of a single independent ground-return signalling circuit.

939 **Quadded or Phantomed Cable.** A quadded or phantomed cable is a cable adapted for the use of phantom circuits.

Note: The type of cable here defined has frequently been designated as "Duplex Cable"—a term which is objectionable., both on account of its lack of description and its widely different use in telegraph practice.

LOADING

950 **Loaded Line.** A loaded line is one in which the normal inductance of the circuit has been altered for the purpose of increasing its transmission efficiency for one or more frequencies.

951 **Series Loaded Line.** A series loaded line is one in which the normal inductance has been altered by inductance serially applied.

952 **Shunt Loaded Line.** A shunt loaded line is one in which the normal inductance of the circuit has been altered by inductance applied in shunt across the circuit.

953 **Continuous Loading.** A continuous loading is a series loading in which the added inductance is uniformly distributed along the conductors.

954 **Coil Loading.** A coil loading is one in which the normal inductance is altered by the insertion of lumped inductance in the circuit at intervals. This lumped inductance may be applied either in series or in shunt.

NOTE: As commonly understood, coil loading is a series loading, in which the lumped inductance is applied at uniformly spaced recurring intervals

955 **Microphone.** A contact device designed to have its electrical resistance directly and materially altered by slight differences in mechanical pressure.

956 **Relay.** A relay is a device by means of which contacts in one circuit are operated under the control of electrical energy in the same or other circuits.

957 **Resonance.** Resonance of a harmonic alternating current of given frequency, in a simple series circuit, containing resistance, inductance and capacity, is the condition in which the positive reactance of the inductance is numerically equal to the negative reactance of the capacity. Under these conditions, the current flow in the circuit with a given electromotive force is a maximum.

958 **Retardation Coil.** A retardation coil is a reactor (reactance coil) used in a circuit for the purpose of selectively reacting on currents which vary at different rates.

NOTE: In telephone and telegraph usage, the terms "impedance coil," "inductance coil," choke coil" and "reactance coil" are sometimes used in place of the term "retardation coil."

959 **Skin Effect.** Skin effect is the phenomenon of the non-uniform distribution of current throughout the cross-section of a linear conductor, occasioned by variations in the intensity of the magnetic field due to the current in the conductor.

960 **Telephone Receiver.** A telephone receiver is an electrically operated device, designed to produce sound waves or vibrations which correspond in form to the electromagnetic waves or vibrations actuating it.

961 **Telephone Transmitter.** A telephone transmitter is a sound-wave or vibration-operated device designed to produce electromagnetic waves or vibrations which correspond in form to the sound waves or vibrations actuating it.

962 **The Coefficient of Coupling of a Transformer.** The coefficient of coupling of a transformer at a given frequency, is the vector ratio of the mutual impedance between the primary and secondary of the transformer, to the square root of the product of the self-impedances of the primary and of the secondary.

963 **Repeating Coil.** A term used in telephone practice meaning the same as transformer, and ordinarily a transformer of unity ratio.

APPENDIX I.

STANDARDS FOR RADIO COMMUNICATION

The following Sections **1000** to **1033** have been abstracted from the report of the Standardization Committee of the Institute of Radio Engineers, and are here included by permission as an Appendix, until further revised. For full particulars, see the I.R.E. Standardization Committee report.

1000 Acoustic Resonance Device. One which utilizes, in its operation, resonance to the audio frequency of the received signals.

1001 Antenna. A system of conductors designed for radiating or absorbing the energy of electromagnetic waves.

1002 Atmospheric Absorption. That portion of the total loss of radiated energy due to atmospheric conductivity.

1003 Audio Frequencies. The frequencies corresponding to the normally audible vibrations. These are assumed to lie below 10,000 cycles per second.

1004 Capacitive Coupler. An apparatus which, by electric fields, joins portions of two radio frequency circuits, and which is used to transfer electrical energy between these circuits through the action of electric forces.

1005 Coefficient of Coupling (Inductive). The ratio of the effective mutual inductance of two circuits to the square root of the product of the effective self-inductances of each of these circuits.

1006 Direct Coupler. A coupler which magnetically joins two circuits having a common conductive portion.

1007 Counterpoise. A system of electrical conductors forming one portion of a radiating oscillator. the other portion of which is the antenna. In land stations a counterpoise forms a capacitive connection to ground.

1008 A Damped Alternating Current is an alternating current whose amplitude progressively diminishes.

1009 The Damping Factor of an exponentially damped alternating current is the product of the logarithmic decrement and the frequency.

Let I_0 = initial amplitude

I_t = amplitude at the time t

ϵ = base of Napierian logarithms

a = damping factor

Then: $I_t = I_0\, \epsilon^{-at}$

1010 Detector. That portion of the receiving apparatus which, connected to a circuit carrying currents of radio frequency, and in conjunction with a self-contained or separate indicator, translates the radio frequency energy into a form suitable for operation of the indicator. This translation may be effected either by the conversion of the radio frequency energy, or by means of the control of local energy by the energy received.

1011 **Electromagnetic Wave.** A periodic electromagnetic disturbance progressing through space.

1012 **Forced Alternating Current.** A current, the frequency and damping of which are equal to the frequency and damping of the exciting electromotive force.

1013 **Free Alternating Current.** The current following any electromagnetic disturbance in a circuit having capacity, inductance, and *less* than the critical resistance.

1014 **Critical Resistance of a Circuit.** That resistance which determines the limiting condition at which the oscillatory discharge of a circuit passes into an aperiodic discharge.

1015 **Group Frequency.** The number per second of periodic changes in amplitude or frequency of an alternating current.

NOTE 1. Where there is more than one periodically recurrent change of amplitude or frequency, there is more than one group frequency present.

NOTE 2. The term " group frequency" replaces the term " spark frequency."

1016 **Inductive Coupler.** An apparatus which, by magnetic forces, joins portions of two radio frequency circuits and is used to transfer electrical energy between these circuits. through the action of these magnetic forces.

1017 **Linear Decrement of a Linearly Damped Alternating Current** is the difference of successive current amplitudes in the same direction, divided by the larger of these amplitudes.

Let: I_n and I_{n+1} be successive current amplitudes in the same direction, of a linearly-damped alternating current.

Then: The linear decrement, $b = \frac{I_n - I_{n+1}}{I_n}$

Also: $I_t = I_0 (1 - bft)$

Where: I_0 = initial current amplitude

I_t = current amplitude at time t

f = frequency of alternating current

1018 **Logarithmic Decrement** of an exponentially damped alternating current is the logarithm of the ratio of successive current amplitudes in the same direction.

NOTE: Logarithmic decrements are standard for a complete period or cycle.

Let: I_n and I_{n+1} be successive current amplitudes in the same direction.

d = logarithmic decrement

Then: $d = \log_e \frac{I_n}{I_{n+1}}$

1019 Radio Frequencies. The frequencies higher than those corresponding to the normally audible vibrations, which are generally taken as 10,000 cycles per second. See also Audio Frequencies.

NOTE: It is not implied that radiation cannot be secured at lower frequencies and the distinction from audio frequencies is merely one of definition based on convenience

1020 Resonance of a circuit to a given exciting alternating e.m.f. is that condition due to variation of the inductance or capacity in which the resulting effective current (or voltage) in that circuit is a maximum.

1024 A Standard Resonance Curve is a curve the ordinates of which are the ratios of the square of the current at any frequency to the square of the resonant current, and the abscissas are the ratios of the corresopnding wave length to the resonant wave length; the abscissas and ordinates having the same scale.

1026 Sustained Radiation consists of waves radiated from a conductor in which an alternating current flows.)

1027 Tuning. The process of securing the maximum indication by adjusting the time period of a driven element. (See Resonance.)

1028 A Wave-Meter, is a radio frequency measuring instrument, calibrated to read wave lengths.

1030 Decremeter. An instrument for measuring the logarithmic decrement of a circuit or of a train of electromagnetic waves.

1031 Attenuation, Radio. The decrease with distance from the radiating source, of the amplitude of the electric and magnetic forces accompanying (and constituting) an electromagnetic wave.

1032 Attenuation, Coefficient of (Radio). The coefficient, which, when multiplied by the distance of transmission through a uniform medium, gives the natural logarithm of the ratio of the amplitude of the electric or magnetic forces at that distance, to the initial value of the corresponding quantities.

1033 Coupler. An apparatus which is used to transfer radio-frequency energy from one circuit to another by associating portions of these circuits.

APPENDIX II.

ADDITIONAL STANDARDS FOR RAILWAY MOTORS

1100 In comparing projected motors, and in case it is not possible or desirable to make tests to determine mechanical losses, the following values of these losses, determined from the averages of many tests over a wide range of sizes of single-reduction single-geared motors, will be found useful, as approximations. They include axle-bearing, gear, armature-bearing, brush-friction, windage, and stray-load losses.

TABLE XX
Approximate Losses in D-C. Railway Motors.

Input in per cent of that at nominal rating	Losses as per cent of input
100 or over	5.0
75	5.0
60	5.3
50	6.5
40	8.8
30	13.3
25	17.0

1101 The core loss of railway motors is sometimes determined by separately exciting the field, and driving the armature of the motor to be tested, by a separate motor having known losses and noting the differences in losses between driving the motor light at various speeds and driving it with various field excitations.

1102 **Selection of Motor For Specified Service**

The following information relative to the service to be performed, is required, in order that an appropriate motor may be selected.

(a) Weight of total number of cars in train (in tons of 2000 lb.) exclusive of electrical equipment and load.
(b) Average weight of load and durations of same, and maximum weight of load and durations of same.
(c) Number of motor cars or locomotives in train, and number of trailer cars in train.
(d) Diameter of driving wheels.
(e) Weight on driving wheels, exclusive of electrical equipment.
(f) Number of motors per motor car.
(g) Voltage at train with power on the motors—average, maximum and minimum.

(h) Rate of acceleration in mi. per. hr. per second.
(i) Rate of braking (retardation in m. per hr. per second).
(j) Speed limitations, if any (including slowdowns).
(k) Distances between stations.
(l) Duration of station stops.
(m) Schedule speed including station stops in m.p.h.
(n) Train resistance in pounds per ton of 2000 pounds at stated speeds.
(o) Moment of inertia of revolving parts, exclusive of electrical equipment.
(p) Profile and alignment of track.
(q) Distance coasted as a per cent of the distance between station stops.
(r) Time of layover at end of run, if any.

1103 **Stand-Test Method of Comparing Motor Capacity with Service Requirements:** When it is not convenient to test motors under actual specific service conditions, recourse may be had to the following method of determining temperature rise.

1104 The essential motor losses affecting temperatures in service are those in the motor windings, core and commutator. The mean service conditions may be expressed, as a close approximation, in terms of that continuous current and core loss which will produce the same losses and distribution of losses as the average in service.

A stand test with the current and voltage which will give losses equal to those in service, will determine whether the motor has sufficient capacity to meet the service requirements. In service, the temperature rise of an enclosed motor (**§164**), well exposed to the draught of air incident to a moving car or locomotive, will be from 75 to 90 per cent (depending upon the character of the service) of the temperature rise obtained on a stand test with the motor completely enclosed and with the same losses. With a ventilated motor (**§165 and §167**), the temperature rise in service will be 90 to 100 per cent of the temperature rise obtained on a stand test with the same losses.

1105 In making a stand test to determine the temperature rise in a specific service, it is essential in the case of a self-ventilated motor (**§ 167**), to run the armature at a speed which corresponds to the schedule speed in service. In order to obtain this speed it may be necessary, while maintaining the same total armature losses, to change somewhat the ratio between the I^2R and core-loss components.

1106 **Calculation for Comparing Motor Capacity with Service Requirements.** The heating of a motor should be determined, wherever possible, by testing it in service, or with an equivalent duty cycle. When the service or equivalent duty-cycle tests are not practicable, the ratings of the motor may be utilized as follows to determine its temperature rise.

1107 The motor losses which affect the heating of the windings are as stated above, those in the windings and in the core. The former are proportional to the square of the current. The latter vary with the voltage and current, according to curves which can be supplied by the manufacturers. The procedure is therefore as follows:

1108 (a) Plot a time-current curve, a time-voltage curve, and a time-core loss curve for the duty cycle which the motor is to perform, and calculate from these the root-mean-square current and the average core loss.

1109 (b) If the calculated r.m.s. service current exceeds the continuous rating, when run with average service core loss and speed, the motor is not sufficiently powerful for the duty cycle contemplated.

1110 (c) If the calculated r.m.s. service current does not exceed the continuous rating, when run with average service core loss and speed, the motor is ordinarily suitable for the service. In some cases, however, it may not have sufficient thermal capacity to avoid excessive temperature rises during the periods of heavy load. In such cases a further calculation is required, the first step of which is to compute the equivalent voltage which, with the r.m.s. current, will produce the average core-loss. Having obtained this, determine, as follows, the temperature rise due to the r.m.s. service current and equivalent voltage.

Let t = temperature rise, p_0 = I^2R loss, kw., p_c = core loss, kw. } with r.m.s. service current, and equivalent service voltage.

T = temperature rise, P_0 = I^2R loss, kw., P_c = core loss, kw. } with continuous load current corresponding to the equivalent service voltage.

Then

$$t = T\,\frac{p_0 + p_c}{P_0 + P_c}\text{, approximately.}$$

1111 (d) The thermal capacity of a motor is approximately measured by the ratio of the electrical loss in kw. at its nominal (one-hour) capacity, to the corresponding maximum observable temperature rise during a one hour test starting at ambient temperature.

1112 (e) Consider any period of peak load and determine the electrical losses in kilowatt-hours during that period from the *electrical* efficiency curve. Find the excess of the above losses over the losses with r.m.s. service current and equivalent voltage. The excess loss, divided by the co-efficient of thermal capacity, will equal the extra temperature rise due to the peak load. This temperature rise added to that due to the r.m.s. service current, and equivalent voltage, gives the total temperature rise. If the total temperature rise in any such period exceeds the safe limit, the motor is not sufficiently powerful for the service.

1113 (f) If the temperature reached, due to the peak loads, does not exceed the safe limit, the motor may yet be unsuitable for the service, as the peak loads may cause excessive sparking and dangerous mechanical stresses. It is, therefore, necessary to compare the peak loads with the short-period overload capacity. If the peaks are also within the capacity of the motor, it may be considered suitable for the given duty cycle.

APPENDIX III.

BIBLIOGRAPHY OF LITERATURE RELATING TO ELECTRICAL ENGINEERING STANDARDIZATION

Engineering Manual of the American Electric Railway Engineering Association.

Standardization Rules of the Electric Power Club.

Report of the Committee on Standardization of the Institute of Radio Engineers.

National Electric Code.

Meter Code—Code for Electricity Meters of the A. E. I. C. and N. E. L. A.

Standardization Reports of the Association of Railway Electrical Engineers.

Publications of American Society for Testing Materials.

The U. S. Bureau of Standards' various publications including Circulars 15, 22, 23, 29, 31, 34, and 37.

Reports of Committee on Nomenclature and Standards of Illuminating Engineering Society.

National Electric Light Association.

American Institute of Electrical Engineers, Specifications.

FOREIGN PUBLICATIONS.

Publications of the Engineering Standards Committee of Great Britain.

Institution of Electrical Engineers, London, Wiring Rules and other publications.

Verband Deutscher Elektrotechniker.

British Electrical and Allied Manufacturers' Association, Reports ef the

INTERNATIONAL PUBLICATIONS.

Publications of the International Electrotechnical Commission,

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REPORT OF THE JOINT RUBBER INSULATION COMMITTEE—1916

PART I—GENERAL REPORT

Need of Specifications

1. A demand for specifications which will enable purchasers of rubber insulation for wire or cable to secure good material on the basis of competitive bids has existed for many years.

2. In recent years, there has been no difficulty in securing insulation having the dielectric strength, specific resistance, elasticity and mechanical strength required in practise. Indeed, with the possible exception of dielectric strength, these qualities are usually in excess of actual service requirements. There is another quality, namely, permanence, which although equally essential, has not been so easy to obtain.

3. While the physical properties of rubber insulation are susceptible of positive determination by tests which can be made before acceptance by the purchaser, the permanence of insulation can be ascertained with certainty only by actual trial, often at great loss, inconvenience and even danger. It should, therefore, be the aim of specifications to overcome this difficulty and by some indirect means, ensure that the manufacturers supply compounds having the required endurance.

4. This obviously presents a difficult problem, as it requires that some relation be established between permanence and one or more of the properties which are susceptible of test. It has been established by experience that Hevea rubber or the rubber of the Hevea Brasiliensis tree, when properly cured. is a superior grade which is entirely satisfactory for electrical insulation of the class under consideration. Hevea rubber may, therefore, be specified with advantage, although certain other rubbers of good quality may thereby be excluded. The rubber has to be Hevea rubber of good quality, the materials associated with it in the compound must be known to be non-deleterious and the compound itself must be well prepared, applied and vulcanized.

Types of Specifications

5. Two types of specifications have been devised to compass these restrictions. The first type of specification proceeds on the assumption that certain physical characteristics are developed to an unusual degree by the use of Hevea rubber, especially the grade known as fine Para. Among the qualities affected by the grade of rubber, and alleged to be useful indications of the presence of Para rubber, are the tensile strength, elasticity and specific electrical resistance. Accordingly some specifications have been issued in which one or more of these qualities is specified

This report has been approved, by the Standards Committee, and is published by order of Board of Directors.

in an exaggerated degree. Experience has shown that such specifications are ineffective, as the specified physical quality can be obtained either by manipulation of poor compounds or at the expense of permanence in compounds made originally of good materials. In consequence of this, specifications based exclusively on physical tests have fallen into disrepute, but such tests now serve in modified form as adjuncts to other types of specifications.

6. The second type of specification to be considered is that in which a more or less rigid formula for the compound is specified and compliance with it exacted either by inspection during manufacture, or by chemical analysis supplemented by other tests of the finished product. Inspection which will really ensure compliance with such specifications is usually impracticable. Reliance must, therefore, be placed principally upon chemical analysis. Three difficulties at once arise. In the first place chemical analysis cannot directly ascertain the quality of the rubber which has been used in the manufacture of a compound; it can only determine quality by the indirect method of measuring certain characteristic constituents. It is, therefore, necessary to present in the specification, a relation between the desired formula and the chemical findings. The second difficulty is that in the past, chemists have employed diverse methods of analysis which give inconsistent results. It is, therefore, necessary to establish a satisfactory and standard procedure for analysis. The method of analysis must not only yield the information desired, but it must also be practical and capable of yielding uniform results when applied to the same compound by different chemists. In order to secure this uniformity, it is important to describe the methods of analysis in detail. The third difficulty has been the non-uniform interpretation of analytical results.

7. The specification hereinafter presented is of the second or chemical type, in which an endeavor has been made to meet the three objections hitherto urged against such specifications. It contains a table showing the range of analytical results that should be obtained from a good compound containing 30 per cent of high class Hevea rubber, and is supplemented by a detailed analytical procedure. The specification is not complete as given, it being necessary to add appropriate electrical and mechanical test requirements. Examples of complete rubber insulation specifications are cited in Part VI. of this report.

8. The specification should always be used in conjunction with the analytical procedure. The latter will, however, serve for the analysis of any compounds of the 30 per cent Para type with mineral fillers, provided the interpretation is made to correspond.

History of Committee

9. The necessity of purchasing insulated wire under conditions of competitive bidding led the various departments of the government, the railroads and other large consumers, to issue specifications for rubber insulation. These specifications were based upon the individual experience or theories of a number of engineers, aided by suggestions from some of the manufacturers. For several years no attempt was made to standardize these specifications, and much trouble was given to the manufacturers by

the diversity of requirements contained in them. In 1906, the Rubber-Covered-Wire Engineers' Association, consisting of representatives of the leading manufacturers, prepared a specification which was offered as a standard. This was followed in 1911 by the revised specifications of the National Board of Fire Underwriters, which, however, call for a comparatively low grade of compound. The former specification, although the best that could be agreed upon at that date, was so defective as to afford little or no protection to consumers. The latter occupies a field by itself, and makes no pretension to specifying the highest quality of compound. Consumers desiring high grade insulation of great permanence, therefore, continued to use their own specifications, altering them from time to time, in accordance with the best information available, with a growing tendency to rely upon chemical rather than physical tests. Some difficulty was experienced both in obtaining bids and in enforcing these specifications owing to the inability of chemists to make concordant analyses of rubber compounds. This matter reached an acute stage in 1911, when a number of manufacturers and consumers held a conference in order to discuss the possibility of standardizing specifications and analytical methods for rubber insulation. This conference was held at New York on the seventh of December, 1911, Col. Samuel Reber of the U. S. Signal Corps presiding.* The following interests were represented:

Signal Corps, U. S. Army,
American Chemical Society,
Lederle Laboratories,
New York Central Lines,
Pennsylvania R. R. Co.,
General Electric Co.,
Hazard Manufacturing Co.,
Simplex Wire & Cable Co.,
Standard Underground Cable Co.

10. After a full discussion of the subject, a committee was appointed to devise a specification and an analytical procedure for rubber insulation, the committee to report at a future conference. The chairman, assisted by other members, appointed the following to serve upon this committee which was named "The Joint Rubber Insulation Committee."

C. R. Boggs, Simplex Wire & Cable Co.,
W. S. Clark, General Electric Company,
W. A. Del Mar, N. Y. C. R. R. Co., (later Interborough Rapid Transit Co.)
W. B. Geiser, N. Y. C. R. R. Co.,
J. P. Millwood, Consulting Chemist,
P. Poetschke, Lederle Laboratories,
H. B. Rodman, Pennsylvania R. R. Co.

Later, at the request of the committee and by unanimous consent of the members of the original conference, the following were added:

J. B. Tuttle, U. S. Bureau of Standards,
E. L. Willson, Hazard Manufacturing Company.

* The invitations were issued by Mr. E. B. Katte, Chief Engineer of Electric Traction, of the New York Central R. R. Co.

11. W. A. Del Mar was elected secretary of both the Conference Committee and of the Joint Rubber Insulation Committee. No permanent chairman was elected, it being left to the committee to elect a chairman at each meeting.

12. The committee immediately upon its formation decided to confine itself to the development of a specification and an analytical procedure for compounds of the 30 per cent Para type. In accordance with this policy it made a study of the chemical characteristics of Hevea rubber and of the available analytical procedures. New procedures were also developed and studied. Samples of different rubber compounds were analyzed by these tentative methods. The results were unsatisfactory and the discrepancies were investigated. Sub-committees were formed to do much of this work. Twelve regular committee meetings, besides numerous sub-committee meetings, were held; many different compounds were distributed to be analyzed by the entire committee, and others were experimented upon by the sub-committees and individual members.

13. After two years of this work the committee presented a preliminary report to a second conference which was held at New York on October 15th, 1913, Col. Reber again presiding. The report was unanimously accepted by the conference and the committee authorized to continue in existence for another year for the purpose of making any revisions that might appear necessary in its report, as the result of a year of experience with it.

14. The committee was also authorized to publish the preliminary report. This was accomplished through the courtesy of the American Chemical Society, the American Institute of Electrical Engineers, and the U. S. Bureau of Standards; the report appearing in their official publications, the Journal of Industrial and Engineering Chemistry, (January 1914), the Proceedings of the American Institute of Electrical Engineers, (January 1914), and Bureau of Standards Circular No. 38, respectively.

15. Instead of reporting in a year, the committee found it necessary to devote nearly three years to this work, holding 13 additional meetings, or a total of 25 general meetings exclusive of sub-committee meetings.

16. The committee was authorized, at the second conference, to increase its personnel without securing the approval of the Conference Committee. It has added the following chemists to its membership:

A. E. Ellis, Interborough Rapid Transit Co., New York,
G. d'Eustachio, Standard Underground Cable Co.,
E. W. Gundy, Pennsylvania R. R. Co.,
C. W. Walker, American Steel & Wire Co.,
C. F. Woods, A. D. Little Co., Inc., Boston.

17. The following resignations have been accepted since the second conference:

J. P. Millwood,
P. Poetschke.

Mr. Geiser also resigned, due to stress of other work, but has been re-elected.

18. The Joint Rubber Insulation Committee's specification for rubber insulating compound has been adopted by the principal engineering so-

cieties which issue standards of the kind. Among these are the American Electric Railway (Engineering) Association, the Association of Railway Electrical Engineers and the American Society for Testing Materials. The specification has also been adopted by a large number of important purchasers of insulated wire, including The U. S. Signal Corps, the Panama Canal, the New York Central R. R. Co., the Interborough Rapid Transit Co., the Public Service Corporation of New Jersey, etc.

19 The committee also desires to express its thanks to the many gentlemen not members, who have actively participated in the work, especially to Messrs. F. S. Deemer, F. A. Hull, M. M. Kahn, C. B. Martin, G. H. Savage, J. F. Tinsley and D. Whipple.

Part II—Specification for 30 Per Cent Hevea Rubber Compound (Chemical Clauses)

1. A 30 per cent fine Para or best quality plantation Hevea rubber compound with mineral fillers, shall be furnished. It shall contain only the following ingredients:

   Rubber,
   Sulphur,
   Inorganic mineral matter,
   Refined solid paraffine or ceresine.

2. The vulcanized compound shall conform to the following requirements, when tested by the procedure of the Joint Rubber Insulation Committee, results being expressed as percentages by weight of the whole sample:

Requirements Independent of the Amount of Rubber Found

	Maximum	Minimum
Rubber	33	30
Waxy hydrocarbons	4	..
Free sulphur	0.7	..

Red lead, carbon, or organic fillers shall not be present.

Requirements Dependent Upon Amount of Rubber Found.

(Requirements for intermediate percentages shall be in proportion to the percentage of rubber found).

Limits allowed for 30 per cent Rubber Compound.	Maximum	Minimum
Saponifiable acetone extract	1.35	0.55
Unsaponifiable resins	0.45	....
Chloroform extract	0.90	....
Alcoholic potash extract	0.55	....
Total sulphur (see note 2)	2.10	....
Specific gravity	....	1.75
Limits allowed for 33 per cent Rubber Compound.		
Saponifiable acetone extract	1.50	0.60
Unsaponifiable resins	0.50	....
Chloroform extract	1.00	....
Alcoholic potash extract	0.60	....
Total sulphur (see note 2)	2.30	....
Specific gravity	....	1.67

3. The acetone solution shall not fluoresce.

4. The acetone extract (60 cu. cm.) shall be not darker than a light straw color.

5. Hydrocarbons shall be solid, waxy and not darker than a light brown.

6. Chloroform extract (60 cu. cm.) shall be not darker than a straw color.

7. Failure to meet any requirement of this specification will be considered sufficient cause for rejection.

8. Contamination of the compound, such as by the use of impregnated tapes, will not excuse the manufacturer from conforming to this specification.

Note: 1—This specification shall be supplemented by appropriate clauses relating to tensile strength, elasticity, electric insulation resistance and dielectric strength. (See the Wire and Cable specifications of the American Society for Testing Materials, the Association of Railway Electrical Engineers etc., for examples of such clauses.)

Note 2:—The limit on total sulphur may be omitted at the option of the purchaser. See Part IV, of Report.

Part III—Analytical Procedure

Object of the Analysis

1. The object of this procedure of analysis is to determine whether rubber compounds comply chemically with the accompanying specification which is intended to secure compounds containing 30 per cent of the best Hevea rubber, and mineral fillers.

Outline of Procedure

2. The general procedure is shown by the accompanying Diagram A.

General

3. Make the analysis upon the insulation after vulcanization and, whenever possible, before the saturation of the braid. Wipe the insulation thoroughly with a damp cloth to remove any adhering material, but do not remove waxy hydrocarbons from the surface.

4. If, however, a saturated braided sample must be used, remove the braid and sandpaper the insulation to a depth of at least 0.005 of an inch and wipe with a damp cloth. The latter procedure, however, is not to be recommended, as it may cause an appreciable error in the acetone extract. In such cases report the condition of the sample.

5. Perform all determinations in duplicate and take the average value arbitrarily as the true value. Duplicate determinations must check within the limits specified.

6. Make blanks on all determinations and deduct the results accordingly.

Sample

7. Remove the insulation entirely from sufficient wire to give a sample weighing about 25 grams. Cut this into small pieces* and grind slowly in either a No. 0 Enterprise coffee mill or a mill such as shown by the accompanying Diagram B. Adjust the grinder so that not more than 20 per cent will pass through a 40-mesh sieve. Sift all the material through a

* This is most conveniently done with a meat-chopper.

20-mesh sieve, regrinding what is retained on the sieve until the entire sample has passed through. The wires of the sieves shall be evenly spaced in both directions and shall be of 0.016 and 0.010 inches diameter in the 20-mesh and 40-mesh sieves respectively. Remove with a strong magnet any metal that may have come from the grinder and thoroughly mix the sample.

Extraction Apparatus

8. The extraction apparatus shall conform with the accompanying Diagram C. It shall be heated so that the period of filling an empty syphon cup with acetone and completely emptying it, will be between two and one-half and three and one-half minutes.

Preparation of Reagents

9. Acetone shall be freshly distilled over anhydrous potassium carbonate using the fraction 56-57 deg. cent.

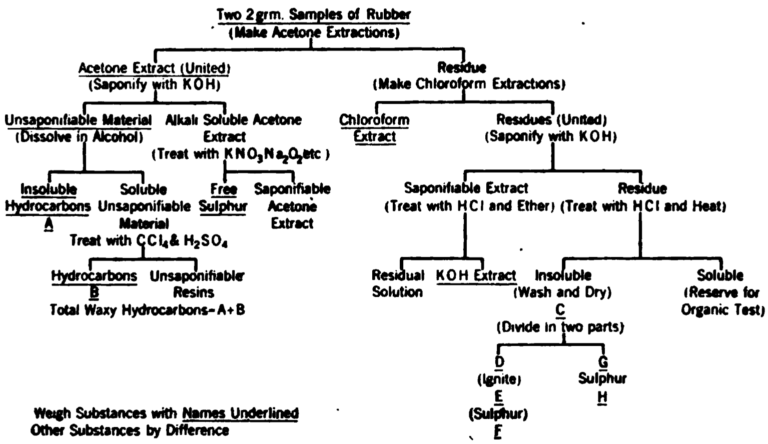


DIAGRAM A—OUTLINE OF METHOD OF RUBBER ANALYSIS EXCLUSIVE OF TOTAL SULPHUR DETERMINATION

10. Alcoholic potash solution shall be of normal strength and shall be made freshly by dissolving the proper amount of potassium hydrate (purified by alcohol), in 95 per cent alcohol which has previously been distilled over potassium hydrate. The solution shall be allowed to stand for 24 hours and only the clear liquid used.

11. Ether shall be washed with three successive portions of distilled water and distilled, using the fraction 34-36 deg. cent.

12. Chloroform shall be shaken with water, dried by calcium chloride, decanted, and freshly distilled, only the clear distillate being used.

13. Carbon tetrachloride shall be pure and freshly distilled.

14. The nitric acid bromine reagent shall be prepared by adding a considerable excess of bromine to the concentrated nitric acid shaking thoroughly and allowing it to stand for some hours before using.

15. The fusion mixture for sulphur determinations shall be made by

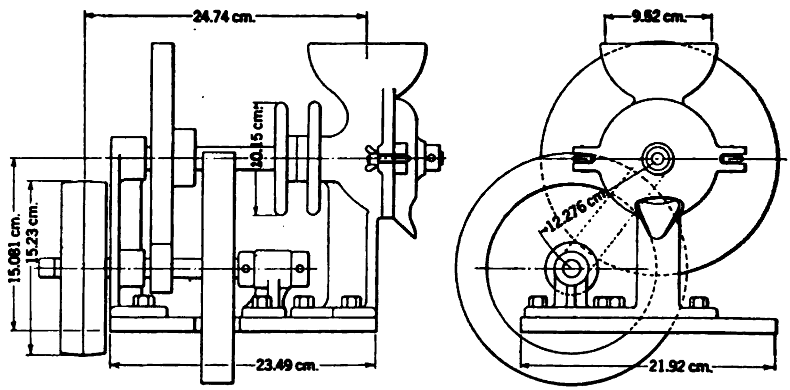
mixing equal quantities of sodium carbonate and powdered potassium nitrate.

16. The barium chloride solution shall be made by dissolving 100g. of crystallized barium chloride in one liter of distilled water and adding two or three drops of concentrated hydrochloric acid. If there is any insoluble matter or cloudiness, the solution shall be heated on a steam bath overnight and filtered through 589 S. and S. blue ribbon filter paper.

17. Distilled water only shall be used in preparing solutions and in all washing operations. Reagents not otherwise specified shall be of a "c.p. tested" quality.

Acetone Extract

18. Extract continuously with 60 cu. cm. acetone for eight hours, two 2-g. samples that have been prepared within 24 hours. Unite the extracts in a weighed flask, using hot chloroform to rinse the flasks. Distill off the reagents and dry the flask and contents for four hours at 95-100 deg.



Grinding plates of the No. 0 Enterprise Coffee Mill to be used

DIAGRAM B—RUBBER GRINDER

cent. Desiccate until cool and weigh. Continue to dry for two-hour periods until constant weight is obtained. In drying, place the flask on its side but at a sufficient angle from the horizontal so that the extract does not appreciably run down the side of the flask.

Unsaponifiable Material

19. Add to the acetone extract 50 cu. cm. alcoholic potash solution, boil under a reflux condenser for two hours, and evaporate on a water bath until all alcohol is removed. Add 10 cu. cm. water and 20 cu. cm. ether; heat until the wax etc. are in solution, cool, transfer to a separatory funnel, wash out the flask with warm water, cool and finally wash with two 20 cu. cm. portions of ether. The water volume should be 100 cu. cm. and the ether at least 40 cu. cm. Shake vigorously for two minutes, and allow the solutions to separate thoroughly. Draw off the aqueous solution into a second funnel, leaving in the first funnel the ethereal solution and any flocculent material that may be present. Again rinse the flask

with 20 cu. cm. ether and add it to the aqueous solution; shake vigorously for two minutes, and when separated draw off the aqueous solution and unite in the first funnel the ethereal solutions and any flocculent material. Repeat, shaking with 20 cu. cm. portions of ether, until no residue is obtained on evaporating a 20 cu. cm. portion. The aqueous solution and subsequent washings shall be reserved for the free sulphur determination. Wash the flask and the funnel, from which the ethereal solution has been taken, with water, until they are free from alkali. Wash the ethereal solution with water until it has been washed twice after the wash water shows no alkaline reaction. Retain with the ethereal solution any flocculent material. Filter the ethereal solution from the flocculent material,

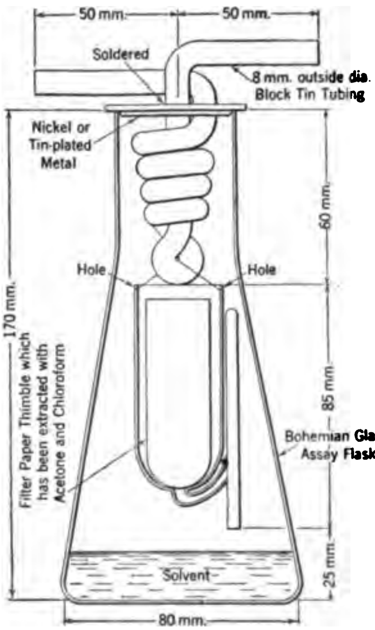


DIAGRAM C—RUBBER ANALYSIS EXTRACTION APPARATUS

through a small pellet of extracted cotton, into a weighed flask, washing first with ether and subsequently with hot chloroform, using this to rinse the original flask and both separatory funnels. Evaporate the solvents and dry the extract at 95-100 deg. cent.; cool in a desiccator and weigh. Continue to dry until constant weight is obtained.

Hydrocarbons A

20. Add 50 cu. cm. absolute alcohol to the unsaponifiable material and warm until solution is as complete as possible. Cool the solution to -4 or -5 deg. cent. and maintain at this temperature for one hour by packing the flask in a mixture of ice and salt. Filter out the waxy hydrocarbons, using a funnel packed with ice and salt, and apply suction if necessary. Wash the flask and filter with about 25 cu. cm. of 95 per cent alcohol,

which has been previously cooled in the same temperature. Catch the filtrate in a flask which is afterwards cooled to -4 to -5 deg. cent. to make sure that all possible waxy hydrocarbons have been removed, and refilter if necessary. Dissolve the residue on the filter paper with hot chloroform, into the original flask. Evaporate the chloroform and dry the flask at 95-100 deg. cent.; cool in a desiccator and weigh. Continue to dry until constant weight is obtained.

Hydrocarbons B

21. Evaporate the alcohol from the flask containing the alcohol-soluble unsaponifiable material, add 25 cu. cm. of carbon tetrachloride, and transfer to a separatory funnel. Shake with concentrated sulphuric acid, drain off the discolored acid and repeat with fresh portions of acid until there is no longer any discoloration. After drawing off all the acid, wash the carbon tetrachloride solution with repeated portions of water until all traces of acid are removed. Transfer the carbon tetrachloride solution to a weighed flask; evaporate off the solvent and dry the flask at 95-100 deg. cent.; cool in a desiccator and weigh. Continue to dry until constant weight is obtained.

Free Sulphur

22. Add two grams potassium nitrate to the aqueous solution and washings from the ethereal separation of the unsaponified material. Evaporate to dryness in a silver or nickel dish and heat to quiet fusion, avoiding contamination with sulphur fumes. Transfer with cold water to a beaker, neutralize with hydrochloric acid; add 2 cu. cm. concentrated hydrochloric acid; filter and wash, making a volume of 200 cu. cm. Heat to boiling and add slowly a slight excess of hot barium chloride solution. Allow to stand over night, filter, wash, ignite, weigh the barium sulphate and calculate to sulphur.

Definition of Terms Describing Components of Acetone Extract

23. The difference between the acetone extract and the free sulphur shall be called the Organic Extract.

24. The difference between the organic extract, and the unsaponifiable material shall be called the Saponifiable Acetone Extract.

25. The sum of the hydrocarbons A and B shall be called the total Waxy Hydrocarbons.

26. The difference between the unsaponifiable material and the waxy hydrocarbons shall be called Unsaponifiable Resins.

Chloroform Extract

27. Extract continuously, the residues from both of the acetone extractions (without necessarily removing the acetone that may be on them), for four hours with 60 cu. cm. chloroform. Unite the extractions in a weighed flask, using hot chloroform to rinse the flasks. Distill off the solvent and dry the flask and contents for two hours at 95-100 deg. cent. Cool in a desiccator and weigh. Continue to dry for one-hour periods until constant weight is obtained. In drying, place the flask on its side but at a sufficient angle from the horizontal so that the extract does not appreciably run down the side of the flask. (If it is needful to wait after the acetone extraction, before starting the chloroform extraction, the sample must be kept in a vacuum of at least 50 mm. of mercury.)

Alcoholic Potash Extract

28. Dry the residues from the chloroform extractions at 50-60 deg. cent. until the odor of chloroform can no longer be detected; unite the residues from the two 2 g. samples in a 200 cu. cm. Erlenmeyer flask. Add 100 cu. cm. alcoholic potash solution and boil for four hours under a reflux condenser. Filter the solution by decantation through an 11 cm. hardened filter paper into a beaker and wash twice, using each time 25 cu. cm. hot absolute alcohol and then wash thoroughly with hot water. Wash any rubber on the filter paper back into the original flask and reserve this for the determination of rubber hydrocarbons. Evaporate the solution to approximate dryness, take up in warm water and transfer to a separatory funnel. Acidify with 30 cu. cm. of 5 N hydrochloric acid, using this to rinse the beaker. Add sufficient water to make the bulk of the solution 100 cu. cm. When cool add 40 cu. cm. ether, using it to rinse the beaker in 20 cu. cm. portions. Shake the aqueous and ethereal solutions thoroughly. After complete separation, draw off the aqueous solution and treat in another separatory funnel, with a fresh 20 cu. cm. portion of ether. Continue to shake the aqueous solution with fresh portions of ether until a colorless portion has been obtained, then shake out twice more. Unite the ethereal solutions and wash with successive additions of water, continuing twice after the water shows no acid reaction. Filter through a plug of extracted cotton into a tarred flask, wash the filter and funnel with ether, evaporate the ether without boiling and dry the residue at 95-100 deg. cent.; cool in a desiccator and weigh. Continue to dry until constant weight is obtained.

Rubber Hydrocarbons

29. Add to the flask containing the rubber residue from the alcoholic potash extraction, sufficient water to make the total volume of the solution 125 cu. cm. and then add 25 cu. cm. concentrated hydrochloric acid. Heat for an hour at 97-100 deg. cent. Decant the supernatant liquid through a hardened filter paper on a Buchner funnel 7 cm. diameter, using suction; wash the residue with 25 cu. cm. hot water and decant. (While a Buchner funnel is recommended, it is permissible to use an 11 cm. hardened filter paper with platinum cone, in a 60 deg. funnel). Perform this entire treatment with water and hydrochloric acid, three times and save the first and second decantations for the "organic matter" test described in section 36. The rubber at this stage should be white and practically free from black specks of undissolved fillers; if not, continue the acid treatment until the black specks disappear. (If carbon is present, all the particles of rubber will be greyish, bluish, or black, depending on the form and quantity of carbon used. Black specks in light particles of rubber usually indicate the presence of lead sulphide which must be removed to prevent the formation of lead sulphate on igniting the residue *C*.) Add 150 cu. cm. hot water to the flask and let stand on a steam bath or hot plate for half an hour and decant through the filter paper. Return to the flask any rubber that goes on the filter paper. Repeat until the washings are free from chlorides. (See section 36). Transfer all the rubber in the flask to the filter paper and dry as much as possible by suction. Wash the rubber with 50 cu. cm. of 95 per cent alcohol, using suction. Transfer the entire residue to a

weighing bottle. Dry at 95 to 100 deg. cent. for an hour, cool in a vacuum dessicator under reduced pressure and weigh.. Dry for a half hour, cool and weigh, repeating this process until either constant weight is reached or the weight starts to increase. Let this weight be represented by *C*. On a portion *D* of this residue *C* determine the ash *E* according to section 30 and the sulphur *F* in the ash *E*. Determine the sulphur *H* in another portion *G* of residue *C*. Make all sulphur determinations as described under Total Sulphur.

30. Place about 0.5 g. of residue *C* into a weighed porcelain crucible. Let the weight of residue be represented by *D*. Heat gently, gradually driving off the volatile matter. When the crucible has ceased to smoke, raise the temperature gradually to between 450 and 500 deg. cent. until all organic matter has been burned away, which is usually indicated by the ash becoming white. (An electric muffle furnace with pyrometer is recommended for this purpose). Cool in a desiccator and weigh, the weight of ash being represented by *E* in the formula for rubber hydrocarbons. Make sulphur test on ash by the method described under Total Sulphur. If, however, $50 \times C \times E$ is not over unity, the determination of sulphur in the ash may be omitted and *F* assumed to be zero.

Then,

$$\text{Rubber Hydrocarbons} = \frac{100\ C}{4}\left[1 - \frac{E-F}{D} - \frac{H}{G}\right]$$

expressed as a percentage of the total sample.

Total Sulphur

31. Place a 0.5g of rubber in a porcelain crucible of about 100 cu. cm. capacity. Add 20 cu. cm. nitric-acid-bromine reagent, cover the crucible with a watch glass, and allow to stand for one hour. Heat very carefully for an hour, remove the cover, rinsing it with a little water, and evaporate to dryness. Add 5g. of the $KNO_3 - Na_2CO_3$ fusion mixture, and 3 to 4 cu. cm. of distilled water. Digest for a few minutes, and then spread the mixture half way up the side of the crucible to facilitate drying. Dry on a steam bath or hot plate. Fuse the mixture, using a sulphur-free flame until all the organic matter has been destroyed and the melt is quite soft. Allow to cool, place the crucible in a 600 cu. cm. beaker, and cover with water. Digest three or four hours on the steam bath. Filter into an 800 cu. cm. beaker, washing thoroughly with hot water. The total volume should be about 500 cu. cm. Allow to cool, add 7 to 8 cu. cm. concentrated hydrochloric acid to the filtrate, and heat on the steam bath. Test the solution for acidity with congo paper and add 10 cu. cm. of hot barium chloride solution. Allow to stand over night, filter, wash, weigh the barium sulphate, and calculate to sulphur.

Specific Gravity

32. The specific gravity shall be the ratio of the weight of a given volume of the compound, to the weight of an equal volume of water, both at 20 deg. cent. Cut strips of the largest practicable size from the conductor and use about 5 g. for the sample. Determine the specific gravity in the usual manner by means of a specific-gravity bottle. Care must be taken that no air bubbles adhere to the sample.

Checks

33. Specific gravity determinations shall check within 0.01. The other duplicate determinations shall check within the following limits expressed as percentages of the original sample.

Determination	Check
Acetone Extract	0.10
Saponifiable Acetone Extract	0.10
Unsaponifiable Resins	0.10
Waxy Hydrocarbons	0.10
Free Sulphur	0.05
Chloroform Extract	0.10
Alcoholic Potash Extract	0.10
Rubber Hydrocarbons	0.20
Total Sulphur	0.10

Interpretation

34. The percentage of rubber shall be considered to be the sum of the rubber hydrocarbons, saponifiable acetone extract, unsaponifiable resins, chloroform and alcoholic potash extracts, expressed as percentages. If the chloroform extract is over 3.0 per cent of the rubber so calculated, subtract the excess from the rubber. If the alcoholic potash extract is over 1.8 per cent of the rubber, as first calculated, subtract this excess also from the rubber.

Red Lead

35. Dissolve 1 g. of the sample in 75 cu. cm. Xylol at a temperature of about 100 deg. cent. When the rubber is dissolved, the absence of any red particles indicates the absence of red lead. If red particles are present, filter the solution into a Gooch crucible and wash thoroughly with benzol, acetone and alcohol successively. Remove the felt and residue to a distilling flask, add 25 cu. cm. 10 per cent hydrochloric acid, and distill over the chlorine liberated by the lead peroxide, absorbing the gas in a solution of potassium iodide and starch. Not more than 0.1 cu. cm. of 0.1 N thiosulphate shall be required to titrate the iodine liberated.

Organic Fillers.

36. Transfer the first and second decantations of the hydrochloric acid solutions to a carefully cleaned porcelain dish and add 20 cu. cm. concentrated sulphuric acid. Place dish on steam bath or hot plate to drive off water and hydrochloric acid. A pronounced charring of the residue indicates the presence of organic matter soluble in water or hydrolyzed by hydrochloric acid.

Examine filter paper and rubber while decanting acid solution and again while washing free of chlorides. Some types of organic fillers not removed by water and hydrochloric acid, would be plainly visible at this point.

Place a small portion of residue *C* under a microscope and examine for fibrous and other characteristic organic material. If organic fillers are indicated and not clearly proven by this test, place 1 g. of the organic sample in a beaker, add 75 cu. cm. Xylol and heat on hot plate until the rubber is dissolved. Decant Xylol solution and wash residue with ether several times by decantation. Dry residue and examine under the microscope.

Statement of Results

37. The results of the analysis shall be stated in the following form:

	per cent
Acetone extract..................................	
Saponifiable acetone extract.........................	
Unsaponifiable resins..............................	
Waxy hydrocarbons................................	
Free sulphur....................................	
Chloroform extract................................	
Alcoholic potash extract............................	
Total sulphur....................................	
Rubber...	
Color of acetone extract (60 cu. cm. vol.)...............	
Fluorescence in acetone extract solution (present or absent)	
Hydrocarbons *A* (consistency and color)................	
Hydrocarbons *B* (solid or liquid)......................	
Color of chloroform extract (60 cu. cm. vol.)............	
Carbon (present or absent)...........................	
Organic fillers (present or absent).....................	
Red lead (present or absent)..........................	
Specific gravity...................................	
Sample braided or not..............................	

Part IV—Explanation of Specification

1. Experience has shown that compounds of the grade which contains only good Hevea rubber, may be relied upon to be more permanent than those made of rubber of other grades. It is not affirmed by the committee that a compound which conforms with this specification, is necessarily permanent, or that a better compound cannot be made, but it is believed that enforcement of the specification will limit the use of inferior materials and that it will put the manufacturers more nearly upon an equality of endeavor, where they can use their experience to obtain the best results. Used in connection with the analytical procedure, the specification will enable purchasers to order a good compound and to ascertain with a greater certainty than heretofore, whether the material received, represents the compound specified.

2. The term Hevea applied to rubber means rubber from the Hevea Brasiliensis tree whether wild or cultivated and regardless of the locality in which it has been grown. Para rubber is Hevea rubber of the kind originally shipped from the port of Para, Brazil, and comes in several grades. The rubber required by this specification should be Hevea rubber of good quality, such as fine Para or best quality plantation rubber.

3. Carbon is excluded not only because it is considered, by some purchasers, to be deleterious, but because it interferes with the determination of rubber hydrocarbons.

4. Red lead is excluded because of the possibilities of its deleterious effects on the rubber.

5. Ozokerite is prohibited because the acetone extract obtainable from it interferes with the separation of the acetone extract obtainable from the rubber, thereby vitiating the assay of the rubber extract. This prohibition is unimportant to the manufacturers, as ceresine, which is permitted, is the essential constituent of ozokerite.

6. An upper limit is placed upon the rubber in order to prevent the attainment of electrical and mechanical strength by the use of an extra quantity of inferior rubber whose lasting qualities might not be satisfactory.

7. The hydrocarbons are limited owing to their tendency to separate from the compound and thus possibly cause porosity.

8. The free sulphur is limited because an excessive amount may be deleterious.

9. The maximum limit on the saponifiable acetone extract is to prevent the use of raw or reclaimed rubber with high saponifiable extract. The minimum limit assists in forcing the use of Hevea rubber, since it is characteristic of the acetone extract from Hevea rubber to be largely saponifiable.

10. The unsaponifiable resins are limited because a low proportion of unsaponifiable resins is characteristic of Hevea rubber. A high result might be due to the presence of reclaimed rubber.

11. The chloroform extract is limited, first to prevent the use of bituminous substances, and second, to limit depolymerized and undercured rubber.

12. The alcoholic potash extract is limited to prevent the use of saponifiable rubber substitutes.

13. The specific gravity is limited to reconcile the specification of ingredients by weight with the practise of purchasing material by volume.

14. Fluorescence of the acetone solution is prohibited as it indicates the presence of bituminous substances, rosin oil, or mineral oils.

15. The color of the acetone extracts is specified to conform with the normal color of the extract from Hevea rubber. A darker color indicates adulteration or an inferior grade of rubber.

16. The hydrocarbons are required to be solid in order to prevent the use of oils and paraffine of low melting point. The shade required is that obtained from paraffine wax or ceresine. If hydrocarbons *B* are liquid this would indicate reclaimed rubber softened with mineral oil, or paraffine of low melting point.

17. The color of the chloroform extract is specified to conform with the color of dissolved gum in minute quantities. The presence of bituminous substances would be indicated by a brown or black color.

18. It would be desirable that the sulphur of vulcanization be limited to exclude reclaimed rubber, which contains the sulphur of its previous vulcanization, but the committee has not yet developed an acceptable method for determining this quantity. It is, therefore, confronted with the choice of either placing a limit on the total sulphur or giving up the attempt to exclude shoddy by sulphur limitation. Option is therefore given to the purchaser to insert or omit the limit on total sulphur. Such insertion will at times exclude reclaimed rubber and the committee believes it possible to make a suitable compound with this limitation. The com-

mittee thinks that a sulphur limit positively excluding reclaimed rubber, would place too great a hardship, in other ways, on the manufacturers. Where the specification is used with no total sulphur limit, the use of many kinds of, or much, reclaimed rubber, will be guarded against by the limits of the various components of the acetone extract. When the limitation on total sulphur is omitted, sulphur-bearing fillers, which possess certain advantages, may be used.

19. This specification should be supplemented by appropriate elasticity and tensile strength tests, in order to add to the assurance that good rubber has been used and that the vulcanization process has been properly carried out; also by appropriate electric stress and resistance tests, to assure proper insulating qualities and homogeneity of structure. The exact value of the limits for these tests will depend upon the use to which the material is to be put.

PART V—EXPLANATION OF PROCEDURE

General

1. The tentative report of the committee, presented in October, 1913, provided for the determination of the percentage of rubber present by the method of difference. The mineral fillers were determined by the terebene solution method. Results obtained in the use of this method showed that it gave inaccurate results on some compounds. The committee therefore determined to abandon it and to find a suitable substitute. It is believed that the method now recommended will satisfactorily solve the problem.

2. The most feasible means of limiting the kind of rubber was considered to be the determination of the saponifiable and unsaponifiable resins. These are fairly constant characteristics of the resins of Hevea rubber, and of compounds made from the same. Other methods, such as the determination of the saponification number and the optical activity of the resins, were thought to be unpractical.

3. The method as developed is applicable to the analysis of any pure rubber compound containing only mineral matter with or without ceresine or paraffine wax, regardless of the kind or amount of rubber, and can be used in conjunction with other specifications provided the limits are changed to correspond with the amount and kind of rubber desired, and due consideration is given to interfering mineral matter. When applied to a compound without ceresine or paraffine wax the unsaponifiable acetone extract is the unsaponifiable resins.

4. The method has been definitely described, to make it certain that experienced chemists may obtain concordant results. The interpretation has been rigidly defined, obviating any ambiguity as to the meaning that will be assumed, even though this sometimes appears to be arbitrary.

Sample

5. In order to obtain uniform results, the committee has established by experiment that a definite method of sampling has to be adopted and that for all extractions the sample must be reduced in a prescribed manner to at least an approximately similar degree of fineness. For this reason the procedure specifies a definite type of grinder obtainable in two forms, and also specifies definite sieves.

Extraction Apparatus

6. The committee has proved that the extraction apparatus used by different chemists must be of exactly the same form and the same size. It was also proven that small samples in the apparatus give the maximum results and that the rate of extraction is dependent upon the amount of solvent and its temperature as it passes through the sample. The apparatus finally adopted combines the advantages of several forms that were studied and together with simplicity of operation and adjustment to uniform conditions, gives practically complete extraction when used as specified. A number of other variations that might have a possible effect upon the amount of extract, were tried but found to be inappreciable.

Acetone Extraction

7. The extraction is made within 24 hours of the preparation of the sample, so obviating any appreciable oxidation. Two samples are extracted and united, so that a larger amount of extract may be obtained for the subsequent separations, and the extraction apparatus kept within a convenient size. Hot chloroform is used to facilitate the complete transference of the extract. The flasks are placed on their sides when drying, to hasten the emission of the solvent and thus reduce chance of volatilizing, through longer heating, some of the more volatile constituents of the extract. Drying in vacuo at room temperature, does not remove all the moisture if paraffine is present and such drying with heat or at 100 deg. cent. in an inert gas, presents no practical advantage over the method given.

Separation of the Acetone Extract

8. The method given was developed so that all the desired constituents could be determined on one sample.

9. Emphasis is laid on thorough extraction of the unsaponifiable material and the retention of the flocculent material with the ethereal solution. This latter material is not soluble in either ether or water, but it was proven that if such as was chloroform-soluble was included in the unsaponifiable material, the subsequent determination of the hydrocarbons would be more exact. A portion of this flocculent material is insoluble in chloroform.

10. The hydrocarbons are determined in two places, making an approximate separation between the solid and the liquid ones, if both are present. The first hydrocarbons *A* are those insoluble in the solvent at a low temperature. The presence of unsaponifiable resins in the solution prevents the more complete freezing out of the hydrocarbons, but the remainder is obtained after treatment of the resins with sulphuric acid. In this way, chance of loss through the action of the acid has been largely eliminated.

11. The method for free sulphur gives all the sulphur in the acetone extract with the exception of negligible amounts which may be in the unsaponifiable material. It was proven that the results agree with determinations made directly on other acetone extracts.

12. The saponifiable and unsaponifiable resins are obtained by difference.

Chloroform Extraction

13. The chloroform extraction should be made at once after the acetone extraction, or the sample put in a vacuum, so as to avoid the danger of an abnormally high extract. When the extract is dried as specified, constant weight is obtained before any appreciable oxidation occurs. If bituminous substances are present, that portion which has not been extracted by the acetone, will be largely soluble in chloroform and can be readily distinguished by its color. The amount of extract is also affected by the presence of uncured and inferior rubber. A properly cured Hevea compound will always give a little extract with chloroform, which varies somewhat with the method and conditions of cure.

Alcoholic Potash Extraction

14. The alcoholic potash extraction is the usual saponification process for obtaining the fatty acids of rubber substitutes. The total amount of such substitutes is not obtained, but if any appreciable amount is present, the value will exceed that of the limit allowed. When no substitutes are present, this determination always yields a small amount of extract from Hevea rubber.

Rubber Hydrocarbons

15. Methods for the determination of the percentage of rubber are of two kinds, the direct and the difference methods. The committee adopted a difference method after trial of various methods, both direct and indirect.

16. The difference methods are those in which the rubber is removed and the residue weighed. This may be done in either of two ways; by the use of solvents, or by ignition. The early work of the committee was largely along the line of removing the rubber by means of solvents. Many kinds and probably every class of rubber solvents were tried. Some did not completely dissolve the rubber at low temperatures and ordinary atmospheric pressure; others appeared to dissolve the rubber, but formed a colloidal solution holding some of the fillers, which could neither be filtered nor centrifuged clear of mineral matter. Many of them were so time-consuming as to render them worthless, even if accurate results could be obtained. The solvent method given in the Preliminary Report was found to give inaccurate results with compounds containing much litharge or zinc oxide, but gave very good results on most classes of compounds if xylol, instead of terebene is used as the solvent. It has since been demonstrated, however, that it is practically impossible to obtain correct results on an important class of compounds and that method was, therefore, abandoned.

17. Ashing the compound gives fairly accurate results provided no volatile or decomposable fillers are included. This, however, cannot be assumed to be the case. In the method which the committee recommends, these objectionable fillers are largely removed before the compound is ignited, and provision is made for testing those few materials which are volatile, but not removed. This method is a modification of an unpublished one devised, some years ago, by G. H. Savage.

18. In the testing of this method, compounds containing most of the known commercial inorganic fillers were analyzed. Whiting, talc, magnesium, and lead compounds and barium carbonate which are objection-

able in direct ashing do not in any way interfere with the determination of rubber by this method. A number of organic fillers were used, but these too, did not cause any great error.

19. The securing of accurate results by the method given depends largely on two things; the complete solution of decomposable fillers, and the removal of all chlorides. With these precautions, the analyst is almost certain to obtain reasonably accurate results. The formula for calculating the rubber hydrocarbons presents no difficulty if the exact quantities called for in the method are used.

20. The rubber as it is weighed under *C* contains sulphur in combination with the rubber. On ignition sulphur is driven off with the rubber. By determining the sulphur before and after ignition, the amount so lost can readily be calculated, and the proper correction made.

Total Sulphur

21. The sodium peroxide method, specified in the Committee's Preliminary Report, is widely used in the analysis of wire insulation, and is known to yield accurate results on such compounds. The liability of explosion with that method, however, renders it somewhat objectionable.

It will be noted that the bromine-nitric-acid method which is now specified does not require the dehydration and separation of silica. If the filtrate after the fusion and extraction with water, is acidified in the cold, and after the precipitation of the barium sulphate the solution is not permitted to concentrate to a relatively small volume, any silica which is in solution will remain dissolved. The elimination of this step by proper precautions saves considerable time without in any way interfering with the accuracy of the determination.

Interpretation of Results

22. Emphasis is laid on the method of calculating the results. The saponifiable acetone extract and the unsaponifiable resins are considered to be parts of the rubber. The chloroform and alcoholic potash extracts, when within the limits specified, are also so considered. Any quantity in excess of these limits is assumed to be due to foreign substances or in case of chloroform extract, to undervulcanized rubber. No allowance is made for the ash in the raw rubber, as it is considered to be negligible. This method of calculation has to be adopted if the rubber found is to agree with that originally put into the compound.

Moisture

23. A determination of moisture is not given, as electrical tests will detect its presence if in excess. If electrical tests are required, the error introduced by the omission of this determination is very small.

Note:—With a procedure of this length it is impossible to explain every detail without undue elaboration, and the committee wishes to point out that while to experienced chemists the procedure may seem over burdened by detail, yet every specified detail was found necessary in order that the conditions essential to accurate and consistent work might be reproduced by all chemists using the procedure. For this reason it is extremely important that all instructions be observed, even if their significance is not perceived by the individual chemist. It will probably be found that even with the instructions properly observed, some experience will be needed to apply the method successfully.

Part VI—List of Important Specifications Containing the Joint Rubber Insulation Committee's Chemical Clauses or Analytical Procedure

American Electric Railway (Engineering) Association:
Standard Specification for Rubber Insulated Wire and Cable.

American Society for Testing Materials:
Proposed Specifications for Insulated Wire and Cable; 30-per cent Hevea Rubber.

Association of Railway Electrical Engineers:
Standard Specifications for Wire and Cable.

Interborough Rapid Transit Co., Motive Power Department, New York:
Specification No. 2.

New York Central Railroad Co. Electrical Department:
Specification No. 300.

Panama Canal:
Office of General Purchasing Agent, Circular No. 1038.

Signal Corps, U. S. Army:
General Specification No. 581—A., etc.

A PRELIMINARY REPORT

Prepared for Submission to its Principals

BY

THE AMERICAN COMMITTEE ON ELECTROLYSIS

APPOINTED BY

National Engineering Societies

and other

Interested Associations and Corporations

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PREFACE.

Those familiar with the history of the electric railway industry in the United States in the early 90's and subsequently for a decade, will recall the great rapidity with which the electric railway was developed and the litigation that resulted between the gas and water companies and the electric railway companies over the introduction into the field of the electric railway using a grounded return circuit. The utility companies whose properties were threatened with damage from electrolysis due to these grounded return circuits of the railway companies, attempted by all legitimate means to prevent the acceptance of the grounded return circuit, with the result that in one or two cases,—for instance, in the city of Cincinnati, a complete metallic overhead return circuit was adopted and is still in operation, but the electric railway operated with a grounded return circuit in connection with the overhead trolley became the standard, and rapidly spread throughout the country, and still remains the standard for electric traction systems.

At first when the electric railway systems were small, and light cars were used, the quantity of current flowing through the rails was not large, and the possibility of damage from electrolysis was comparatively small, but as the systems were extended and the weight and number of cars greatly increased, the problem became much more serious, and began to demand special attention. It is only within the past four or five years that the subject has been sufficiently well understood by engineers generally to make it probable that their opinions could be made to agree upon standard methods for the prevention or adequate mitigation of electrolysis.

At the present time, due to the fact that the grounded return circuit system has been so long established and so extensively adopted, with the result that millions have been invested in copper for supplemental rail return circuits, the engineers now endeavoring to seek a solution of the question find themselves confronted with the problem not only how best to design and install a new system to prevent damage from electrolysis, but also what can be done with the electric railway systems as they exist in cities today.

While recourse to the courts has always been open, the proving in court of the precise amount of damage that has been occasioned by electrolysis, as distinct from other causes, and accurately proportioning such damage between various electrical companies, has made the fixing of responsibility extremely difficult. In view of this unsatisfactory condition it was thought best by the National Societies representing those connected with the various utilities involved to take up the subject comprehensively and endeavor, if possible, by co-operation among themselves and with other interested associations and corporations to gather and classify information, and if then found feasible to agree upon and recommend methods which without being financially prohibitive will nevertheless practically eliminate damage from electrolysis.

The American Institute of Electrical Engineers with this object in view invited the following bodies to officially appoint representatives to serve upon a committee for which the name The American Committee on Electrolysis was finally adopted:

American Electric Railway Association.
American Gas Institute.
American Institute of Electrical Engineers.
American Railway Engineering Association.
American Telephone & Telegraph Company.
American Water Works Association.
National Bureau of Standards.
National Electric Light Association.
Natural Gas Association.

The first meeting of the Committee was held in the Directors' Room, American Institute of Electrical Engineers, 33 West 39th Street, New York City, May 27th, 1913, to make preliminary arrangements, and the second meeting held at the same place on February 25, 1914, resulted in the selection of a permanent chairman and secretary, and the appointment of the various sub-committees.

The result of the work of these sub-committees is embodied in the various sections of the accompanying report.

Owing to the complexity of the subject and the need for thorough discussion in the several technical bodies, and for further investigation by the interests involved the Committee has thought best not to attempt to issue a final report at the present time, but has endeavored to present the subject in this preliminary report by such statements of fact as its members can, at this time, unanimously agree upon, with the expectation that, after the consideration of these statements of fact by the bodies whom the members of this committee represent, and such further investigation as may be necessary by the Committee, a report will ultimately be prepared, embodying principles, rules and recommendations which will form a basis for solving this complicated problem.

New York City,
September 21st, 1916.

PRELIMINARY REPORT.

THE AMERICAN COMMITTEE ON ELECTROLYSIS.

GENERAL INDEX.

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I. PRINCIPLES AND DEFINITIONS.

A. ELECTROLYSIS IN GENERAL.

1. Electrolysis is the process by which *chemical changes are caused* by an electric current, independent of any heating effect.

NOTE. These changes usually occur in a water solution of an acid, alkali or salt. By the passage of an electric current through it, water (containing a trace of acid) is decomposed into hydrogen and oxygen, copper is deposited from a solution of copper sulphate, silver from solutions of silver salts. Electroplating, electrotyping, and refining of metals by electrodeposition are useful applications of electrolysis in the arts. Electrolysis is involved in the charge and discharge of storage batteries, and in the operation of primary batteries.

In order that electrolysis may occur, the following conditions must be present:

(a) There must be a flow of electric current through a conducting liquid from one terminal to another;

(b) The conducting liquid must be a chemical compound or solution which can be altered by the action of the electric current.

2. Electrolyte, Electrode, Anode, Cathode. The *electrolyte* is the solution (or fused salt) through which the electric current flows; the conducting terminals are the *electrodes*; the terminal by which the current enters the solution is the *anode*; the terminal by which it leaves is the *cathode*.

NOTE. The chemical changes caused by the current may affect both the electrolyte and the electrodes. In the case of a solution of copper sulphate with copper plates as electrodes, copper is removed from the anode by the current and carried into solution; an equal amount of copper is deposited upon the cathode. In general, the metal travels with the current toward the cathode.

3. Amount of Chemical Action. (*Faraday's Law*). The amount of chemical action taking place at the anode and also at the cathode (as expressed by Faraday's law) is proportional to (1) the strength of current flowing, (2) the duration of the current, and (3) the chemical equivalent weights of the substances.

NOTE. Otherwise expressed, the quantity of metal or other substance separated is proportional to the total quantity of electricity passing and the electro-chemical equivalent of the substance or substances concerned. The electro-chemical equivalent of a metal is proportional to its atomic weight divided by its valence. Faraday's law is so exactly realized in practice under favorable conditions that it is used as the basis for the definition of the international ampere, one of the fundamental electrical units.

4. Cause of Current Flow. The current flowing through the electrolyte may be due (1) to an external electromotive force or (2) to the *difference of potential* due to the use of electrodes of different materials or to solutions of different concentrations.

NOTE. The first case is illustrated by electrolysis of dilute sulphuric acid using two lead plates and an external battery; the second by the electrolysis of the same solution using a zinc and a copper plate, which touch each other inside or outside the solution. The first occurs in charging a storage battery; the second in the discharging of a primary battery or a storage battery.

5. Electrolysis by Local Action. Instead of two plates of different metals the same result may follow with *one plate if* it is chemically impure or otherwise heterogeneous, when immersed in dilute acid.

NOTE. Such a plate excites local currents and a loss of metal occurs at all the anode areas. This *local action* causes impure zinc to dissolve rapidly in a solution which has no action on pure zinc.

6. Anodic Corrosion is the term applied to the loss of metal by electrolysis at the anode.

NOTE. When iron is anode the iron is carried into solution by the current, the first product being a salt of iron, the nature of which depends upon the character of the electrolyte. In dilute sulphuric acid, ferrous sulphate is formed, in hydrochloric acid, ferrous chloride, etc. These first products of the electrolysis are frequently modified by *secondary reactions*.

7. Secondary Reactions are the chemical changes which occur at or near the electrodes, by which the primary products of electrolysis are converted into other chemical substances, and are sometimes followed by other reactions.

NOTE. Ferrous hydroxide formed by the union of iron with hydroxyl ions set free at the anode, is subsequently converted into iron oxide due to the reactions with oxygen dissolved in the electrolyte. When lead is cathode in an alkali soil or solution, the alkali metal (such as sodium or potassium) reacts with water at the cathode and forms alkali hydroxide, setting free hydrogen. This hydroxide may (especially after the current ceases) react with the lead chemically and form lead hydroxide, which in turn may combine with carbon dioxide, forming lead carbonate.

8. Cathodic Corrosion is the term applied to the corrosion due to the **secondary** reactions of the cathodic products of electrolysis, as described in the preceding paragraph. The metal of the cathode is not removed directly by the electric current but may be dissolved by a secondary action of alkali produced by the current.

NOTE: The anodic corrosion is more common and more serious; cathodic corrosion, however, sometimes occurs on lead and other metals that are soluble in alkali. Cathodic corrosion never occurs in the case of iron.

B. ELECTROLYSIS OF UNDERGROUND STRUCTURES.

9. General. In the electrolysis of gas and water pipes, cable sheaths, and other underground metallic structures, and the rails of electric railways, the moisture of the soil with its dissolved acids, salts, and alkalis is the *electrolyte*, and the metal pipes, cable sheaths and rails are the *electrodes*.

NOTE. Where the current flows away from the pipes, the latter serve as anodes and the metal is corroded. Metal or gas or alkali, according to the nature of the soil, will be set free at the cathode.

10. Self Corrosion is the term applied when a pipe or other mass of impure or heterogeneous metal buried in the soil is *corroded due to electrolysis by local action.*

NOTE. This is called "self corrosion" because the electric current originates on the metal itself, without any external agency to cause the current to flow. Self corrosion may also be due to direct chemical action.

11. Acceleration of Local or Self Corrosion. Self corrosion is accelerated by the presence of *acids* or *salts* in the soil water which lower its resistance as an electrolyte, and also by *cinders*, *coke* or other conducting particles of different electric potential which augment the local electric currents. In the latter case the metal need not be heterogeneous.

NOTE. A pipe may be destroyed in a relatively short time by self corrosion or local action if buried in wet cinders or in certain soils.

12. Coefficient of Corrosion. The coefficient of electrolytic corrosion, (sometimes called corrosion efficiency) is the quotient of the total loss of metal due to anodic corrosion (after deducting the amount of self corrosion if any) divided by the theoretical loss of metal, as calculated by Faraday's law, on the assumption that the corrosion of the anode is the only reaction involved.

NOTE. In practice it is found that the coefficient of corrosion varies widely from unity, being sometimes as low as 0.2 and sometimes even above 1.5, but commonly between 0.5 and 1.1.

13. Anodic and Self Corrosion. Anodic corrosion due to external currents and *self corrosion* due to local action may occur simultaneously, and the *former may accelerate the latter*.

NOTE. Hence the corrosion due to a given current plus the increased self corrosion induced by that current may give a greater total corrosion than called for by Faraday's law. This explains how the coefficient of corrosion may exceed unity.

14. Passivity is the name given to the phenomenon in which a current flows through an electrolyte without producing the full amount of anodic corrosion which would occur under normal conditions.

NOTE. This restricted definition of passivity has regard only to its effect in electrolysis. Many conditions affect the degree of passivity attained, an initial large current density being favorable to it. Plunging iron into fuming nitric acid renders it temporarily passive. A satisfactory explanation of passivity has not been given.

15. Polarization Voltage (sometimes called polarization potential) is the temporary change in the difference of potential between an electrode and the electrolyte in contact with it due to the passage of a current to or from the electrode. This change in potential difference, is due to the change in the conditions of the surface of the electrode or change in the concentration of the electrolyte (or both), and under some conditions is approximately proportional to the current flowing, but in many cases is not so proportional. The magnitude of the polarization voltage also depends on the material of the electrode, the nature of the electrolyte and the direction of the current.

16. Alternating or Frequently Reversed Direct Currents. If alternating currents (or frequently reversed direct currents) flow through the soil between pipes or other underground metallic structures, the metal removed during the half cycles when a pipe is anode may be *in part replaced* when it is cathode. Hence, the total loss of metal on a given pipe is less than one-half of what it would be if the pipe were an anode with direct current of the same average value in the case of frequently reversed direct current and in the case of alternating current at commercial frequency it is less than 1% and in most cases negligible. (See Section 52.)

NOTE. In slow reversals of current, the recovery effect is less,but the loss will be less than with direct current continuously in the same direction (excepting possibly where the phenomenon of passivity may affect the result).

17. Action on Underground Metallic Structures. Faraday's Law applies to electrolysis of metallic structures in soil as elsewhere, the total chemical action being proportional to the average current strength and the time the current flows and to the electrochemical equivalent of the metal or other substances concerned. Although local action and passivity affect the loss of metal and so apparently modify Faraday's law, it is still true that the total chemical action resulting from the current flow is proportional to the total current when local currents are included.

NOTE. Sometimes this chemical action is concerned only with corroding the anode; sometimes it is concerned with breaking up the electrolyte, as when the anode is a noble metal or in the passive state (as iron and lead sometimes are); sometimes both these effects occur.

The theoretical loss of lead from a lead pipe or cable sheath is 3.7 times as great as that of iron (ferrous) from an iron pipe due to the same current because of the larger electrochemical equivalent of lead.

18. Stray Current. If the railway return utilizes the grounded rails of the tracks, part of the current will flow off the rails or other grounded returns and return through other paths; the current observing the law of divided circuits; *i.e.* the current flows through all possible paths in parallel, the strength of current in each path being inversely proportional to its resistance. This statement excludes the effect of polarization on rails and underground structures, which in some cases is appreciable.

19. Electrolysis Mitigation. The two primary features of electrolysis mitigation are (1) the reduction of the flow of current through the earth and the metallic structures buried in the earth, (2) the reduction of the anode areas of such structures to a minimum, where the current is not substantially eliminated in order to reduce the area of destructive corrosion as far as possible.

NOTE: The current in the underground metallic structures will be decreased, other conditions remaining the same, by (1) increasing the conductance of the return circuit, (2) increasing the resistance of the leakage path to earth, (3) increasing the resistance between the earth and the underground metallic structures, (4) increasing the resistance of the underground metallic structures.

The anode areas of the underground metallic structures will be decreased, other conditions remaining the same, by providing suitably placed metallic conductors for leading the current out of the underground structures so that the flow of the current directly to the earth shall be minimized. This will change a portion of the anode area to cathode.

20. Electrolysis Surveys. A term applied to investigations made to determine the condition of grounded metallic structures and the soil in which they are imbedded and of the overall drops, potential gradients, local potential conditions, current densities, etc. in the railway tracks, or other grounded metallic structures, and positive and negative feeders connected to them to determine what conditions tending to produce damage exist.

21. Overall Potential Measurements. Overall potential measurements show the difference in electric potentials between points in the tracks at the feed limits of the station and the point in the tracks which is lowest in potential, and are obtained by means of pressure wires and indicating or recording voltmeters.

NOTE: The pressure wires may be telephone or other wires utilized temporarily, or wires permanently installed for the purpose.

22. Potential Gradients. The potential gradient is the rate of change of electric potential along the rails of a track or other grounded structure in the earth, and is usually expressed in volts per thousand feet or volts per kilometer.

23. Positive and Negative Areas. Positive areas are those areas where the current is in general leaving the pipes or other underground metallic structures for the earth. Such areas are often called *danger areas.*

Negative areas are those areas where the current is in general flowing to the pipes or other underground metallic structures.

NOTE: As the current often flows from one underground metallic structure to another, it is evident that within a positive area there are local negative areas and vice versa. Hence the terms are applied somewhat loosely, and according to which condition predominates.

Besides the positive and negative areas there are areas of more or less indefinite extent in which the current flow between metallic underground structures and earth normally reverses between positive and negative values. These areas are called *neutral areas* or *neutral zones.*

24. Drainage Systems. A drainage system is one in which wires or cables are run from a negative return circuit of an electric railway and attached to the underground pipes, cable sheaths or other underground metallic structures which tend to become positive to earth, so as to conduct current from such structures to the power station, thereby tending to reduce the flow of current from such structures to earth.

NOTE. Three kinds of drainage systems may be distinguished. (1) where direct ties with wires or cables are made between underground metallic structures and tracks, (2) where uninsulated negative feeders are run from the negative bus to underground metallic structures, (3) where separate insulated negative feeders are run from the negative bus to underground metallic structures, or a main feeder with taps to such structures.

25. Uninsulated Track Feeder System. An uninsulated track feeder system is one in which the return feeders are electrically in parallel with the tracks. Under such circumstances the cables may be operating very inefficiently as current conductors and as a means of reducing track voltage drop, particularly where voltage drops in the earth portion of the return are maintained at the low values usually required for good electrolysis conditions. (See Section 47 (d)).

26. Insulated Track Feeder System. An insulated track feeder system, sometimes called an insulated return feeder system, is one in which insulated wires or cables are run from the insulated negative bus in a railway power station and attached at such places to the rails of the track as to take current from the track and conduct it to the station, in such a manner as to reduce the potential gradients in the tracks and the differences of potential between underground metallic structures and rails, and so reducing the flow of current in underground metallic structures. (See section 53).

> NOTE. The insulated negative feeders may run separately from the negative bus to various points in the track network, or a smaller number of cables may be used with suitable resistance taps made to tracks at various places.
>
> With this system the drop of potential in the track feeders is independent of the drop of potential in the tracks.

METHODS OF MAKING ELECTROLYSIS SURVEYS.

A: GENERAL.

27. General Principles of Electrolysis Surveys. The principal measurements made in electrolysis surveys of underground structures are measurements of the potential differences between the structure tested and all other neighboring metal structures in earth, neighboring rails, and neighboring earth, and measurements of current flow on selected sections of the structural system under test. The potential difference between the structure tested and earth affords more complete information than can be secured from the results of any other practicable class of observations. The difficulties are, however, to make these measurements so as to obtain the true potential difference between the earth and the earthed structure, and frequently also to obtain contact with earth in the immediate neighborhood of the structure tested. If an electrode is used for the earth potential measurement, not consisting of the same metal as the structure tested an error may still be introduced due to difference in the polarization potential of the two electrodes. A non-polarizable electrode has been devised by Dr. Haber, as described later in this report, but it has been used only to a very limited extent in this country. On account of the difficulties of making earth potential measurements, measurements of the potential differences between the structure that is being surveyed and neighboring metal structures are much more generally made.

Measurements of stray current flowing in selected sections of any structural system are practicable if a suitable length of the structure can be made accessible. By comparison of such measurements conclusions can be reached as to the areas in which stray currents are being taken from or delivered to the earth and as to the amounts of current which are concerned in these exchanges. Measurements of this character usually cannot be made on sections so close together as to give for many points definite values for the current flowing to or from earth on account of the high cost of the necessary excavations and permanent replacements. We have therefore included a description of the "earth ammeter" which has been used abroad, and to a limited extent also in this country, for obtaining direct measurements of current flow in the earth.

A survey of the earthed structures which are liable to electrolytic corrosion by stray currents consists in making such observations relating to their electrical condition as may determine the route followed by the stray current and its degree of concentration, thereby permitting deductions to be made relative to the extent and the intensity of the electrolytic injury to which the structures may be subjected. While measurements of potential are most frequently made (to such an extent that the term "Potential Survey" is often applied to this work), it should be borne in mind that the real object of the survey is to determine where current may flow from structure to earth or from earth to structure and the magnitude of the current flowing for each of the smallest sections into which the structure can practically be subdivided.

In discussing methods of survey, the measurements of potential and current peculiar to each class of earthed structures will first be described, together with any special observations or precautions to be taken. A discussion of the measurements of a general nature common to all classes of structures will then follow. Measuring instruments and other apparatus employed in connection with this work will be described in detail in the section devoted to apparatus.

28. Electric Railways. Before making measurements relating to an electric railway system the available information as to its extent, its construction features and particularly the arrangement of its earthed return circuit and the connections thereto should be collected. The best available maps should be procured and all information pertinent to the electrolysis investigation recorded, either by annotation on a suitably arranged map, or in some other convenient form. All electrical connections made for any purpose with the rails or other parts of the return circuit should be noted with special care, and the location of any structures to which connection is thus made ascertained and recorded.

The principal measurements to be made upon the grounded return system of an electric railway are as follows:

1. Potential differences between the point of lowest potential on the tracks, and selected points on the tracks throughout the feeding district of the station under observation.
2. Potential gradient measurements along the railway tracks to determine the difference of potential between points on the track separated from each other by distances of from 1,000 to 3,000 feet.
3. Differences of potential between all points where negative feeders or other connections between bus-bars and rail return make contact with track; also differences of potential between these points and the station bus-bar.
4. Currents carried by each separate connection between bus-bar and rail.

For most of the potential measurements listed above, it is necessary to have available insulated wires connected with all points on the railway return system, whose potential relations are to be determined, all of these insulated wires being brought to some common point so that measurements may be made between them. Where pilot wires have been installed by the electric railway, many, if not all of the points at which it is desired to make tests will be accessible without the necessity of any special preparations. Where pilot wires are not available or where it is desired to reach points not included in the pilot wire system, the most economical plan will be to procure the use of any available circuits found in the local telephone distribution system. Short lengths of insulated wire will need to be run to connect such circuits with the tracks and the testing circuits thus established can readily be brought together at some common point for measurements between them. Where neither of the above alternatives is available, wires can be installed in some temporary manner over available pole line routes to connect with the points whose potentials are to be observed. Such wires should be insulated from earth except at the point where they connect with the tracks.

When the testing circuits are established, the required potential measurements should be obtained by connecting to a voltmeter the wires leading to the two points where difference of potential is to be determined. The voltmeter should be kept in circuit and under observation for a time sufficient to insure that the normal fluctuations of the railway load have been accounted for. When long time observations of the potential difference between two points are desired, a recording voltmeter should be employed. If circuits to a sufficient number of points have been installed, the measurements of potential gradient in the tracks may be taken by connecting the proper wires at the central point to the voltmeter. If the requisite number of pressure wires for gradient tests is not available, these measurements may be obtained by carrying a suitable length of insulated wire along the track and connecting it through a voltmeter to the track at the two points between which the gradient is to be measured.

Measurements of current flowing in negative feeders or in other connections to the track return can be taken by inserting an ammeter in the circuit to be measured, when this is possible, or by taking the voltage drop along some accessible section of the connecting lead, which is sufficiently uniform in dimensions to permit of a ready calculation of its resistance. It is important that all such measurements of current should be taken either simultaneously with measurements of potential difference between the bus-bar and the track end of the connection, or under such conditions as to permit of their accurate correlation with the potential observations. A station load curve should also be obtained on account of the information which it gives as to the characteristics of the power supply.

Measurements of rail bond resistance are not necessarily a part of the work to be done in an electrolysis survey. It is, however, occasionally necessary in connection with a survey to test the resistance of particular rail bonds in order to obtain data necessary for the explanation of results obtained in making some of the regular measurements. When such tests are made, the fall of potential across the joint in the rail should be observed simultaneously in comparison with the difference of potential for some short measured length of the adjacent rail. If one of the special rail bond testing devices is not available for this work, two voltmeters can be employed and read simultaneously, or one voltmeter can be connected with a quick acting switch and employed so as to secure practically simultaneous observations. This latter method may give unreliable results unless a large number of readings are averaged.

29. Earthed Piping Systems. Before tests are made to determine the electrolytic condition of any piping system, all available information as to its extent and the characteristics of its construction should be collected and studied. The best available maps of the system should be procured and any special information of importance in connection with an electrolysis survey not noted on the maps, such as the metals of which the pipes are composed, the location of insulating joints, the relative locations of other piping, and cable systems, the location of electric railway tracks and return circuits, etc., should either be recorded upon them or arranged in some convenient form for reference.

The observations which should systematically be taken in examining a piping system are as follows:

1. Difference of potential between piping system and electric railway rails, other piping systems, cable systems, metal bridges, steam railway rails, etc., at points where these cross the piping system or come in close proximity to it. (Potential survey).

2. Measurements of potential difference between adjacent hydrants, or adjacent drip or service connections. (This will serve to give the direction of the current flowing in the pipe line and some rough indications of its amount).

3. Measurements of current flowing upon exposed sections of pipe. (Current survey).

4. Difference of potential between points on the piping system and the adjacent earth if contacts with earth can be obtained:

To make a potential survey, potential differences between the underground pipes and rails are usually measured at a number of points along every street where there are pipes and electric railway tracks. Where there are other underground pipes and lead-sheathed cable systems, it is desirable to make simultaneous measurements of potential difference between the piping system being surveyed and the neighboring pipe and cable sheaths. It is desirable to make all of the measurements of potential difference at any one point simultaneously between all structures tested. Contact with the underground pipes for these potential measurements may be made by means of service pipes, hydrants, or drip connections. The connections used for the potential measurements may be tested for electrical continuity by means of an ammeter connected between the contacts with a dry cell in series if necessary.

Measurements of potential difference between adjacent test points on the piping system should also occasionally be taken. As the resistance of pipe joints is usually not uniform, only an approximate idea of the current flowing can be obtained in this manner. The principal object of this test is to obtain an indication of the direction of the flow of current.

It is therefore desirable to make a rather large number of these tests at quite frequent intervals, since the results may be interpreted only in a general way; individual tests may be expected to vary widely, and in some cases they may even conflict. This test may be made for shorter intervals and in greater detail, where some sudden change of potential difference to earth or neighboring structures has been observed. Owing to the uncertainties as to resistance of joints it is best not to attempt to translate these voltage readings into terms of current. They may, however, be used in comparisons to assist in fixing the points for more accurate measurements of current as described in the next paragraph.

When the potential observations have been completed and transferred to a map or in some other way assembled for study, consideration should be given to them with a view to determining what parts of the piping system appear likely to be receiving substantial amounts of current from earth or passing substantial amounts of current to earth. The neutral sections of piping between positive and negative potential zones should also be located. With this information at hand sections of the piping system should be selected both in the positive and negative zones and in the neutral area at which excavations can be made and determinations of the current flowing in the pipes obtained. In selecting points for excavations, preference should in general be given to the main piping routes, but attention should also be given to any branch lines which appear likely to be receiving or delivering relatively large amounts of current. Any cases where sections of the system located within the "negative area" give positive readings to earth, should also be given preference in this study.

The method of measuring current consists in determining the fall of potential along a measured length of pipe of known dimensions. For the purpose of this measurement it will generally be found advisable to attach insulated wires permanently to the pipe and to carry them to some suitable point underneath the sidewalk from which they may be led up to the surface to terminate in service or other suitable boxes so as to be available for measurements of current in the future after the excavation has been filled. (See Fig. 1.) Tables giving the resistances of unit lengths of pipe of different diameters and materials are attached

**DIAGRAM SHOWING
PIPE CURRENT TESTING INSTALLATION**

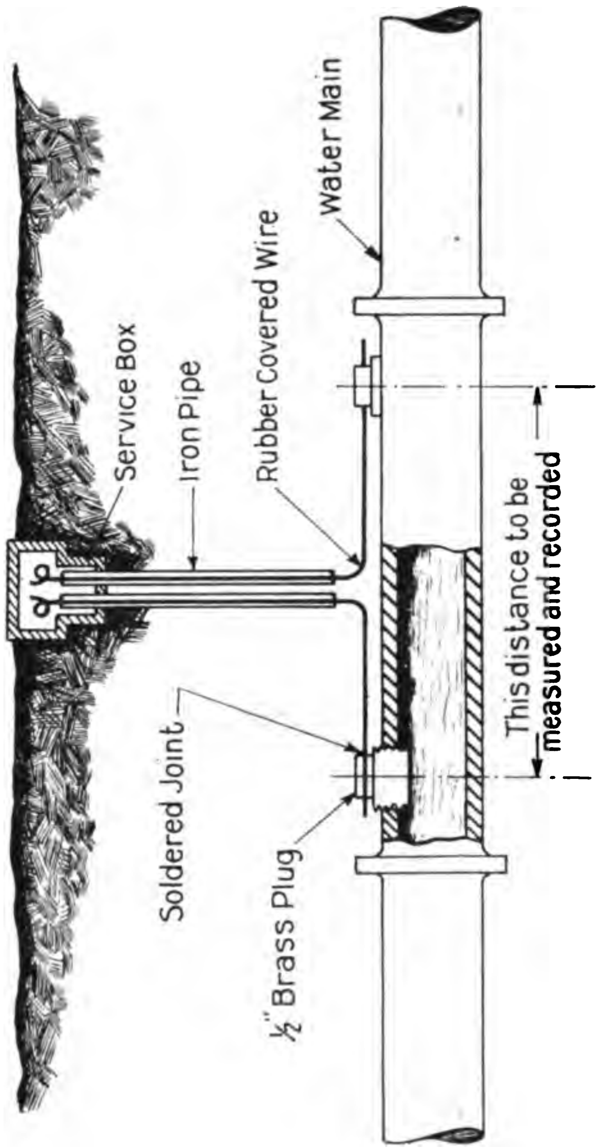


Figure 1

to this report. (See Appendix Tables 9-10). The current flowing in the pipe may be obtained by computation from the observed drop of potential and the unit resistance for the class and weight of pipe.

In addition to the observations made upon the piping system, careful attention should be given to the condition of the service pipes to buildings, particularly in locations where the services cross other piping systems, cable systems, etc. The potential between these service pipes and earth and between the service pipes and the other earthed structure crossed should be determined. It will not be within the scope of the usual survey to determine the condition of all service pipes in the area covered, but it is desirable that some of the services be tested in order to ascertain whether there is any serious tendency towards the local electrolytic corrosion of service pipes. When buildings are entered for the purpose of testing service connections, tests of potential should always be made to any other service pipes or cables which enter the same building, in order to detect cases where one structural system is making contact with the other. Current measurements may also conveniently be made on service pipes in buildings, since the pipes are exposed. Such tests should be made frequently, as they often reveal an interchange of stray current between piping systems which may be in contact in the building.

30. Underground Cable Systems. Before tests are made to determine the electrolytic condition of any cable system, all available information as to its extent and the characteristics of its construction should be studied. Available maps of the system should be procured and any special information of importance in connection with an electrolysis survey not noted on the maps, such as the metals used for the armor or sheathing of cables, the location of drainage connections, insulating joints and other protective devices, the relative locations of other cable systems and of piping systems, the location of the electric railway tracks and return circuits, etc., should either be recorded by annotation upon them or arranged in some convenient form for reference.

The observations which should systematically be taken in examining the cable system are as follows:

1. Difference of potential between the cable system and electric railway rails, other cable systems, piping systems,

metal bridges, steam railway rails, etc., at points where these cross the cable system or come in close proximity to it.

2. Difference of potential between points on the cable system and the adjacent earth.

3. Difference of potential between cables in the same subway system where they are not cross bonded.

4. Current flowing upon the cables.

In making surveys the potential of the cable with respect to the adjacent earth should always be determined at each testing point. In original surveys the greatest practicable number of testing points should be utilized. In some systems it will be desirable to test at every manhole, but in extensive networks of power cables it will ordinarily be sufficient to test at less frequent intervals in many districts, if tests are made at shorter intervals in the most important places. The potential difference between the cable and rails in the same street should also be determined, but in cases where the street railway rails parallel the cable route for a considerable distance, such tests may be made less frequently. If pipes or other earthed metallic structures run close to the cable system at the point of testing, it is desirable that the potential difference between the cable system and the other structure be determined, provided an electrical connection can be made, *e.g.*, through a hydrant, etc.

Tests to determine the direction and amount of stray current flowing on the cable sheaths should be made at appropriate intervals. In fairly simple cable systems, with few laterals, it may be sufficient to make these tests at comparatively infrequent intervals, such as every fifth manhole. In complicated networks, however, such as power distribution systems with many branches and service connections, it will generally be desirable to test more frequently. The current flowing on the cable sheath is to be calculated from the observed fall of potential over a measured length of sheath, and the known resistance of this length of sheath. A table for determining current on lead cable sheaths from voltage drop in measured length of sheath is appended. (See Table 11.)

In the course of the survey, measurements should also be made of the current flowing in any drainage connections or in any accidental connections which connect the cable system with the electric railway return if any such exist. In case insulating joints have been inserted to protect any parts of the cable system from electrolytic corrosion, measurements of the potential difference between cable sheath and earth should be made at each side of the insulating joint, and also of the difference in potential across the joint.

In a preliminary study it should be ascertained whether it is the local practice to insulate from the main cable system those branches which enter buildings. When such branches are not insulated from the main system, tests of difference of potential should be made, between the branch cable and any pipes or other cables which may enter the same building. From such tests it may be ascertained whether there are accidental contacts between the cable system and other earthed structures within buildings, and if any such are found in a portion of the total number of installations, a conclusion can then be reached as to the desirability of checking the conditions in all buidlings entered. In localities where it is the practice to insulate from the main system cable branches entering buildings, the possibility of defective insulation should be checked by measuring the potential difference between cable inside of the building and cable outside at some point beyond the supposed location of any insulating joint. Tests for differences of potential between the branch cable and other metal structures within a building can be omitted in case the insulating joint is found to be in good condition.

The condition of the bonds installed to equalize the potential of the cables entering such manhole should be observed and noted. If bonds are lacking, or if it is suspected that the condition of any bond is faulty, observations of the difference of potential between the cables should be taken and recorded.

31. Bridges, Buildings and Other Earthed Structures. Through the study of maps, etc., collected as preparatory data for surveys of piping and cable systems, information will presumably have been secured concerning the locations, and some, at least, of the structural characteristics, of the highway and railway bridges located within the area to be studied. The locations of steam railway tracks will similarly have been obtained.

In making electrolysis surveys of bridges, measurements of potential to earth should be made at each end of the metal structure. In case the bridges are crossed by electric railway tracks, piping systems or cable systems, measurements should also be made from the metalwork of the bridge to these structures to determine whether there is any difference in potential between them. Where the metalwork of the bridge structure, piers, or other intermediate supports makes contact with earth or with water, measurements of potential difference to earth or to water also should be made. The observer should follow up closely any indication of poor electrical contact between different sections of the metalwork of the bridge, or between the metalwork and any other of the earthed structures crossing the bridge which are supposed to be in good electrical contact with the metalwork.

In the course of the survey, metal frame buildings may be found in locations where it would be possible for them to collect appreciable amounts of current, either directly through the earth or indirectly through the contact of rails, pipes, or cables with the framework. If it appears that such contacts exist, measurements by the fall of potential method should be made to ascertain whether appreciable currents are flowing into the building through these contacts, if this is found to be the case tests should be made at a number of points from the building structure to ground for the purpose of determining where the current leaves the framework and whether there is any indication that appreciable damage is being done. In the case of buildings extending over a considerable area it is desirable that measurements of potentials be made from the framework to earth at a number of points, even in case no contacts are found between the metal framework of the building and other metal structures which may be carrying stray currents.

32. Steam Railway Rails. Steam railway rails, either through direct contact with electric railway rails or, in the absence of an insulating ballast, through contact with earth, are liable at times to collect and discharge appreciable amounts of stray current, and this may occur in such a manner as to be detrimental to the track rails, spikes and adjacent earthed structures. Because of this, as has already been indicated, measurements of potential to steam railway rails should be made whenever the structures that are being surveyed are in close proximity to steam railway tracks, and it is also desirable to determine directly by survey the condition of metal steam railway bridges as well as the condition of metal highway bridges. When steam railways are equipped for electric block signaling the signal battery will affect the potential of the rails. The potential due to the signaling connection is, however, practically uniform in value and can be determined through observations made at times when no stray current can be flowing. With this potential fixed, a conclusion as to the presence and amount of any potential can readily be reached.

33. General Survey Practices. All measurements, excepting 24-hour records, should be made during the period of normal load on the portions of the railway system which are suspected of being the sources of stray currents. In general, it is desirable to express the results of short time measurements in terms of "average day load" on the railway system. In localities distant from the source of railway power supply, the foregoing considerations make it necessary to take into account the presence or absence of moving cars at points beyond the testing station, especially on the tracks nearest to the structure which is being tested. In such localities the duration of a test should be extended to include at least one complete cycle of car movement, unless previous experience at other testing points in the immediate neighborhood have clearly indicated that parts of the cycle may safely be neglected. As the railway lines converge toward a common center, or as the source of railway power supply is approached, the probability of normal load condition increases but even under these conditions it is necessary for the tester to insure that the railway load conditions are substantially normal, when measurements are being made.

At a number of points observations of potential differences and of current flowing along the structure should also be made with 24-hour recording instruments and the characteristics of these currents and potentials compared with the characteristics of railway load curves. This will serve to indicate whether the current and the potential are identified with the railway source. The 24-hour averages for currents and potentials obtained at these points of measurement will also be of use in indicating what allowances should be made in the readings taken systematically at all points of the system in order to make them represent the average day conditions.

During observations of potential or current the movements of the needle in the measuring instrument should be closely watched so that the maximum and minimum readings may both be obtained as well as any change in the polarity of the potential or in the direction of the current. The observer should also bear in mind that collected results of the individual tests will be plotted on a map or otherwise compared so as to get a general idea of the conditions prevailing. When, therefore, there is reason to believe that the recorded maxima and minima are abnormal, notes should be made giving the reasons for such a belief and indicating the value which is thought to be more nearly comparable with the values obtained at other points.

In regular field survey work portable measuring instruments, will be found most suitable for the great majority of the measurements to be taken. Occasionally, however, conditions will arise under which it is desired to observe the potential or the current at some particular point for several hours and even for one or more 24-hour cycles. In the case of such long period observations recording voltmeters, millivoltmeters and ammeters will be found of great assistance and should be employed if available. Instruments of this kind are described in the apparatus section. (Sec. 35-39.)

When bodies of water or areas of swampy earth cross or are located in close proximity to earthed structures, stray current may flow from the structure to earth locally. This is particularly true if the water is brackish or salty. In case such relatively high conductive sections of the earth afford a path of lower resistance for the return of current than the structure itself, the probability of a large flow of current to earth is considerable. The flow of current from the earthed structure is not necessarily stopped when such highly conductive strata have been hidden by building over them or by filling in with surface soil. It is, in consequence, necessary to observe closely the physical geography of the areas covered by the survey and unless the observer is personally familiar with the history of the locality and the changes which have occurred, it is desirable for him to ascertain the facts from those familiar with them. If the structure under observation is accessible for tests at intervals of a few hundred feet and care is taken to make tests of potential to earth at all of these points, the presence of any condition which tends to cause the localized flow of current from the structure to earth will usually be detected. While the labor of making the survey is increased through the necessity of such frequent observations, it is preferable to include all accessible points in the original survey and to eliminate testing points in subsequent surveys when sufficient experience has been gained to indicate that greater distance between points of observation is safe.

When the electric railways in the area under investigation receive current from two or more sources of supply and there are indications that electrolytic damage is occurring at any point upon the earthed structures investigated, it may become necessary to ascertain the origin of the current causing the injury. The preliminary study of the electric railway system or systems will have included the detailed methods for distributing power, whether the trolley systems are interconnected or divided into insulated sections and whether or not all of the rails are interconnected at junctions, etc., as well as the methods of bonding and cross-bonding. If the trolley is supplied from several sources in parallel, the effect of any one of these upon the distribution of stray currents may most easily be studied in connection with the starting or shutting down of that particular source. When substations are operated only during part of the day, tests may be arranged to take advantage of this. When the substations are continually in operation, resort may be had to the method of simultaneously observing the load indicated by the station instruments, and the quantities to be measured on the structure being surveyed. Recording instruments are often useful for this purpose.

When the sources of power are not supplying the trolley in parallel but are confined to certain definite districts, a close study of the railway schedule should be made as it will frequently be possible to select some set of conditions where the current at points of observation must be coming almost wholly from one of the sources on account of the relative positions of cars, etc. Where two electric railways operate independently without connection between their trolleys but with intersections or junctions between their tracks, the situation is similar to that just described where the railway trolley is divided into insulated sections and the same methods of investigation can be followed. Where there is no connection between either trolleys or tracks of two independently operated electric railways this same method should also be followed, *i.e.*, of observing stray current conditions when one road is using considerable current in the immediate neighborhood and the other road is using little or none and comparing the observations with those obtained when both roads are using normal amounts of current in the neighborhood. It is to be noted that when two railways are without any electrical interconnections between either trolleys or tracks, the track return of either may carry stray current from the other railway and if the track return is of high conductivity it may assist materially in producing adverse electrolytic conditions on other earthed structures particularly in cases where it provides a short route between two points between which considerable potential difference exists.

The earth ammeter, previously referred to, may occasionally be found useful in checking up conditions indicated in the systematic survey observations. The construction of the device is described in the apparatus sections. If care is taken to have the plates placed perpendicular to the direction of current flow, the current density at the point of measurement may be indicated by the current flowing through the instrument. If necessary, the lines of current flow may be determined by voltage readings between test electrodes before burying the instrument.

The greatest care should be taken in placing the instrument to avoid unnecessary disturbance of the soil, in order that the flow lines may follow, as nearly as possible, their normal directions.

Whenever excavations or other exposures of pipe surfaces make it possible, measurements of the resistance of pipe joints should be made. Where the joints are of moderate resistance, that is, not so high as to prevent current flow upon the pipes, this measurement may be made by simultaneous observations of the fall of potential across the joint, and along a measured length of the pipe; the pipe joint resistance may then be expressed as equivalent length of pipe, or, by reference to tables, in ohms. These measurements are of importance in indicating the characteristics of the pipe line as an electrical conductor, in estimating the probability of corrosion at joints due to shunting, etc.

Wherever the surfaces of the earthed structures under investigation are exposed during the course of the tests, their conditions should be noted. The pitting of the metal surfaces or the presence upon them of rust or other oxidation products, or an obvious reduction in the thickness of the metal or any other evidence that corrosion has taken place, is not of itself direct evidence that electrolytic corrosion has occurred. Corrosion from any cause whatever would be expected to reduce the thickness of the metal, and the rate at which such corrosion occurred and its possibilities in the way of irregularity of attack on different portions of the surface, would determine the occurrence of pitting. Many of the products of corrosion which will be encountered can also be produced through purely chemical reactions, as well as by electrolysis. When the measurements made in the survey demonstrate that current is flowing from structure to the earth at the point where corrosion is observed, conclusions can be drawn as to the causative relation between the presence of stray current and the evidences of corrosion. Whatever the conditions found in the survey readings, the condition of obviously corroded metal surfaces should always be carefully noted, as it is, of course, always possible that at some past time stray current has been flowing from the surfaces to earth, or that some local condition has been favorable to the "self-corrosion" of the structure. Points where substantial corrosion of the structures under investigation is found, are always to be regarded as good locations for taking the samples of soil referred to in the following paragraph.

It is often desirable to gather data relative to the electrical and chemical characteristics of the soils in the area studied. As different types of soil are encountered in the course of the survey either in the making of excavations or through the observation of changes in surface conditions, samples should then be taken and their electrical conductivities determined. It is often desirable also to make chemical analysis of a number of samples of ground waters and of the water-soluble portion of soil samples secured for conductivity tests.

34. Application of Remedial Measures—Re-surveys. The survey methods described in the previous paragraphs include practically all of the work which would be done in an extensive original survey, that is, in a district where no work had been done previously. While this problem in all of its aspects has been investigated in only a few American communities, it will be found that more or less complete surveys have been made in almost any area traversed by electric railways.

The test methods described are not all of equal value for all problems; their application depends upon the particular problem under consideration. Further, many of the tests require considerable experience and technical skill in application, to avoid erroneous and misleading results. For these reasons, extensive surveys should only be undertaken by experienced investigators.

Following the completion of the original survey, a decision will be reached as to whether measures for mitigating electrolytic corrosion are necessary, and if so, what methods are to be applied. Conclusions as to the effectiveness of any protective measures should be based upon repetitions of the test made in the orginal survey. The amount of repetition necessary will depend upon the character of the protective measures adopted. Thus, general improvements in railway return circuits will ordinarily require a complete re-survey of the affected area. The insta'lation of an insulating joint between the main line structure and a branch should, on the other hand, require little more than tests over short sections either side of the joint, to determine that the current flowing has been reduced and that no objectionable corrosive conditions have been introduced at the joint itself.

If railway return circuits are being changed, some observations of overall potentials and potential gradients will naturally be made during the course of reconstruction, to check the design upon which the work has been based. Observations should be made before installing drainage systems for cables, if necessary using available conductors temporarily to connect the cable sheath and the railway bus-bar or some other suitable point on the railway return, and the effect of drawing current from the cable system observed. The installation of such protective measures as insulating joints or insulating coverings should be carefully supervised as much depends upon the thoroughness with which the work is done.

In re-surveys after the installation of protective measures, the character of the underground structure will make it necessary to pay special attention to some particular class of observations. With piping systems and power distributing cable systems special attention should be given to the amount of stray current flowing on the structures, since a principal object of the remedial measures will have been a reduction in this current. When insulating joints have been installed tests of potential to earth from each side of the joint are required to make sure that the local flow of current to earth has not risen to an amount which will endanger the structure. Tests of stray current in the system on either side of the joint are also required to determine that the effect desired from its installation has been obtained.

When drainage connections are attached to cable systems, tests of potential to earth must be made throughout the area affected. The connection should make the cable negative to earth at all points, but only by slight amounts at or near the point of its attachment, as otherwise the cable will carry more stray current than is needed for its protection, and it becomes a source of danger to other undrained structures.

Where insulating joints or other protective measures are applied to structures buried in the earth, care should be taken to attach testing leads to be used in future surveys. Such connections will be of the same general type as the current measuring leads for pipes (See Fig. 1.).

Electrolysis surveys should be repeated at suitable intervals. In case the original survey did not disclose conditions requiring the application of remedial measures, it is still necessary to make sure that adverse conditions have not since arisen. Where protective measures have been applied, surveys are needed to make sure that the remedies remain effective and adequate. The interval between surveys will depend upon the importance of the structure and upon the time required to produce appreciable damage in case a substantial change in stray current conditions occurred. The results of all such surveys should always be compared with those of previous surveys to ascertain whether changes in stray current conditions are taking place. When any substantial changes or additions are made in the electric railway plant, surveys of the earthed structures liable to be affected by the new conditions should promptly be made.

B: APPARATUS.

In this section descriptions are given of the apparatus and tools which are essentially special for electrolysis work. The tools ordinarily used for handling wires and making good contacts in electrical work will also be needed but no special description or listing of them seems to be necessary in this place.

35. Portable Measuring Instruments. The portable measuring instruments required in electrolysis survey work include voltmeters, millivoltmeters and ammeters. Separate instruments of each kind can, of course, be carried but it will usually be found more convenient to employ the special portable instruments which have been designed particularly for this work.

Two such instruments which the Weston Electrical Instrument Company manufacture for this class of work are as follows:

> Model 1, combination millivoltmeter and voltmeter, has its zero in the center of the scale and reads in both directions. Ranges of 5, 50 and 500 millivolts and of 5 and 50 volts are convenient. It is made with a specially high resistance of from 500 to 600 ohms per volt so that the 5 millivolt range has a resistance of about 3 ohms. These high resistances increase the accuracy of measurements and particularly minimize errors due to resistances of leads or contacts. Ordinary switchboard shunts provided with binding posts and adjusted for 50 millivolts may be used to make this instrument serve as an ammeter. Convenient ranges for these shunts in electrolysis work are, 5, 50 and 500 amperes.
>
> Model 56, combination volt-ammeter, has its zero in the center of the scale and reads in both directions. Ranges of 10, 50 and 500 millivolts, 5 and 50 volts and 100 amperes are convenient.

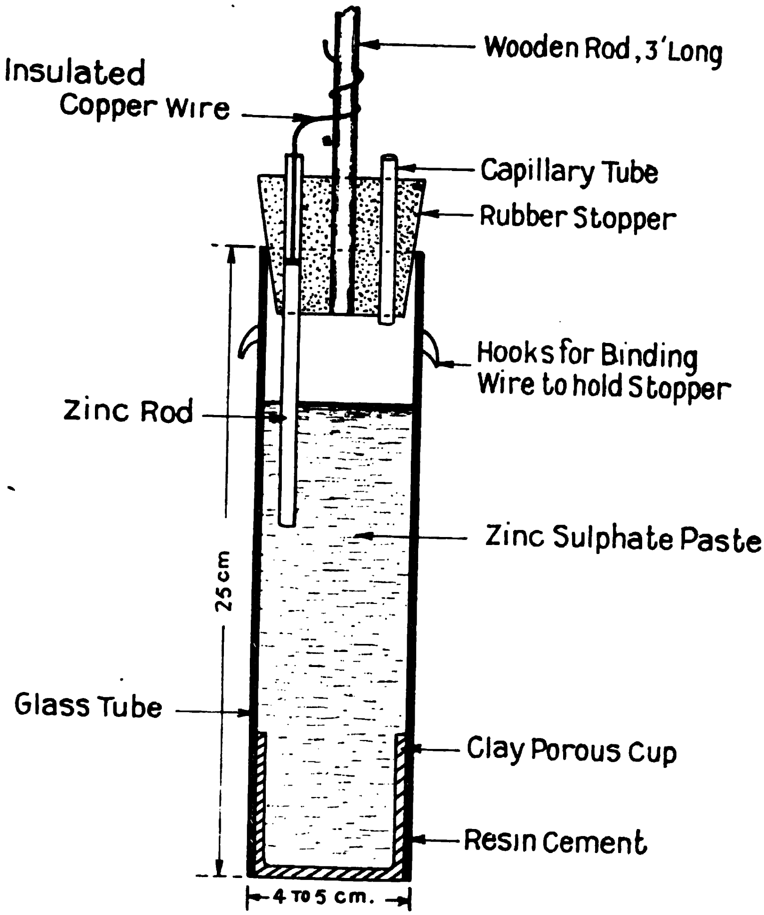
The center scale feature referred to in the description of these instruments is an important one in electrolysis work, as it is not always possible to determine in advance the direction of current or potential, and readings may also vary from positive to negative values during the making of observations at many testing points. When simultaneous readings have to be taken at two or more testing points it is important to use similar instruments at all points. If dissimilar instruments are used their periods of vibration may differ and with the fluctuating voltages and currents encountered in much of this work accurate simultaneous measurements cannot be made unless the instruments used have the same periods of vibration.

36. Recording Instruments. Recording measuring instruments are usually arranged to give 24-hour records without change of chart. By using a sensitive millivoltmeter in the recording instrument and providing it with a number of voltage ranges as well as with suitable shunts, a single instrument can be made available for taking all of the voltage and current readings required in electrolysis work. The original type of Bristol recording instruments make their records upon a smoked chart which has to be treated subsequently with a fixative supplied with the instrument in case it is desired to preserve the record. The Bristol instruments are regularly made with a clock supplied with a changing lever so that the disc can be made to rotate either in one hour or twenty-four hours. Both the Bristol Company and the Esterline Company have recording instruments which give an ink record on a paper strip. In either type of instrument center scale zeros should be called for so that variations between positive and negative values will be recorded on the chart.

37. Normal Electrode. The Haber normal electrode also called non-polarizable electrode consists of a rod of zinc which is enveloped in a wet paste of zinc sulphate contained in a glass tube which has had cemented to it at the bottom a porous clay cell. The other end of the tube is closed with a stopper from which the zinc rod is supported. an insulated wire is led from the end of the zinc rod through this stopper to the upper end of a wooden rod which also enters the stopper and serves for the purpose of handling the electrode. A capillary tube is also run through the stopper in order to have the interior of the tube at normal atmospheric pressure. The zinc sulphate paste is made by adding saturated zinc sulphate solution to fine zinc sulphate crystals until the mixture has attained a semi-fluid condition A sketch showing details of construction for this device is shown on the opposite page. (See Fig. 2.)

38. Earth Ammeter. The Haber earth ammeter consists of two thin copper sheets laid one upon the other with a thin sheet of mica or other non-absorbent insulating material between them. These two plates are gripped in a hard rubber rim which forms part of a square wooden frame. A paste made by mixing powdered copper sulphate crystals with a 20% aqueous solution of sulphuric acid is spread over the exterior surfaces of each of the two sheets of copper, the paste being enclosed on each exterior surface by a covering of parchment paper or some similar tough permeable membrane. Insulated wire leads of suitable length are run from each plate through the frame to connect with the measuring instrument. The opening in the frame may conveniently be square. Four inches is a convenient dimension for the sides of this square opening as this will yield an area of one-ninth of a square foot which is approximately equivalent to a square decimeter. The detailed construction of the instrument is shown in an attached sketch. (See Fig. 3.) When using the instrument, the spaces between the parchment paper and the outer edges of the wooden frame are first filled with

SECTION OF
NON-POLARIZABLE ELECTRODE



CROSS SECTION
Figure 2

SECTION OF EARTH AMMETER

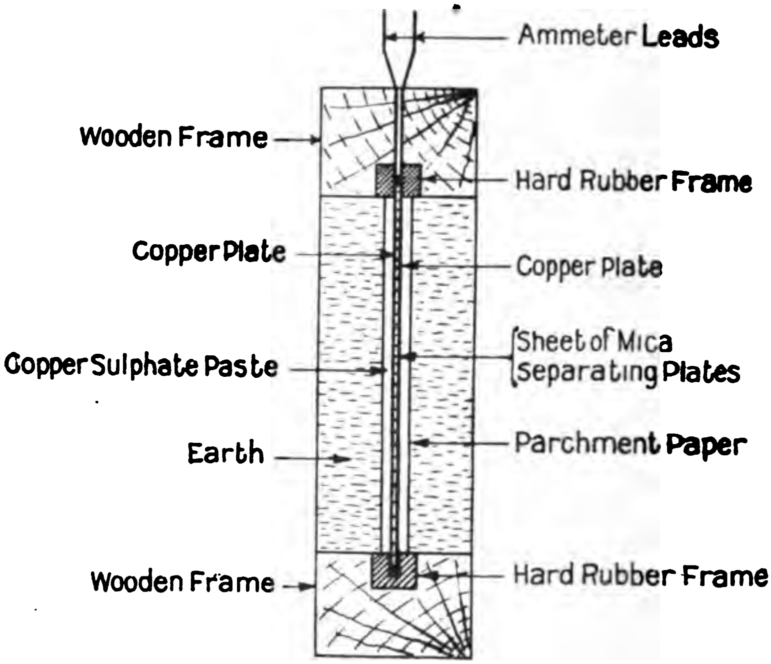


Figure 3

closely packed soil taken from the spot where it is intended to make the measurement and the frame is then placed in a position perpendicular to the flow of current which it is desired to measure and completely buried in earth removed in the course of making the excavation to reach the structure whose condition is to be determined. A suitable low resistance milliammeter can then be connected to the two terminal wires and observations of the current flowing made.

39. Testing Electrodes. The details of metal tipped testing electrodes for use in readings of potential to earth are given in an attached sketch. (See Fig. 4.) Two of these testing rods may be conveniently carried at all times; one of the two should have as its testing tip a piece of the same metal as that contained in the structure whose potential to earth is to be tested, the other should be provided with a steel tip so that contact may be maintained from a distance with any pipe or cable which is below the surface of the ground. The metal on the tips of these rods should always be kept clean and bright and care should also be taken to remove rust and other products of corrosion from the points on the surface of the structure to be tested against which the steel tip presses so that a clean, bright surface will be available for the contact.

C: RECORDS AND REPORTS.

40. General. Much detailed information is necessarily gathered in the course of an electrolysis survey. It is desirable to prepare in advance of the work for the convenient recording of these data upon suitably arranged testing sheets, which either have upon one line or upon one sheet, as may be necessary, all of the data collected at any stated testing point during a single period of observation. Several typical data sheets prepared for recording observations made upon piping and cable systems are attached hereto as suggestive of possible arrangements for report sheets. The data thus collected can usually be best aranged for study if they are transferred to a map showing the system or systems included in the tests, and indicated thereon either in numerical form or through some graphical representation. It is desirable to indicate positive and negative relations by making records on the maps in different colors.

Apart from the data obtained through observations in the

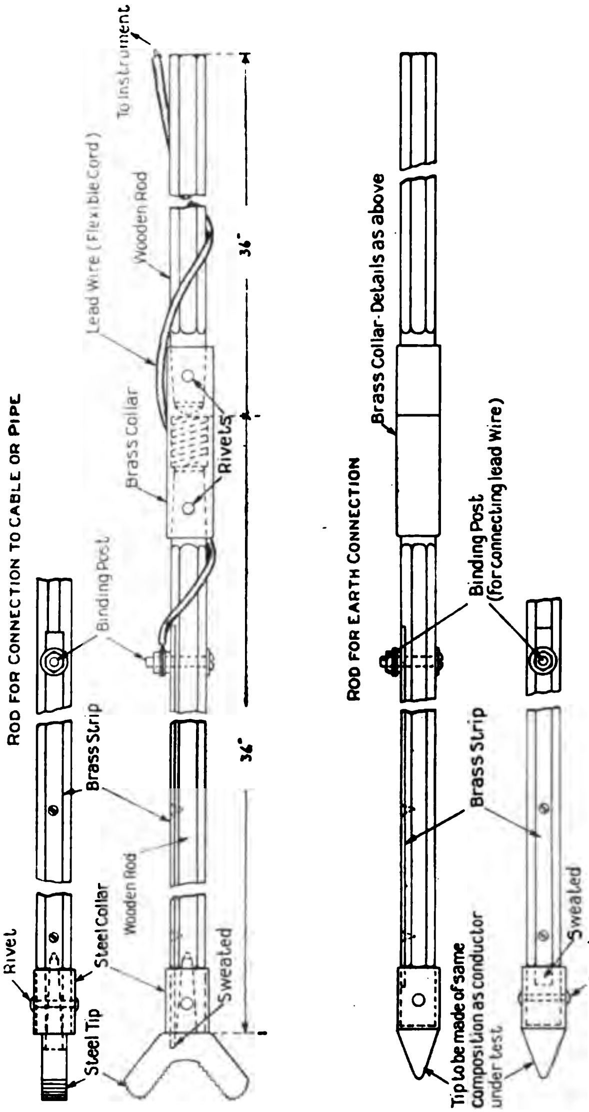

ROD FOR CONNECTION TO CABLE OR PIPE
Rivet
Steel Tip
Steel Collar
Brass Strip
Binding Post
Wooden Rod
Sweated
36"
Brass Collar
Rivets
36"
Lead Wire (Flexible Cord)
Wooden Rod
To Instrument
ROD FOR EARTH CONNECTION
Tip to be made of same composition as conductor under test
Brass Strip
Sweated
Rivet
Binding Post (for connecting lead wire)
Brass Collar-Details as above

Figure 4

work of the electrolysis survey it will be seen that the records obtained relating to the systems under observation should include the following:

41. Electric Railways.

1. Maps showing locations of sources of power supply, tracks, and negative feeders and other connections between bus-bar and track. Also locations of positive feeding connections to trolley and of all section insulators in trolley.

2. Information as to size of rails, methods of bonding and standards of bond maintenance.

3. Information as to any direct ground connections applied to the railway return system, and any special track features which may affect the flow of stray currents.

42. Piping Systems.

1. Maps showing all main piping lines and branches (except building connections) and sources of water, gas, etc., from which the piping systems are supplied.

2. Information as to sizes of pipes and metals of which they are composed, and details of the standard methods of joining main and branch line pipe sections.

3. Information as to method of joining building connections to main supply pipes including metals used for the building connection pipes and the depth to which such connections are buried.

4. Location and description of any protective devices such as insulating joints or drainage connections which may have been made a part of the piping system.

5. Information as to methods of attachment and construction employed in carrying pipes over highway or railway bridges or under water courses, swamps, etc.

43. Cable Systems.

1. Maps showing locations of all subway and conduit routes and giving number and sizes of cables in place therein or the total cross-section of lead sheaths expressed in equivalent copper, also locations of power stations, sub-stations or other centers from which cables radiate.

2. Locations, route and sizes of all drainage connections attached to cable systems, also locations of all insulating joints in cable systems, of any jumpers which may be run to establish a metallic circuit across an insulated gap in the cable system and of any conductors run to reinforce the carrying capacity of the cable system for stray currents.

3. Information as to methods of attachment and construction employed in carrying cables over highway or railway bridges or under water courses, swamps, etc.

44. Bridges and Buildings.

1. Locations of structures with respect to electric railways.

2. Information as to methods of construction employed in carrying electric railway, pipes and cables across bridges and particularly as to whether any of these other structural systems make electrical contact with the metal structure of the bridge.

45. General Conditions.

1. Maps showing locations of water courses, swamps and other features tending to produce locally earth of high unit conductivity.

2. Records of electrical resistance of soil samples representative of the area.

3. Records of experience obtained in the use of different metals for pipes, etc., in the soils of the area.

It is desirable that in the preparation of records and of reports, consideration be given to the necessity of their perpetuation. All records which will be of permanent value in connection with the continued study of electrolysis conditions within the area which will be necessary in order to make sure that injurious changes in conditions do not occur, should be prepared in a permanent form capable of withstanding considerable handling.

III. AMERICAN PRACTICE.

There is no standard practice in the treatment of electrolysis problems in America. In many localities the existence of such a problem is scarcely recognized; in others the problem has been given much study, and mitigating systems widely varying in character have been installed.

Much of the information made available to the committee is contained in confidential reports to which it is not possible to make reference, because electrolysis is the subject of controversy between conflicting interests. Unfortunately, also it is impossible in some cases even to refer to places where particular expedients have been employed, or to state either the extent or the results of such use. It has, therefore, been necessary in most instances to make statements of what is the practice, without citing the authority or naming the places where such practice may be found. In compiling this report, therefore, the committee has been influenced most largely by those instances of practice within its knowledge where the greatest amount of study has been given to the subject, and where the results obtained seem best to justify its use. The committee has embodied in this report only matters of fact for which it has authority.

A. MEASURES APPLIED TO RAILWAYS.

46. Insulation. Under this sub-heading have been considered three general measures, namely: *a. Complete Insulation*, which does not involve the use of the running rails as a portion of the electric circuit, *b. Substantial Insulation*, which does involve the use of the running rails as a portion of the circuit, but, due to the type of construction employed, to a very large extent prevents stray currents, and *c. Partial Insulation*, which comprises using such means as are available to insulate the running rails of ordinary street railways in so far as practicable.

(a) Complete Insulation. Instead of using the running tracks as part of the return circuit, a separate insulated return conductor is employed for this purpose. In this case the entire electric circuit of the railway system is insulated from ground, and, there being no voltage drop in contact with earth, stray currents are entirely prevented. Complete insulation of the railway circuit is accomplished in the double underground conduit trolley system, by employing insulated positive and negative conductors in underground conduits. This system is in use on the surface lines on Manhattan Island and in portions of Washington, D. C. This is also accomplished in the double overhead trolley system by employing separate positive and negative overhead trolley wires insulated from ground; many years ago examples of this system were installed in Washington, D. C., and Cincinnati, Ohio. The practice while effective in this respect and in use for a long term of years has not spread to other cities possibly because of the unsightly appearance of the overhead structures due to the multiplicity of wires and because of the increase in operating difficulty and expense which it entailed.

(b) Substantial Insulation. Interurban and electrified steam roads generally require the rails to be supported on wooden ties set in well drained broken stone or gravel ballast. The insulation afforded by such construction practically removes danger from electrolysis. Leakage is in some instances found to be as low as .00016 ampere per rail per tie under dry weather conditions, increasing to .0055 ampere when wet with 10 volts between the rail and ground. On steel structures where the ties are only partially in contact with ground and the ties cannot become waterlogged, this leakage is even less. The substantial insulation of a ballasted roadbed has, in some installations, been rendered ineffective by bare negative cables in damp earth or by metallic connections between the tracks and steel supporting construction. Conditions are found to be very favorable for rail insulation where the tracks are in subways or under cover protected from the weather, permitting the ballast and ties to become permanently dry.

(c) Partial Insulation. The escape of current from tracks largely buried is decreased by high contact resistances between the tracks and the surrounding medium. The total resistance to flow of escaping current is found to vary with the earth resistance and the contact resistance between earth and rail. Since the earth resistance is usually low, the contact resistance is generally found to be the controlling factor in the leakage path; hence, partial insulation is found effective in reducing leakage with the low voltages commonly encountered. On a grounded trolley system in city streets it has been found beneficial to have the rails as nearly enclosed with insulating material as possible.

47. Reduction of Track Voltage Drop.

(a) **Bonding.** The best types of solid rail joints in actual use give the same electrical conductivity at the joint as in any other part of the rail length. The standard of good practice in some electrified steam roads is that, the resistance through the rail joint shall be equivalent to that of a 20-inch length of the rail adjacent, and should the resistance exceed 42 inches, that the bond should be remade. With respect to the practice of bonding in street railway systems, it may be said that there is no standard equivalent length of rail to cover all conditions, but each railway company establishes its own standard, depending on local conditions. The equivalent resistance of the rail joint in terms of length of rail will depend on the length and size of the bond, the terminal contact resistance and the conductivity of the rail. In large cities bonding to an equivalent resistance of from three to six feet of rail is common practice. In suburban districts higher bond resistances are often used. The equivalent resistance of rail joint which is adopted by different railroads necessarily varies widely with the condition of load and class of bond employed. The class of bond chosen is in many cases determined by mechanical conditions, such as the foundation upon which the track is laid.

Bonds are generally classified according to the method of fastening them to the rail. *Soldered bonds* are soldered to the head, base or web of the rail. *Pin expanded bonds* have holes drilled in their terminals, through which a steel pin is driven to expand the terminal into a hole drilled in the rail. After expansion a steel cylindrical plug is driven in the expanded hole to prevent contraction. *Brazed or welded bonds* are attached to the rail by heat generated electrically or by an oxy-acetylene flame applied to the terminal of the bond. *Compressed terminal bonds* and *compressed multiple terminal bonds* have their terminals formed into a solid cylindrical stud, or studs, and are compressed in the rail holes with screw or hydraulic compressors or by hammer blows, which expand the studs in threaded or beaded holes of the rail. A special type of this bond has large contact surfaces about the terminal, so that the bonds can be soldered and compressed to the rail.

The carrying capacity of bonds has sometimes been found insufficient to keep their temperature within safe limits under conditions of maximum load where bonds involving soldered joints are used. The resistance of a rail joint is found to be affected largely by the contact resistance between the bond terminals and the rail. Good contact and large surface of contact at the bond terminals are found necessary to low joint resistance. Replacement of bonds is generally made necessary by depreciation at the contacts, the breaking of strands by vibration or by mechanical injury.

There are now in general use several different types of rail joints which render additional bonding unnecessary. Among these types of rail joints are the following: *Cast Welded*: The rails are connected together by pouring molten iron into a mold that surrounds the joint, and when the metal cools the joint is rigid and of low electrical resistance. Thermit welding is another example of this method, the iron being liberated at a white heat from a mixture of iron oxide and aluminum which is ignited in a crucible. *Electrically Welded*: Iron splice plates are electrically welded to the rail. *Nichols Zinc Joints*: This joint is made by pouring molten zinc between the fish plates and the rail ends. The zinc is poured in after the fish plates are bolted on, and the expansion of the zinc in solidifying is relied upon to make a contact between the fish plates and rail ends which is reported to be permanent. *Romapac Continuous Rail*: The rail consists of two pieces which are so laid that the rail head joint and the rail base joint are staggered, then the rail head is rolled or crimped on to the rail base thus forming a continuous electrical path.

(b) **Cross-bonds** are electrical conductors for equalizing the current flow in the rails. When the roadbed is dry they are usually installed bare in the ground. Insulated cable is, however, sometimes used, and the insulation is protected by a heavy braid or circular loom tubing.

The important objects of cross-bonding are to equalize the current flow between rails and to insure continuity of the return circuit in case of a broken rail or bond in any one rail. It is usual practice on suburban railways to place cross-bonds at intervals of 1,000 to 2,000 feet and at shorter spacing, sometimes as low as 300 feet on street railways. Cross-bonding between parallel tracks is in some cases installed with the same frequency as between the rails of the single track; in other cases at less frequent intervals.

In determining the location of cross-bonds in connection with alternating current single track signal circuits, a departure from ideal spacing becomes necessary, owing to the fact that cross-bonds are permissible only at the reactance bonds. The signal reactance bonds are located between the signal block sections, and these sections are more or less fixed for train operating conditions. The general method used under these conditions is to cross-bond at all signal reactance bonds and install additional cross-bonds with reactance bonds at intermediate locations to obtain the most satisfactory resistance conditions in the sections fixed by the signal system.

The common practice of electrified steam railroads is to use cross-bonds with a conductance equal to one track rail, or about 1,000,000 circular mils. Street and interurban railways employ copper having a cross-section of from 200,000 to 500,000 circular mils.

Some companies provide jumpers at switches, frogs and at other special track work, to insure that the electrical continuity of the bonded rail will be maintained. This is usually accomplished by jumpers extending around the special work, except where broken rail signal protection is required, and in such cases the frogs are bonded in the return current system. In recent practice these jumpers are made of insulated copper cables, except in dry locations, as, for instance, in permanently dry rock ballast, or on elevated structures with wooden ties and no ballast, the cables being kept clear of the steel structure. The electrical leakage from a bare negative jumper in damp earth has been known to offset the effect of many miles of most careful track insulation. Under such conditions the bond is gradually destroyed by electrolysis.

(c) **Conductivity and Composition of Rails.** The conductivity of the track rails used by several interurban and electrified steam railroads has been found to be equivalent to about 1/12 that of copper, and this figure generally holds approximately true for girder types of rails, except when alloy steel is used, in which case higher resistances are found. The track rails are specified for their mechanical qualities, and, where these interfere with the electrical requirements, it is customary to give the mechanical qualities preference. The composition of rails for heavy service used by one of the large electrified steam railroads, in percentages, is as follows:

Carbon	0.62 to 0.75
Manganese	0.70 to 1.00
Silicon	0.10 to 0.20
Phosphorus	not to exceed 0.04

The American Electric Railway Engineering Association has adopted the following standard composition for heavy service rails:

	Class A Rails	Class B Rails
Carbon	0.60 to 0.75	0.70 to 0.85
Manganese	0.60 to 0.90	0.60 to 0.90
Silicon	Not more than 0.20	Not more than 0.20
Phosphorus	Not more than 0.04	Not more than 0.04

d. Reinforcement of Rail Conductivity. Early track construction practice in this country often included bare wire laid between the rails and connected to each bond. Sometimes one such wire was used for each rail; sometimes one for each track, and sometimes one served for a double track. The wires varied from No. 4 to No. 1, and were either of copper or galvanized iron. Their conductivity was small and they were subject to electrolytic injury and frequent breakage. This construction has practically gone out of use. It is, however, common to find the rails supplemented in the vicinity of supply stations by large conductors connected in parallel to the rails. This is not infrequently done by the use of bare copper wire or cable buried between rails, and hence in full contact with the earth. Old rails, bolted and bonded together and buried beneath or beside the track, have also been used in some cases.

Buried bare conductors, however, increase the contact area between the return circuit and the earth, and the tendency to augment stray currents thus caused off sets, to a greater or lesser extent, the benefits attained by the reduction of drop. The benefits to be derived, therefore, from an electrolysis standpoint, may, if use is made of bare conductors buried in the earth, be open to question. The direct benefits that accrue from the practice of reinforcing the conductivity of the rail, listed in what may be considered their order of importance, are: (1) Reduction of energy losses; (2) The maintenance of a higher average voltage at the cars, especially at times of peak load, thus resulting in improved car service and car lighting; and (3) The reduction in potential drop in the rails, thus reducing stray currents and, in turn, therefore, lessening the damage to the extent that these stray currents are reduced, qualified, however, in accordance with the statement previously made if buried bare conductors are used.

Where conductors paralleling the rails are installed as an electrolysis mitigation measure, they are usually insulated from earth by carrying them overhead or in underground conduit. The practice varies as to the method of connecting such conductors to the rail; they are sometimes connected at the ends only but more generally at intermediate points also. Where this arrangement is used the track rails are connected to the negative bus at the nearest convenient point.

Conductors are here regarded as in parallel with the rails when one end is connected to the track and the other to a station bus-bar which is connected directly to the rail by a conductor of negligible resistance. The use of such conductors should not be confused with the "Insulated Track Feeder System," which has for its prime object the mitigation of electrolysis. This is treated under a subsequent heading.

(e.) **Use of Additional Power Supply Stations and Distribution of Load.** The growth of electric railway systems in large cities has often led to the installation of additional power stations or substations for the more economical and satisfactory operation of the railroad. This has also reduced the track voltage drop and subdivided the areas over which leakage from rail to earth occurs and thus has had the effect of reducing the stray currents.

The effect of providing additional centers of power supply can best be illustrated by the curves on Figure 5, which, while deduced from theory, illustrate in a simple case effects such as have been observed in practice.

The curve *SAO* of Figure 5 represents the track voltage

REDUCTION OF TRACK VOLTAGE DROP BY
ADDITIONAL POWER SUPPLY STATIONS

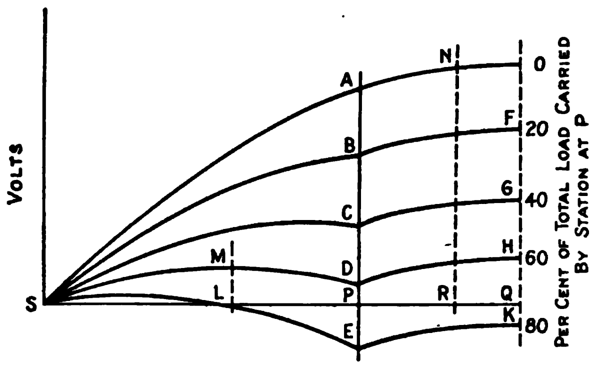


Figure 5

drop on a portion of an electric railway system having a uniformly distributed load. This curve is a parabola with a vertical axis and with the apex at *O*—that is, at the end of the line.

The curve *SBF* illustrates the condition of a substation located at *P* (33 per cent of the distance from *Q* to *S*) carrying 20 per cent of the total load. In this curve the portion *BF* is identical with *AO*. As the load is uniformly distributed, 33 per cent of the load is on the portion of the line shown by *PQ*, and of this 33 per cent, 20 per cent is carried by the substation *P*. The remainder, or 13 per cent, is carried by the station *S*. The point *B* on the curve *SBF*, therefore, corresponds to the point *N* on the curve *SAO*, the distance *QR* being 13 per cent of *QS*.

In the same manner the curves *SCG*, *SDH* and *SEK* are drawn showing the conditions when the station *P* carries 40 per cent, 60 per cent and 80 per cent, respectively, of the total load. The summit of the curve *SMD*, in which the station *P* carries 60 per cent of the load, is located so that *PL* equals 60 per cent minus 33 per cent, or 27 per cent of the total length *SQ* to the left of *P*. The distance *QL* is, therefore, 60 per cent of the total length *QS*.

In general, the conditions are more complicated than those here assumed, and will ordinarily prevent an accurate determination of the relative location of the negative busses of the two stations. It is possible, however, to make tests which will verify each of the points which have been used in preparing the curves, although it may not be possible to verify all of them at any one test or in one location.

48. Three-wire Systems. As far back as 1894, and possibly earlier, consideration was given to a three-wire system of operation for electric street railways, wherein the tracks acted as the neutral circuit. The reason for considering such a system was to reduce stray currents through the earth. Installations of this sort were tried out in Pittsburgh, Pa., Lowell, Mass., Portland, Ore., and Seattle, Wash., in the earlier days; somewhat later an experimental installation was made in Cambridge, Mass. In the *Transactions* of the American Institute of Electrical Engineers for 1907, Vol. XXVI, No. 1, pages 268 to 280, Messrs. Paul Winsor and J. W. Corning report the results of an investigation to determine the feasibility of using the three wire system for the purpose of reducing stray currents through the earth. This investigation showed that the three-wire system of operation materially reduced the track voltage drop, and therefore reduced the amount of stray current in the earth and in underground metallic structures. The figures and curves shown by Mr. Corning indicate that there is a reduction in current flowing on pipe lines tested by him of the order of nearly 90 per cent.

Until very recently it was thought that three-wire systems contained certain serious inherent disadvantages. It was felt that the complications in machinery, difficulties in successfully insulating trolleys of different polarities, difficulties in equalizing the load between different sections, and, further, the necessity for the installation of larger generating units to compensate for the difficulties in balancing than were required with the single-trolley grounded system, were so great as to preclude the consideration of the three-wire system for electrolysis mitigating purposes. Recently, however, interest in this system has been renewed, and at least some of the difficulties successfully overcome, with the result that at the present time there are in operation or being installed two sectionalized three-wire systems—one in operation in the Hollywood district of Los Angeles, Cal., and the other in process of installation in West Springfield, Mass. It is known that the three-wire system has been in operation for some twelve years in Nürnberg, Germany, and for a considerable length of time in Brisbane, Australia.

The three-wire system may take two different forms, which, though the same in principle, differ decidedly as to the arrangement of the feeders. In one form, known as the *Parallel Three-wire System*, one trolley of a double track road is negative and the other positive, the tracks being neutral. In the other form, known as the *Sectionalized Three-wire System*, the feeding district is divided into sections and alternate sections are supplied by feeders running directly from the positive bus, while the remaining sections are supplied by feeders from the negative bus. For a more detailed description of these two forms of three-wire systems reference is made to the Bureau of Standards' Technologic Paper No. 52.

49. Reversed Polarity of Trolley System. With the ordinary construction of electric railways using the running tracks as a part of the electric circuit, the overhead trolley wire or third rail is made the positive conductor, and the running tracks the negative or return conductor, only one exception to this rule being known to the Committee. With the usual arrangement stray currents escape from the running rails into ground and flow to underground structures at points distant from the power station, and such escape of stray currents from the rails generally takes place from a large area of outlying lines. The current then returns to the tracks from ground and from underground structures in the neighborhood of the power station. For this reason the most acute danger from electrolysis is usually produced on underground structures in the neighborhood of the power station.

To reverse this arrangement of polarity and make the rails the positive conductor, causes current to leave the structures over widely scattered areas, so that the current density leaving the underground structures will be so small as to prevent acute danger from electrolysis. This arrangement is being used in New Haven, Conn. at the present time. It is found, in this instance, that all potentials and currents which formerly existed when the rails were the negative conductor have now reversed in direction, but have the same magnitude. It is also found that current leaves underground structures over a widely scattered outlying area. This arrangement has not been in operation a sufficiently long time to determine whether or not the danger from electrolysis at any one outlying point will become acute. The reversal of polarity renders extremely difficult the effective drainage of underground structures, because there is no definite point of minimum potential to which to drain.

50. Booster System. Negative boosters have, in the past, been employed in connection with drainage systems, and are in use in connection with the insulated track feeder system abroad, but not in this country, so far as known. The use of negative boosters is simply a means of caring for voltage drop other than by the use of copper. Boosters have proved economical under certain conditions, and uneconomical under others. In general it is simply a question of the fixed charges on copper as against the fixed charges and operating cost of machines. In one instance where a booster was employed in connection with a drainage system it was discontinued, not because the addition of a booster to a drainage system was unsatisfactory, but because the drainage system itself did not adequately care for the trouble. Various special arrangements involving the use of boosters in electrolysis mitigation have been proposed, but in so far as is known they have never been placed in successful operation.

51. Interconnection of Railway Return Circuits. Wherever two or more electric railway tracks come close together, whether they belong to the same railway system or to different railway systems, large differences of potential between them, with resultant high potential gradients through ground, are often found to occur unless the tracks are electrically connected. Interconnection of tracks has been found to be of particular advantage where two or more lines of electric railway, operating in one locality and belonging to the same or to different systems, are supplied from two or more power stations located in different parts of the city. By interconnecting the tracks of such lines in the neighborhood of the power stations, and also at several intermediate points, an interchange of current has been brought about, whereby the drop formerly existing in one track has been balanced by the drop in the opposite direction in the other track, the rail drop in each track greatly reduced, and all high potential gradients between the tracks eliminated. This reduction in rail drop resulted also in a corresponding reduction of losses.

52. Use of Alternating Currents. When the first alternating current railways were proposed, the question of possible electrolytic effects received special investigation. Considerable work was done upon a laboratory scale, in which it was established that alternating currents could produce corrosion on electrodes of the metals commonly used underground, such as lead and iron, but that the effects were very much less in magnitude than those produced by equivalent quantities of direct current, usually less than one per cent and in most cases negligible.

It has not as yet been possible to determine whether these effects, demonstrated in an experimental manner, are being reproduced in the case of actual installations. In the case of practically all actual exposures which have occurred up to the present time it has been impossible to dissociate effects which might be due to an alternating current exposure from the effects which are due to a simultaneous exposure to stray currents from direct current railways. Whether alternating current corrosion is proceeding at the relatively slow rate indicated by the experimental investigations and will at some time produce damage to subsurface structures, cannot now be determined. Special measures for the reduction of leakage of current to earth are being tried out in one alternating current railway, but neither the construction nor the results have yet been made public. (See Bureau of Standards Technologic Paper No. 72.)

53. Insulated Track Feeder System. The insulated track feeder system or the insulated return feeder system is employed in a number of American cities at the present time, and plans are being made looking to its installation in a number of other cities.

The arrangement of feeders described under this title is not generally understood, and as it is commonly confused with the reinforcement of track conductivity, the following explanation is therefore made.

Stray current which is the cause of electrolytic corrosion is traceable directly to voltage drop in the rails. With a given resistance between rails and earth any means which will most effectively reduce this voltage drop is, therefore, the means which will most effectively reduce electrolytic corrosion. The reinforcement of the conductivity of the rails by paralleling them with other conductors operates definitely in this direction, provided the paralleling conductors are not themselves in contact with the earth. When, however, it is desired to reduce the voltage drop to such a point as will insure reasonable immunity from electrolytic troubles, the employment of copper in parallel with the rails generally proves prohibitively expensive. For example, an average grade of rail has a resistance 12½ times that of copper of the same cross-section. Its conductivity is therefore approximately the equivalent of 10,000 c. m. of copper per pound per yard. Such a rail weighing 100 pounds per yard would be approximately equivalent to a 1,000,000 c. m. cable. To reduce the track voltage drop to one-half its former value, where such a rail is employed, would require a 1,000,000 c. m. cable laid parallel to each rail of the track for its entire length. This large investment in copper would reduce the losses of track transmission by but one-half, and would reduce the stray current by one-half. If bare copper in contact with the earth were used the stray current would be reduced by somewhat less than one-half. Thus, the practice to install return copper to reduce track drop with a grounded bus-bar is either prohibitively expensive or ineffective. It was because of these recognized difficulties that the *Insulated Track Feeder System* was introduced.

The insulated track feeder system employed in the American cities above referred to has the following distinguishing characteristics:

(a) The negative bus is insulated—that is, not connected to earth nor directly to the rails at or near the power or sub-station, except that, in some instances, it is connected to the rails through resistances sufficient in magnitude to insure that this point is at approximately the same potential as other track feeder points.

(b) The current is returned to the negative bus by insulated feeders leading from selected points on the track network.

(c) These feeders are connected to the track at their extremities only, or, if connected at intermediate points, are connected through resistances of such magnitude as to keep all connected points at approximately the same potential with respect to the bus.

The *Insulated Track Feeder System* is thus an arrangement having for its prime object the reduction of stray current through the earth. The insulated feeders are installed either overhead or in underground ducts, and extend from the negative bus to such points on the track network as have been determined, by either observation or computation, to be those from which the removal of current will prevent excessive track voltage drop. The negative bus is connected to the rails at the power house only through a resistance sufficient in magnitude to insure that this point is at approximately the same potential as other feeder connection points. When all feeder connection points are at the same potential the maximum effectiveness of the system as a means of reducing stray currents is found. The attainment of this condition requires track bonding of a reasonably high order of uniformity.

In most cases feeder connection points are not brought to the same potential, but a certain drop is allowed in the direction of the power station.

The insulated track feeder system is the equivalent of having the negative bus-bar of the power supply station divided into branches corresponding in number to the number of track feeder points, and distributed geographically over a considerable portion of the track network. This reduces both maximum and average current in the rails and also reverses the direction of the current in the rails on one side of each feeder point. These changes in the rail current directly reduce track voltage drop. The area from which current leaks to earth and to underground structures, and also the area from which current returns from underground structures and earth to the rails are subdivided. The combined effect of these factors is a substantial improvement in electrolysis conditions of underground structures. (See G. I. Rhodes, Trans. A. I. E. E., 1907.)

The efficacy of this system in reducing stray current is practically independent of the weight of copper in the individual feeders—that is to say, the voltage drop in the feeders may be either large or small, without material effect upon the stray currents.

As was pointed out under a prior sub-heading, negative boosters may be used with this system. The principles underlying the insulated track feeder system are the same, whether or not negative boosters are used.

B. MEASURES APPLIED TO AFFECTED STRUCTURES.

54. Insulating Joints in Large and Small Iron Pipes and in Lead-sheathed Cables. In a number of installations flow of stray current on metallic pipe lines has been prevented by the use of a sufficient number of insulating joints. It is found that where a pipe line is laid with every joint an insulating joint, the line has such a high electrical resistance that no measurable current flows on the line, although considerable potential gradient exists in earth parallel to the pipe line. In some installations it has been found sufficient to use comparatively few insulating joints to break up the electrical continuity of a pipe line and protect the line from electrolysis, but in these cases it was necessary to make adequate tests to assure that sufficient current did not shunt through earth around the joint to damage the pipe on the positive side of the joint. In these installations it has been found necessary to install such insulating joints, not only in the positive areas, but also in the negative areas in all places where considerable potential gradient in earth parallel to the pipe existed. It is found, in fact, that the frequency with which insulating joints must be installed in a pipe line in order to assure reasonable protection from electrolysis, depends upon the potential gradient through the earth and upon the electrical resistivity of the earth in the neighborhood of the pipe line.

Tests on joints buried in earth have shown that the resistance of a short insulating joint is practically the same as that of a long joint, but that a long insulating joint gives a more even distribution of leakage current than a short joint, and that, therefore, a long insulating joint is to be preferred where there is considerable potential difference across the joint or where the resistivity of the surrounding soil is very low. It has also been found that the effect of a long joint can be secured from a short insulating joint by surrounding the joint and the pipe for some distance on each side of the joint with a heavy layer of insulating material. In a number of installations of such insulating joints in important pipe lines, each joint and the pipe for a distance of from 5 to 25 feet on each side of the joint have been surrounded by a wooden box leaving a space of from 1 to 2 inches between the outside of the pipe and the inside of the box, and the space then filled with pitch, parolite, or similar material. In this way an insulating joint having an effective length of from 10 to 50 feet was secured. (See also Bureau of Standards Technologic Paper No. 52).

In a large number of cases small service pipes have been damaged by electrolysis from stray current leaving the service pipes for earth, which current was found to flow to the service pipes either from the main or from house piping. In the latter case the current was found to reach the house piping by way of a service pipe from another piping system. In some cases of this kind such current flow to service pipes has been greatly reduced or prevented and the service pipe thereby protected from electrolysis, by placing an insulating joint in the service pipe at the main or in the building, as the case may be.

In some cases it was however found necessary to install an insulating joint in the service at the main and a second joint in the building, the necessary locations of the joints being determined from the results of electrical measurements. This method of protecting pipes has been applied to isolated cases which were specially studied, but has not been generally applied to a large complicated city system of mains and services.

For wrought-iron or steel pipes of small and moderate size, various commercial insulating joints have been largely used. For large sizes of pipe a flanged type of insulating joint has been commonly used. This insulating joint has been made up by placing a disc of insulating material between the surfaces of the flanges, by placing insulating tubes over the bolts, and by placing insulating washers under the bolt heads and nuts. Red fibre has been most commonly used for the insulating material, except that for water pipes in some cases soft sheet rubber has been used for the packing between the flanges. Where such flanged insulating joints have been used in cast-iron mains the flanges have generally been cast as part of the pipe.

For water mains various forms of insulating joints employing white pine wood for the insulating material have also been used to a considerable extent. For cast-iron water mains with bell and spigot joints, these joints have in some installations been rendered insulating by placing a short wooden ring between the inside of the bell and the end of the spigot to prevent metallic contact between the pipe lengths, and then calking the joint with wooden staves of clear white pine shaped to fit the curvature of the pipe. In these cases the spigot end of the pipe was either cast without a bead or the bead was removed. The leaks that developed in the joint were stopped with white pine wedges. These simple joints have been found satisfactory for pressure up to about 75 pounds per square inch (5.27 kg. per sq. cm.) Where with higher pressures leakage developed through the pores of the wood, this was overcome by dipping the inner ends of the staves in red lead. The staves have also been reinforced in some cases by an iron band clamped around the spigot end of the pipe.

It is found that cement joints in cast iron pipes as ordinarily made have a very high resistance between adjoining lengths of pipe and that such joints may properly be classed as insulating joints. When pipe lines are laid with every joint, or even every other joint made of cement, the resistance of the pipe line becomes so great that the current flowing on the pipes will be greatly reduced. In practice, however, for mechanical reasons it has been found that cement or other insulating joints cannot be used under all conditions or for all sizes of pipe. In such cases, the entire drop of potential of the pipe line is distributed more or less uniformly over all of the cement joints and the drop in potential around any one joint is too small to cause any injury through leakage of current around individual joints unless the soil is of great conductivity.

This, however, will not prevent electrolytic corrosion in localities where current can reach the pipe by way of laterals, or when it is closely adjacent to other conducting structures which nullify the effect of the joints, or when there is leakage from another transverse pipe.

Insulating joints in lead sheaths of underground cables are in use to some extent, but they are not found to afford an effective primary means of preventing electrolysis. In some installations such insulating joints have been used in positive areas for the purpose of breaking up the electrical continuity of the lead cable sheathing and stopping rapid localized destruction from electrolysis, but such joints have not generally been found to afford permanent and complete protection. In certain special cases in practice insulating joints have been used in the lead sheaths of certain cables for the purpose of preventing current from reaching the remainder of a cable system. Common examples of this are found where laterals or services from a cable system pick up considerable current from an iron conduit or from pipes with which the cable or iron conduit may be in accidental metallic contact, which current is then delivered to the cable system. Such current flow to the cable system has frequently been effectively stopped by introducing an insulating joint in the lead sheath of the lateral or service where it leaves the iron conduit and before it is connected to the main cable system.

Particular points on main cable runs have also been found where considerable current was picked up. Such cases have frequently arisen where a cable crosses a bridge in an iron conduit, and where the conduit is in metallic contact through the structure of the bridge with trolley tracks on the bridge, whereby large currents were found to flow from the tracks through the bridge structure and iron conduit to the cable system. In such cases insulating joints have been installed on each side of such sections or crossings so as to interrupt the metallic continuity of the main cable sheath and prevent current from the bridge reaching the cable system. Where, after this was done, considerable potential differences were found to exist across the outer ends of the cable sheaths, these were equalized by connecting the cable sheaths at the two ends together by an insulated wire.

A simple and cheap form of insulating joint for lead cable sheaths which has been very generally used consists in cutting out a narrow strip of lead and covering the break with a suitable insulating and waterproof material so as to effectively prevent entrance of moisture.

This method of protecting underground structures has not been widely used as a primary means of electrolysis protection, partly because of the great expense involved. Further, insulating joints unless used with caution may introduce serious trouble at many points. This method has proved useful especially in certain new installations, but to protect existing installations by this means would involve prohibitive cost. It is usually regarded as a suitable auxiliary measure to be used in certain cases which cannot economically be taken care of by other means.

55. Insulating Pipes, Cables and Structural Steel from Earth. Many attempts have been made in practice to protect underground pipes from electrolysis by insulating the pipes from earth by paints, dips or insulating coverings. It has been found, however, that no dip or paint will permanently protect a pipe from electrolysis in wet soil. The first difficulty that is met is to apply the paint so as to form an absolutely perfect coating, and then to prevent mechanical damage to the coating. Where a coated pipe is in a positive area it has been found that aggravated trouble from rapid destruction of the pipe has resulted at spots in the pipe where there are imperfections in the coating. It has further been found that even where paints or dips are apparently intact, electrolytic action has taken place causing severe pitting under apparently good coatings. It has been found that in most cases the coatings applied have either been completely destroyed by the effects of the wet soil and electric currents, or defects in the coating have developed, causing concentrated corrosion at such defective spots. It has, in fact, been found that pipes located in positive areas covered with imperfect insulating coatings are more rapidly destroyed by electrolysis than bare pipes under the same conditions. It has been found that coating pipes in negative areas with insulating coverings accomplishes some good by reducing the amount of stray current which reaches the pipe.

Investigations indicate that the destruction of paints in wet soil where subjected to an electric current is probably due to a trace of moisture finding its way through the coating, giving rise to the flow of a feeble current and resulting in a very slight amount of electrolysis. The gases and other products of electrolysis then form blisters and finally rupture the coating.

Attempts have been made in practice to apply a molten material like pitch or asphaltum to a cold pipe in the field by means of brushes, but it has been found impossible to completely cover the pipe in this way. A type of insulating covering which has been successfully applied in a number of installations, and which appears to afford certain protection, consists of a layer of at least from 1 to 2 inches of a material like pitch or parolite of such a grade that it is not brittle and so will not crack, but yet is hard enough to remain in place. It has been found best to apply such a layer by surrounding the pipe with a wooden box, supporting the pipe upon creosoted blocks of wood or upon blocks of glass, and then filling the space between the box and the pipe with the molten material. The cost of carrying out such an installation is, however, large. The method has been applied in special cases, such as service pipes in very bad localities, and in the case of some very important individual pipe lines of comparatively small size.

Attempts have been made to protect a pipe from electrolysis by imbedding it in cement or concrete, but these attempts have not been successful, even where the cement or concrete was several inches in thickness. The reason for this is that concrete in damp earth acts as an electrolytic conductor, like damp soil, and therefore cannot afford protection from electrolysis.

The following experience and practice is that of a gas company in a large city which uses cast-iron pipes in general in their distributing system with wrought-iron services. They make it a uniform practice to protect all of their service pipes with an insulating coating. As a preliminary the pipes are first cleaned with a wire brush, in order to remove all scale. They are then dipped into a hot coal tar compound, then wrapped for the entire length with a strip of canvas, and then again dipped in the compound. In spite of this protection, however, they have some trouble with their services. The difficulty is due to their inability to get a continuous coating over the entire surface of the pipe. Small pin holes are left in the coating due to minute bubbles of air, or some similar cause, so that if the pipes are positive the flow of current from the pipe through moist earth is confined to these minute pin holes through the insulating compound. The result is that the action of the current forms a small blister of iron rust at the point where the pin hole is located, and after the blister becomes so large as to loosen a piece of the compound, the action takes place at a very rapid rate and soon destroys the pipe. In some locations some of the service pipes have to be renewed within a period of six months on account of the leaks caused by the electrolytic corrosion.

Attempts have been made to insulate lead-sheathed cables from earth, but these attempts have not generally been attended with beneficial results. The experience of the telephone companies, who are the largest users of lead-sheathed cables, has been that it is futile to attempt to insulate lead-sheathed cables from earth. It is, however, the practice of the telephone companies to make every effort to prevent metallic contact between their lead-sheathed cables and other grounded structures throughout the run of the cable, except where it has been determined by a careful survey that a drainage connection to some particular structure is required for the protection of the cable.

The use of insulating ducts has been proposed at various times, but investigations of the telephone companies do not show that their use affords satisfactory insulation of the cable sheaths from earth, with the result that the telephone companies do not place any reliance in any insulating property that any of the duct material may inherently possess. The principal duct material at present used by the telephone companies for main cable subway runs is vitrified clay and creosoted wood. For laterals and short cable runs iron pipe is frequently used.

Laying telephone cables in troughs and surrounding them solidly with asphalt was a method employed in the early days of telephone construction, but this method was abandoned because of its inflexibility and because of the great difficulty of repairing defects or replacing cables. It was further found that this method did not positively insulate the cables everywhere from earth on account of cracks and other discontinuities in the asphalt which were found in practice to develop.

Steel tape armored cables protected with a thoroughly saturated jute covering have been used buried directly in earth. Such covering has been found to be effective for a number of years in protecting the armor against electrolytic corrosion, except at points where the jute has been abraded or cut so as to expose the metal.

Where steel structures extending underground are located so as to be subjected to electrolytic action, the portions below ground have been enclosed with insulating materials. For this purpose any material that excludes water, as for instance paints having an asphalt base, have been successfully used, while many of the ordinary paints have not been found effective. It has also been found that surrounding steel with concrete where this is imbedded in damp earth does not afford absolute protection against electrolysis, although the electrolytic action is most severe at first and becomes less with time, because the formation of chalk in the concrete fills the pores of the concrete and increases its resistance and the iron oxide forming on the surface of the metal also increases the resistance. Special preparations of Portland cement properly applied so as to be watertight have also been found to afford good protection.

56. Shielding, or the Use of an Auxiliary Anode. In some special cases underground structures have been protected from electrolysis by connecting to the structure an auxiliary metallic conductor located so as to cause the current to flow to earth from the auxiliary conductor. This mode of protection is known as shielding. When applying this method it has been found necessary to take care that the auxiliary shielding conductor does not merely increase the electrode areas from which the current leaves, because in this case the current will continue to leave from the structure which is to be protected. This has been found to be the practical result where a shielding conductor of the same or less contact area was placed in earth near the structure to be protected and where the stray current then left from both structures. The shielding conductor must be so placed that current will be prevented from leaving the structure to be protected or so as to cause its magnitude to be greatly reduced. The method has in some installations been applied to a structure which forms the dead end of an underground metallic system and where the structure is highly positive to earth. In cases of this kind it has been found that the current leaves at relatively high density from and near the dead end of the structure, with the result of rapid destruction of the portion near its dead end. In such cases an auxiliary shielding conductor of adequate contact surface extending beyond the dead end and electrically connected to the structure to be protected has been installed in such a manner that the bulk of the current was caused to leave the auxiliary shielding conductor, thus affording a certain degree of protection to the dead end of the structure.

The shielding method has also been effectively applied for the protection of relatively small iron or steel pipes, such as service pipes. In these cases the service pipe has been surrounded by a larger metal pipe electrically connected to the smaller pipe. One application of this method which is in use is that of a service pipe crossing under tracks or crossing other structures to which it is positive and where the pipe comes relatively close to the rails or other structures at the point of crossing. In these cases a larger shielding pipe, usually of heavy cast iron, has been placed around the service pipe and electrically connected to the service pipe and extended sufficiently on each side of the crossing so that the major part of the current was caused to leave the shielding pipe, thereby corroding the shielding pipe while protecting the service pipe.

57. Drainage of Earthed Metallic Structures.

(a) Lead-sheathed Telephone and Power Cables. The method of protection against electrolysis used generally by telephone companies for their cable sheaths consists of installing insulated conductors, called drainage wires, between the negative return system of the railway and points on the cable system where the positive potential to earth is highest. The purpose of these drainage wires is to conduct the stray railway current from the cable sheaths to the railway negative return circuit, thereby preventing this current from flowing from the cable sheaths to earth and causing corrosion from electrolysis. In order to afford complete protection it has been found that such drainage wires must have sufficient conductivity and must be so located that the lead sheath of the cable network is everywhere lower in potential than the adjacent earth.

As the potential of the cable sheath is lowered by the connection of the drainage wire from the railway negative return circuit the current flowing on the cable sheath is thereby increased. In order that this current does not become excessive, care is taken to prevent contacts between cable sheaths and other underground structures, through which currents could flow to the cable sheaths.

The drainage method is also employed to a considerable extent for the protection of underground power cables, and the principles involved in its application are the same as for telephone cables. When power cables are worked at relatively high temperatures they should not also carry a heavy drainage current which might cause over heating. Where such conditions prevail drainage is not employed, but insulating joints are used to break up the continuity of the lead sheaths.

(b) **Pipe Systems:** The early success of the drainage method in affording protection against electrolysis of lead-sheathed cables led to the proposal to apply the same method of protection to underground piping systems. The result has been that in some cases drainage has been applied to gas and water piping systems to a greater or lesser extent. Some of these installations are reported to be a success, while others are reported to have been attended with objectionable results.

It has been found that there are certain differences between the application of drainage to pipes and the application of drainage to cable sheaths. The principal difference that has been found is that the cable sheaths are electrically continuous and uniform conductors, while the pipes are generally non-uniform and sometimes discontinuous conductors, by reason of the joints. It is found that where current flows along a pipe and encounters a high resistance joint, part of the current will leave the pipe on the positive side of the joint to flow to some other underground conductor or to shunt around the joint and thereby cause electrolytic corrosion of the pipe on the positive side of the joint.

Another difference between lead-sheathed cables and piping systems is that the cables are relatively small and are contained in ducts, so that unless they are submerged they are not in direct contact with earth, except at infrequent points, whereas gas and water pipes form extensive systems and are buried directly in earth. It is found as a result of this that a drainage connection from an underground piping system generally causes very much larger currents to flow on the piping system than a drainage connection from an underground cable system.

In the application of the drainage system it has been found that unless all sub-surface metallic structures affected by stray currents have been bonded together in such a way that at every point where the different structures come into proximity to one anotherall are maintained at the same potential, damage to the unconnected structures has in certain instances resulted from a flow of current through earth from the structure of higher to that of lower potential, thus causing electrolysis of the former. As structures owned by different interests cannot be bonded together except by an agreement between the owners, this has frequently of itself made it impossible to apply a comprehensive drainage system to all structures, because of the impossibility of obtaining an agreement of all owners to allow connections to their structures, except on condition that another interest assume liability for any injury which may result from such connections.

Current flowing on piping systems which convey inflammable substances such as gas or oil constitutes a danger, as cases have been reported where stray currents on pipes have caused arcs which have ignited the gas or oil when an intentional or accidental break in the pipe has occurred. In other instances serious damage from explosions and fire has been caused by an arc due to the intermittent contact between pipes.

(c.) **Structural Steel.** In a number of installations special precautions have been taken to prevent stray current from reaching structural steel. Where in these cases such currents were found to reach the structure by means of pipes or other metallic connections, insulating joints have been placed in such connections, or these pipes or conductors have been carried on insulated supports. In some cases where flow of stray currents to a steel structure could not be entirely prevented, drainage connections from the structure to the railway negative return circuit have been installed to remove the stray current from the structure, and where there were expansion joints in the structure these have been bonded across by metallic conductors.

C. PATENTED PROTECTIVE SYSTEMS.

58. Foreign and Domestic Patents. There have been many patents taken out in this country and abroad within the last twenty years, covering systems of electrolysis mitigation. Reference may be had to Technologic Paper No. 52 issued by the Bureau of Standards, Washington, D. C.

D. ORDINANCES AND DECISIONS.

59. Ordinances. A number of cities have ordinances directed to the construction and operation of electric railways. The Committee, however, does not possess sufficiently definite information as to the extent to which they have been put into effect or the results secured to warrant it in stating any facts regarding them at present.

60. Decisions of Courts. While there have been sevéral cases of electrolysis litigation in this country each of these has either been concerned only with certain phases of the subject or has been limited by local conditions, so that there are no leading decisions by courts in this country which define specifically the duties and rights of the several parties concerned.

IV. EUROPEAN PRACTICE.

A. GENERAL.

61. Personal Investigation Necessary. In the study of the practice followed in European countries in handling the problem of electrolysis, it appeared impossible to secure reliable and satisfactory information by mere correspondence and consultation of published reports and regulations; and further, since the important independent investigations made by American investigators several years ago were private and made from the standpoint of some special industry rather than from a comprehensive all-around point of view the necessity of an independent investigation was made evident.

The Chairman of this Sub-Committee, after consultation with its members and the General Chairman decided to visit several important European countries during the summer of 1914. He was accompanied by Mr. A. Maxwell, Testing Officer of The New York Edison Company, who was thoroughly conversant with electrolysis measurements and surveys. The effort to have the Bureau of Standards appoint a representative to join the visiting representatives failed on account of extensive engagements of the Bureau, but a consultation was held in Washington, and the field of inquiry and special points to be looked after were carefully discussed, and a list of classified questions prepared, so that as far as possible uniformity of system of investigation could be followed in all instances. Similar consultations were held with members of the main Committee. Information on important foreign cities and authorities, was received from Mr. H. S. Warren, also foreign papers, suggestions and references from Prof. Albert F. Ganz.

62. Countries Visited. The visiting Committee spent June and July in its investigation, covering Germany, Italy, France and England. In each country an effort was made to take measurements and collect data and surveys, also to interview the most prominent people in each branch of the different interests affected by the problem of electrolysis; in each case extended and often repeated conferences were held with the engineers most familiar with the details, either in their capacity of specialized consulting engineers or officials of corporations or public authorities directly concerned in the surveys, disputes, administrative measures, etc. relating to electrolysis.

The essential and characteristic results of the investigation are briefly outlined in the following paragraphs, classified by countries visited. The references and appendixes to this summary should be consulted for details of design, operation and statistical information.

B. GERMANY.

63. Laws and Ordinances. There are no specific statutory laws. The common law of most States prescribes that all the conditions under which a corporation is to operate must be prescribed in the original grant or for any extension of lines, and the law prescribes that due publicity be given to any request for a franchise or extension of lines, so as to enable all parties which may be affected to place on record any limitation, or possible damage they wish to be protected against, before the concession is granted to the applicant. Hence, a pipe owning company organized subsequently to the existence of an electric railway, could not claim damages for electrolysis from this electric railway unless the original franchise to the railway contained a clause regarding electrolysis damages from stray currents.

On the other hand, when the municipality undertakes the construction and operation of a tramway system, the pipe owning companies then in existence are deprived of the privilege of demanding that protection against possible future damages by electrolysis which would be accorded to them in the case of a new private railway company. The municipality does not assume legally the obligation to protect the existing interests against possible damages by electrolysis. The municipalities, however, both for their new railway constructions, as well as for new extensions of existing companies' railways, always prescribe that they be constructed and operated in accordance with existing technical standards.

The recommendations of the German Earth Current Commission are recognized as the existing technical standards regarding matters relating to electrolysis, and in this manner they have assumed almost the importance of law.

64. Commission Recommendations. The German Earth Current Commission's recommendations adopted in 1910 by the German Electrotechnical Society prescribe the following:

In large cities, the maximum rail drop is to be limited, in the urban net-work and for a distance of 2 km. beyond, to 2.5 volts and to 1 volt per km. beyond this central district. Exceptions are made for roads operating only a few hours a day. (It may be noted here that the maximum drop is interpreted to be the average maximum drop for the period of the normal day traffic, usually 18 hours in every 24 hours.) Bonds must not increase the resistance of tracks over 20%—must be tested yearly and when a connection shows a resistance higher than 10 meters of rail it must be repaired. Connections to pipes are prohibited. Bare feeder returns are not allowed. Pilot wires are prescribed.

Since these regulations were promulgated from 20 to 30 installations in Germany (some municipally owned and some privately) have taken steps to bring up their standard of construction to meet these regulations.

65. Construction. In large cities, like Berlin, the railways are supplied by a great number of combination light and railway substations feeding limited districts, entailing relatively small positive line drops of potential. In some cases like Berlin, each feeding point is fed by positive and negative cables of equal cross-section.

Insulated returns with balancing resistances are predominantly used in Germany, though there are a few installations with negative boosters, like Danzig, where, however, insulated returns with balancing resistances as well as boosters are used.

There are very few large installations using bare returns. The "drainage system" was used in Aachen but it is now a subject of litigation.

66. Conditions. In general the electrolysis conditions throughout Germany are now very satisfactory. In the past the majority of troubles have been on gas and water pipes, or at least these have received more attention in the reports. The railway experts expressed the opinion that the regulations were too stringent; the gas and water pipe experts expressed the opinion that the regulations were too lenient. The studies are made in the most excellent technical manner and the conclusions arrived at appear to be practicable and reasonably acceptable to all parties concerned.

Measurements were made by the Sub-Committee of one large installation and it was found that the maximum drops in rails were well within the limits prescribed by the German regulations. More extended measurements were omitted, depending for other information on the surveys made by the German Earth Current Commission.

C. ITALY.

67. Laws and Ordinances. The Government has not enacted any law affecting the operation of electric railways in relation to electrolysis problems, nor has any municipality issued regulations on the subject.

68. Construction. Bare returns are generally used, in large installations.

69. Conditions. From a survey made in a city six years ago, it was found that the maximum differences of rail potential were as great as 17.5 volts between station and distant points about three miles away. In this installation they had not received complaints of serious damages by electrolysis, except a few gas service pipes, though the railroad itself had experienced some difficulties on water pipes at one of its yards.

Some of the larger systems in important cities are alive to the situation and are following with interest the developments in other countries.

In general, troubles from electrolysis have been considered insignificant in the Italian practice.

D. FRANCE.

70. Laws and Ordinances. A Ministerial Decree of March 21, 1911, prescribes that the maximum voltage drop in rail returns of *electric tramways* shall not exceed *one volt per kilometer*, except in locations where there do not exist metallic masses in the neighborhood of the tracks, where the limit may be exceeded. No definition is given of the time element in the measurement of the maximum drop, except by stating that it must be the average during the normal passage of the cars. The same decree prescribes that the bonds must be kept in the best possible condition, that the resistance of each must not be greater than 10 metres of normal rail and that periodic tests must be made and recorded on a register which must be subject to inspection on the call of the control service. The return feeders must be insulated.

71. Construction. While the Government regulations prescribe the use of insulated returns, we were informed that in general the practice is to connect the rails to the negative bus and to rarely use insulated returns. Noticeable exceptions are the Paris conduit system tramways using complete insulated returns, and the Paris Nord-Sud Subway Company operating a three wire system with the rails as neutral.

72. Conditions. The investigation was somewhat limited in France. In general serious electrolysis troubles were found only in a few situations, either created by installations of heavy traffic electric lines, or by peculiar conditions not readily explainable. The maximum drop of potential between pipe and rail measured by this Committee was about 6 volts at a location where trouble has been persistent and serious.

Damage has been caused in the past to gas pipes in Paris during the period of transformation of the old two-wire, three-wire and five-wire systems of electric light distribution, but all of these troubles were only of temporary character and were promptly remedied as soon as discovered.

Many suits (about twenty) for electrolysis damages are being tried in Paris. On account of the situation created by these suits the Paris municipality and the government have recently appointed a Commission to investigate the subject and make recommendations regarding the electrolysis situation in the City of Paris.

E. ENGLAND.

73. Laws and Ordinances. The Board of Trade regulations prescribe that the maximum rail drop shall not exceed seven volts. In practice the Board takes as the voltage drop the mean between the average and the momentary maximum values for the period of a schedule run at time of maximum traffic, exclusive of exceptional occasions like athletic games, etc. The periods assumed vary from 15 to 30 minutes. The regulations also contain other requirements, prescribing measurements of track leakage, etc.; in actual practice, however, little attention is paid to any other requirements as long as the seven volt over-all rail drop is not exceeded.

74. Construction. Whenever the resistance of the rails would give a drop in excess of seven volts, insulated return feeders with resistances, or negative boosters are used; the latter more extensively than in any other country.

75. Conditions. The sub-committee found that in all the several cities visited the Board of Trade regulations were met well within the limits. In fact, on the average the maximum drops measured in all large cities visited in the months of June and July were about two volts.

The Board of Trade regulations are not considered onerous by any of the railway engineers we consulted. All authorities representing the pipe owning companies, the railways, the State telegraph and telephone and the Board of Trade were unanimous in stating that the electrolysis situation on the properties under their respective control was entirely satisfactory.

The only question raised, and this only by a limited number of pipe owning entities, is whether the electric railways should not be held legally responsible for any damages, even when they comply with the Board of Trade regulations. Two or three attempts have been made to have a law passed by the Parliament to this effect, and two or three pipe exhibits have been repeatedly presented to prove electrolysis damages, but the Parliament refused to act.

The seven volt limitation is considered somewhat of a haphazard empirical measure formulated many years ago, but having given good results it is considered good enough, though it is conceded that some more rational measure could probably now be devised to replace it. However, no demand was discovered for a change on the part of anyone concerned.

F. SUMMARY AND CONCLUSIONS.

76. Germany through voluntary co-operation has probably remedied the former dangerous electrolysis conditions in all of its important systems. The instrumentality of agreements on definite technical standards was sought in preference to legislation for different states.

Italy will probably give more consideration to the subject of electrolysis whenever the general conditions will permit.

France has not been as successful in bringing prompt results through legislation, as has Germany through technical co-operation.

England, which has had the benefit of Government regulation for many years, has now no electrolysis troubles nor disputes.

In Germany and England, the subject of electrolysis has received extensive study and consideration. The attached typical abstracts of reports of the German Earth Current Commission and the appendix of the detail report of the Sub-Committee are evidence of the methods followed and the satisfactory results obtained abroad by adopting the following measures:

1st. Maintenance of good bonding.

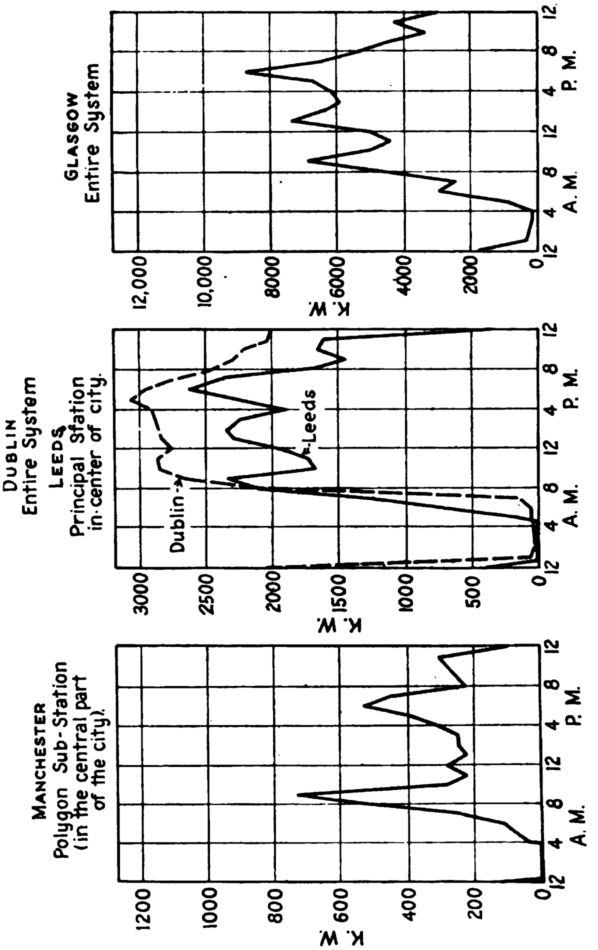
2nd. Elimination of intentional contacts, and liberal separation, whenever possible, of pipes and rails.

3rd. Avoidance of bare copper returns and use of insulated returns in all installations where the conductivity of the rail alone would give a too great maximum rail drop.

4th. Use of insulated returns with balancing resistances, or to a lesser extent "boosters," for the purpose of maintaining equality of rail potential at the feeding points of all feeders.

5th. Small feeder drops and frequent substations to give close line regulation.

77. Application to American Conditions. This study has not been made with the object of arriving at definite recommendations, but to point out that disputes on account of electrolysis troubles have been prevalent in the past in all countries before systematic cooperative studies or regulations had been applied, notwithstanding the fact that the mode of life and distribution of population and industries are more favorable than in American cities. The average weight of cars in foreign cities is essen-



TYPICAL LOAD CURVES, ELECTRIC RAILWAYS, - UNITED KINGDOM

Figure 6

tially less than in most American cities of the same population and the tramway traffic and loads per capita may be one-fifth or even less in Europe than in America. A city like Berlin with over 2,000,000 inhabitants handles all its transportation with a maximum load of about 30,000 k.w. (Chicago and the adjacent territory with 2,600,000 population requires a maximum load of about 200,000 k. w.) Manchester with a population of 1,250,000 and Glasgow with 1,000,000 have traction loads of 11,000 k. w. and 11,500 k. w. respectively. (Boston and the surrounding territory served by the same traction system has an approximate population of 1,150,000 and requires a power station capacity of 75,000 k. w.) Milan with a population of over 600,000 inhabitants has a traction load of approximately 8,000 k. w. and Nürnberg with 350,000 inhabitants uses only 1000 k. w. (The city of Worcester, Mass. with a population of approximately 160,000 requires power station capacity of 7,500 k. w.) These comparisons should not be taken as a definite index to comparative electrolysis conditions since many other factors are involved.

Other similar statistics for smaller places are given in Figure 6, and they should be taken in consideration in applying to this country the results of this investigation of foreign practice. Regardless of the degree of improvement which economical limitations may make permissible to accomplish in local situations, the fundamentals for the solution of the electrolysis problem evolved abroad merit the most careful study to ascertain their possible application to American conditions.

G. REGULATIONS ADOPTED AND PROPOSED.

78. Germany—Earth Current Commission's Recommendations. Recommendations of the German Earth Current Commission as adopted by the Gas, Water and Railway Interests of Germany.

> Regulations for the protection of gas and water mains from the electrolytic action of currents from direct current Electric Railways which use the rails as a return.
>
> Accepted for two years at the yearly meeting of 1910 and for a further two years at the yearly meeting of 1912.
>
> Published in the *Electrotechnische Zeitschrift* 1910, page 491, and 1911, page 511.

SECTION 1. APPLICATION OF RULES.

The following rules govern the installation of direct current railways or sections of direct current railways which use the rails for carrying the return current. Unless otherwise mentioned the herein given admissible potential values should be adhered to when laying out new railways. For determining the resistance of a line, the rails only must be taken into account as current carrying mediums and the assumed resistance of the rails, as well as the assumed percentage increase of resistance due to the bonding, must be stated.

These values must not be exceeded, either when making the necessary calculations or by the plant when in actual normal operation.

These rules do not apply when railways are laid with special track or when the rails are laid on wooden sleepers, in which case there is generally an air clearance between the rails and the stone ballast. But the rules do apply if this air clearance does not exist, as at grade crossings, unless an equivalent insulation is provided for locally. Further, these rules do not apply to railway lines which do not approach closer than 200 meters to an underground pipe network.

EXPLANATION.*

The regulations apply only to direct current railroads or sections of such, using the rails as conductors. Railroads not using the rails as conductors are eliminated from the start, because the same do not send any currents into the earth and therefore cannot have any damaging influence on the pipes. According to the experience reached so far, alternating current seems to have very little effect, so that any extension of these rules to cover also alternating current railways does not seem justified. At any rate, the conditions produced by alternating current railways are not yet sufficiently understood to allow of establishing any restrictions in regard to their equipment and operation for the protection of pipes.

In case a railroad is operated partly with direct current and partly with alternating current, these regulations apply only to those sections the rails of which carry direct current. The fixed upper limits of permissible potentials apply to the design of the plant, unless otherwise stated, and in the

*NOTE: This explanation and the others following are included in the German Earth Current Committees Recommendations.

calculations only the rails and the bonds are to be considered as far as the conductivity and the resistances of the conductors are concerned. The assumed resistance of the rails and the increase of same by the resistance of the bonds is to be stated, and such limiting values are not to be exceeded either by calculations or in practice.

The earth as a shunt is not considered. Through contact of the rail network with the ground, a part of the current passes into the ground and the potentials of the rail network are thereby lowered as compared with a case of perfect insulation from the ground, the effect becoming greater, the more the current passes into the ground. It is, therefore, not correct to take the differences of potentials as found immediately after the construction of a rail network as a basis for estimating the safety against damaging influences, but it is necessary to go back to the first cause, that is to say, the differences of potential as they would be if the rails were completely insulated.

This rule allows of an exact calculation of the conditions during the design of the plant without any uncertain and varying values for different localities. The limit values are not to be exceeded either during the calculations or at the actual practical test. The method of the practical test will be discussed in Section 3. The projection of the plant is, therefore, to be based on assumptions as correct as possible with regard to the resistance of the rail, the cables, and the consumption of current, and it is advisable to consider also a later increase of the traffic.

Railroads, the rails of which are insulated on special roadbeds, generally have such a great resistance against the earth that passage of current into the ground to be considered as dangerous to pipes does not occur. Higher potentials, therefore, are permissible for such railroads, assuming that a sufficient insulation is provided for also on grade crossings, etc.

As a means to this end are to be considered:

Insulating strata between rails and ground, for instance, tar paper, which must extend on all sides sufficiently beyond the place in question; or the surrounding of the pipes with insulating material. Such places are to be inspected from time to time to ascertain the effect of such insulation.

For the exemption from these regulations the laying of the rails on a special roadbed is required, because it is only in this way that a permanent insulation can be reached and maintained. About the details of the system of insulation to be used, no rules were issued. A lasting insulation is to be guaranteed by the way in which the rails are laid. The laying of rails on wooden ties as mentioned above is intended as an example only. At any rate to secure satisfactory insulation it is imperative that the rails be nowhere in contact with the moisture of the ground, as this greatly favors the passage of the current into the ground.

Tracks which are at all points at least 200 m. distant from any pipes are exempt, because any current coming over such an extended area spreads to such a degree that its density cannot possibly be harmful. In this respect concession has been made to long outlying railway lines because the subjection of such to these regulations would entail great economic disadvantages in certain cases. The maintenance of good conductivity on such outlying sections is to be strongly recommended so as to prevent the return currents from reaching a dangerous density where such sections join the rails of an inner rail network, *i.e.*, a density exceeding the limit given in Section 5.

Section 2. Rail Conductors.

All rails serving as return conductors should be built with regard to this requirement, should be made as good conductors as possible and should always be kept in good order.

The percentage of increase of the resistance of a given length of track due to the bonding should not exceed the value assumed when laying out the railway, and must not be more than 20% more than the resistance of the same length of track if the rails were without joints and of the same cross section and the same specific conductivity. On laying out a railway line consisting of main and auxiliary rails, the combined cross section of both rails can only be taken into account when determining the resistance of the track, provided the auxiliary as well as the main rails are properly bonded and cross bonded.

At rail crossings and at switches, the rails must be well bonded by special bridge bonds.

On single tracks as well as on lines where several tracks are lying side by side the rails must be efficiently cross bonded and these cross and bridge bonds must have a conductivity at least equal to a copper conductor of 80 square millimeters.

At all movable bridges or similar structures which necessitate an interruption of the rails, special insulated conductors have to be provided which secure a continuous connection between the two rail ends. In such cases, the voltage drop at average load must not exceed 5 millivolts for each meter distance between the interrupted rails.

All current carrying conductors which are connected to the rails, must be insulated from earth, excepting short connections such as bonds, cross-bonds and bridge-bonds at switches and turntables. If such bonds are laid not deeper than 25 centimeters into the earth, they may be bare conductors.

EXPLANATION.

The first condition for the reduction of stray currents and for the effectiveness of all the proposed precautionary measures, is the good conductivity of the tracks and the maintenance of this conductivity. High resistances of the single sections cause an increase of the current passing into the ground. The maintenance of the good conductivity of the rails also is to the economic interest of the railroad, because a bad conductivity will, under certain circumstances, cause loss of energy.

It is not desirable to issue rules concerning the cross-sections of rails or for the conductivity of the steel because the cross-section and the chemical composition of the steel are both determined by mechanical considerations; the conductivity is dependent on the composition of the steel, while the conductance of the rail depends on both the conductivity and the profile.

The resistance of a rail network is widely influenced by the quality of the electrical connections of the rails at their joints.

The rules do not recommend one or another system of connections at the joints, but give data covering the permissible increase of the resistance by such connections.

In consideration of the varying resistance of rails of different profile, it is not possible to establish a uniform permissible resistance for a bond, but the permissible increase of the total resistance of a section by all the bonds is given. This increase must not be over 20%. Inside of these limits the designing engineer may assume any increase of the resistance by the bond, but it must be considered that the increase assumed must be permanently maintained later on (Compare Sections 6 and 3).

It will be well to assume during the design of the plant, the increase of resistance of the bonds as very near the permissible limit. This is very important when shorter rails are to be used, with the consequent greater number of joints, the maintenance of which is correspondingly more difficult and, therefore, an increase of resistance through deficient bonds to be expected. The conductivity of rails is to be ascertained on a number of samples before the rails are laid, so as to have a guarantee that the calculated resistance will correspond to the resistance of the finished network.

The measurement of the resistance is made by measuring the current and the potential on a rail as long as possible and insulated from its supports; the potential terminals should include a part of the circuit between the current contacts and they should be at least of 0.5 meter distant from these current contacts. A simple calculation gives the conductivity of the rail by using the value shown by ammeter and voltmeter. The conductivity of the rails now in use is generally found to be between 4 and 5.5 Siemens.

In cases where main and auxiliary rails are to be used and where the combined cross-section of both is taken into calculation, the conductivity of the auxiliary rail also is to be measured as the same may differ considerably from the conductivity of the main rail.

At crossings and switches a loosening of the rail connections will take place caused by the vibrations brought about by the passage of the rolling stock, for which reason such places are to be bridged specially by electrical conductors. The cross connections serve the purpose of eliminating differences of potentials between tracks running side by side and also to insure a good metallic connection between the rails on one side of a track in the case of a temporary low conductivity of single joints or interruptions.

It seems advisable in consideration of the different length of rails, not to give an absolute distance between the cross-connections, but to establish their number by the number of joints. The bonds and cross-connections may be of any material as long as their conductivity reaches at least that of a copper connector of 80 square mm. For the connection of interrupted tracks, as for instance at movable bridges, insulated cables are required because of the presence of water or other substances in the soil, which highly favor the passage of currents into the ground. The highest permissible drop in potential at average load has been fixed at 5 millivolts per meter distance between the places of interruption, to insure a small difference of potential between these points.

Furthermore care is to be taken that the tracks in a movable bridge are in good contact with the tracks on both sides of it. The following is an example of the calculation of a cable bridging across the gap.

When the distance between the tracks at the point of interruption equals 30 meters, the permissible difference of potential therefore is 5 × 30 which equals 150 millivolts. The current to be carried across is assumed to be 120 amperes and the length of cable 30 meters. Assuming a specific resistance of 17.5 milliohms per meter and square millimeter, the resulting cross-section is:

$$q = \frac{17.5 \times L\,I}{e} = \frac{17.5 \times 30 \times 120}{150} = 420 \text{ sq. mm.}$$

Inasmuch as the increase of the surface contact between the conductors and ground results in an increase of the current passing from the conductors into the ground, the conductors connected to the rails, especially those lying deep enough to come into contact with the moisture of the ground, are to be insulated conductors. Only short connections such as jumpers on crossings and switches, are exempt from this rule on account of the same not lying deeper than 25 cm. under the surface, which means that they hardly come into contact with the moisture of the ground. The increase of surface of the contacts with the ground by these conductors, is too small in proportion to the total surface of the rail network to cause any apprehension regarding the currents passing into the ground.

Section 3. Rail Potential.

A railway network is divided into two sections, first, the open road connecting the various townships, and second, the urban network.

In the urban network and for a distance of 2 km. beyond, the voltage drop between any two rail points should never exceed 2.5 volts when the line is working under normal conditions, and the drop in the rails for each kilometer of open road should not exceed 1 volt. Occasional night cars are not to be considered in determining the average load.

In townships through which only a single line is run, without local rail network, the total voltage drop in the rails must not exceed 2.5 volts from end to end of the township's pipe network.

Any apparatus which is supplied with current and which is connected to the railway network must not increase the voltage drop above the stated limits.

If various railway systems are connected together either through the medium of the rails or through the power station, each system must fulfill the above conditions. A rail system in a township with an independent pipe network has to comply with the above regulations also.

Exceptions from these rules in regard to the voltage drop in a railway network are admissible if local conditions and service necessitate and justify such exceptions. If, for instance, the service—as is the case in freight yards—covers only a small portion of the day, the above limits of rail drops may be exceeded. In yards with a service up to 3 hours daily, double the above values are permitted, and with a service up to one hour, four times the above values are allowed.

Explanation.

As mentioned in Section 1, the rail network is to be considered as insulated from the ground, so that the earth as a shunt is not considered.

The resistances of the single sections are to be calculated from the resistance of the rails under observance of the rules in Sections 1 and 2.

For the calculation of the potentials the value of the average current is to be used, as the magnitude of electrolytic decomposition of the pipe metal depends on the quantity of current, that is to say, the product of current and time. The highest values have not to be considered for the calculations. To find the consumption of current the average service as per schedule has to serve as the base.

The average current consumed on single sections can be calculated from the number of car km. or ton km. to be covered, by using the value for the consumption of current which, according to experience, and in consideration of the local conditions, is used for one car km., or ton km.

But it is also permissible to distribute the consumption of current over the whole net in a way corresponding to the locations of the single trains at the time of the average load and to calculate for each train the consumption of current taking into consideration the weight of the cars, the speed and operating conditions (grades, stops).

In regard to the schedule, the difference between summer and winter service is to be considered. The increase at regular intervals, as for instance on Sundays, is to be taken into account. Small deviations from the schedule, as for instance, single night cars, or auxiliary cars, shall not be considered, because the first would reduce the average value out of proportion, and the frequency of the second cannot be estimated at the time of the calculations and otherwise are not of any appreciable influence on the final results.

It is impossible to get regulations embracing all conditions and possibilities and it is therefore necessary to consider all peculiarities of a plant during its projection. If there are any additional places connected to the rails, where current is used for stationary motors, station lighting, etc., these are to be considered.

After the drops in potential on the central sections have been tabulated, based on the above calculations, the distribution of the potential in the rail network can be found. In addition to the foregoing data for the calculation of the drop in potential on the single sections, consideration is to be given to the proposed return cables and, in case of a three wire system, to the direction of the current in the districts of different polarity.

Difference in potential between any two points of the rail network must answer the following conditions:

Around every individual pipe network (meaning a network not in metallic contact with any other network) and also around single pipes, a zone of two hundred m. is to be circumscribed and all tracks lying outside of this zone are not to be considered in connection with these regulations, as per last part of Section 1.

For each of the rail branches lying inside of these individual pipe networks, the following rules apply:

If there are any branches of the railroad inside of a pipe network, including the 200 m.-zones, a belt 2 km. wide is to be laid around the inner rail network. Inside this belt the potential of the rails between any different points must nowhere exceed 2.5 v., as long as no portion of the rails is more than 200 m. distant from the nearest pipe along its total length (Compare Fig. 7.).

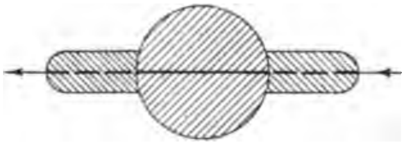
On the sections outside the 2.5 v. districts, the drop in potential must not exceed 1 v. per km. This applies to outlying sections which are shown in Fig. 7 by heavy dotted lines.

In the case of a railroad with no branches (country roads) and a pipe network, the drop in potential inside the pipe net work must not exceed 2.5 v. (Compare Fig. 8). The rule establishing a drop of 1 v. per km. states that the current in the track must not exceed $\frac{1}{W}$, if W is the resistance of the track in ohms per km. For a uniform load of a section of L km. length and a uniform resistance, the permissible drop in potential $= \frac{L}{2}$ v. *i.e.* $\frac{1}{2}$ drop in one rail. The calculation of this drop also is based on the average load, according to the schedule.

Strict rules have been issued for the interior rail network with its many branches, as it mostly covers the same area as the pipe network. This has been done in consideration of the greater surface of contact between ground and rails and pipes respectively which increases the probability of a passage of current through the ground. The potential of 2.5 volts for this district has been judged permissible because, according to the results of previous investigations, it is to be assumed that this potential will not under ordinary conditions cause any danger to pipe lines beyond the practical limits. To avoid as much as possible any greater concentrations of ground and pipe currents at the outlying sections which immediately join the inner rail network, and where important parts of the pipe network often extend, strict rules have been issued covering the district inside the 2 km. belt around the inner rail network.

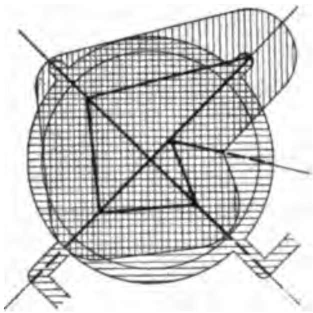
For the outlying section an economical advantage has been contemplated by limiting the drop in potential to 1 v. per km. Railroads interconnected by their rail networks or by a common power plant are to be considered as one system because such railroads influence each other, inasmuch as equalizing currents will flow between their rail networks.

Deviations in both directions from these potentials can be justified by certain circumstances—in case of especially good conditions of the ground, that is to say, in very dry dirt an increase of the potentials may be permissible. But even in such cases it is advisable to be cautious in allowing such an



▨ District of interior pipe - network.
▧ District of 200 m. around pipes with no branches.
—— Railroads in the 2.5 V. District.
— — Railroads in the I V-Km District.
—— Railroads with no Restrictions.

Figure 7



▤ District of the pipe-network with the 200 m. belt surrounding it and the pipes with no branches.
▥ District of the interior Rail-network with the 2 Km belt surrounding it.
—— Railroads in the 2.5 V. District (shaded by both horizontal and vertical lines).
— — Railroads in the I V.-Km. District (shaded by horizontal lines).
—— Railroads with no restrictions (not shaded, or by vertical lines only).

Figure 8

increase, so as not to violate the rules as given in paragraph 5. Where the conditions are unfavorable, for instance, where moist ground of especially high conductivity prevails, it is advisable to remain below the limits. For railroads with brief daily operation concessions have been made because damage to the pipes depends upon the duration of the influence of the current so that, considering the short time of operation, even greater currents cannot cause any appreciable damage to the pipes.

For railroads of three hours daily operation double drop in potential is allowed, while for railroads of one hour operation, four times the drop is permissible. Wherever the rail network is not sufficient to carry the current without exceeding the permissible potential in the network, the whole plan for the return of the current must be altered, and improvement will be reached by providing return cables in which, if necessary, resistances or boosters may be inserted. The resistances should be variable so as to correspond with the variable conditions of service and operation. In cases where the railroad system is fed from several power plants a reduction of the drop in potential in the rails may be brought about by shifting the loads of the several power plants.

The arrangement of the cables and resistances can be made in so many different ways as to make a general rule for all cases impossible. It is recommended to investigate thoroughly the cases under observation, because considerable saving in the construction and operation of the plant may be achieved by a careful layout.

The keeping of the return points at the same potential is recommended as a precautionary measure but not required. The same offers a certain guarantee of the possibility to keep the difference of potential within the 2.5 V. limits.

Furthermore, the use of the 3 wire-system with the rails as a neutral conductor is worthy of consideration. In this system the difference of potential in the rails depends on the distribution of the positive and negative feeder districts. This distribution again depends on the local conditions of the plant, so that no general rules can be given in regard to it.

Alterations of the conditions of operation can be counteracted by switching the load to the positive or negative side of the system. The rules do not recommend any certain system, but leave it entirely to the projecting engineer to select the one best adapted to existing conditions. The damage to pipes takes place mostly at points of low potential on two-wire railroads, in the neighborhood of the return points; and on three-wire railroads, in the districts of negative feeders, because it is mainly here that the current leaves the pipes. It is advisable to place the return points of the negative feeder districts whenever possible in locations with dry ground of low conductivity and as far as possible from such pipe lines as are of importance for the water and gas supply.

The permissible limits of differences in potential in rails must not exceed, either according to calculations, or at the practical trial, the limits given in Section 1 of these rules. The measurement of the difference in potential is made by means of test wires as called for in Section 6. The measurements of differences in potential are limited to those points which, according to the calculations, come nearest to the established limits. Wherever long lines, as, for instance, telephone wires, are available, it is advisable to use them for these measurements, otherwise several test wires may be connected in series or temporary test lines may be installed: finally, the results of single measurements may be computed to reach the same final results. Only high resistance voltmeters should be used for these measurements so as to make the resistances of the test wire and contacts negligible. The pointers of these instruments should have the slowest movements and a good damper arrangement, so as to give good readings even under strong fluctuations. For all measurements only average values are considered. All measurements are to be extended over a full period of operation which results from the average frequency of trains.

SECTION 4. RESISTANCE BETWEEN RAIL AND EARTH.

The resistance between ground and the rail which is used for carrying the return current should be kept as high as possible. When the conditions of the ground or the situation of the track are not favorable for this purpose, the resistance should be increased by a special effective insulation.

The rails or any conductor connected to the rails must not be in contact with the pipes or any kind of metal buried in the ground. Furthermore, care must be taken that the distance between the nearest rail and any metallic part of the pipe lines or connections to them which project above the ground or lie near the surface, be kept as great as possible, and should never be less than one meter.

Stationary motors, lighting installations or any other plant which receives current from a railway system which uses the rails for carrying the return current, must be connected to the rail network by means of insulated conductors. Excepted are short connections of not more than 16 square millimeters which are not deeper than 25 centimeters in the ground and which are at a distance of at least 1 meter from any part of a pipe network. These connections may be of bare metal. In order to increase the resistance between rail and ground it is recommended to use a bedding of high resistance and to provide good drainage, also to render the bedding water-tight to the roadbed for a sufficient width on both sides of the rail.

The use of salt for the melting of snow and ice, should be limited to cases of absolute necessity.

Wherever sufficient distance between the rail and such parts of the pipe line as project above the surface is not obtainable, it is advisable to change the pipe run, or where this is not possible, to use insulating strata (such as vitrified clay, masonry or wooden conduits, etc.).

Explanation.

The magnitude of currents passing into the ground depends not only on the potentials in the rail network, but also on the resistances between the rails and the pipes and on the resistances of the pipe lines themselves. It will always be of advantage to increase the resistance of the ground between the rails and the pipes. An artificial increase of the resistances of the pipe line can be achieved for instance, by the use of insulating flanges, couplings, etc. Aside from the technical difficulties of installing such insulating parts into gas pipes, and especially water pipes with a high pressure, and of insuring their lasting tightness, it would be difficult to provide these insulating pieces in the necessary numbers and to take care of their correct distribution. A wrong arrangement of the same will lead to an extraordinary concentration of currents at these insulations with consequent corrosion in these places. A greater part of the drop in potential between pipe and rail originally takes place in the roadbed as can be easily understood and it is therefore required to render this resistance as high as possible by the good insulation of the roadbed, good drainage, etc., and to maintain it thus.

In the same measure that the increase of the resistances between rail and pipe is recommended, the use of any means to reduce these resistances, is to be warned against. Such means to be considered are ground plates, connections of metals in the ground, and especially metallic connections between the rails and the pipes. The last will reduce the density of the current at the point of connection to the pipe, but they cause an increase of the pipe current and of the ground currents in general which may cause damage in other places, as, for instance, at interruptions in the pipe line or at crossings with other lines. Any local measure taken must be considered with regard to its effect on the pipes in other localities.

Metallic connections between different pipe networks also are to be judged from this viewpoint. Immediate contact of any parts of the pipe lines with the rails, or too close an approach, has the same effect as direct metallic connections and is, therefore, to be avoided. (By a re-location of rails or pipes or installation of insulating strata).

Especially in cases of stationary motors or lighting plants connected to the railroad system, there exists on the premises danger of an accidental or deliberate connection or contact with the pipe lines. It is, therefore, necessary to have strict rules regarding the return cables from such plants.

SECTION 5. CURRENT DENSITY.

The above rules are intended to prevent the destruction of the pipes by electrolysis. The rate of destruction is in direct proportion to the amount of current leaving the pipe.

Any pipe line where the current leaving the pipe exceeds an average density of 0.75 milliampere per square decimeter and where this current is due to a railway, may be considered endangered by this railway, and further preventive measures must be taken.

For railways with freight service when the service is of comparatively short duration, exceptions as already mentioned are permissible.

In cases where the current leaving or passing into the pipes changes its direction, the current passing into the pipe must be taken as nil when determining the average density, until further experience has been gained in this matter.

EXPLANATION.

Inasmuch as a total elimination of all damages to pipes would be in most cases possible only at a disproportionately high cost, which would far exceed the cost of any possible damage to the pipes, it is necessary to allow a certain limited damage, that is to say, a damage which is of little practical importance and which does not noticeably shorten the life of the pipes. These rules have therefore been compiled on the basis of the average conditions, that is to say, such as are mostly met with, and it is to be expected according to previous experience that the damage done to pipe lines by the stray currents from electrical railways, generally will remain limited to the practical allowable limit wherever these rules are observed. Under exceptionally bad conditions, that is to say, under conditions which very much favor the origin of stray currents, greater corrosion of pipes in certain places can hardly be avoided, even if the limits of the drop in the potential in the rails, as laid down in Section 3, are not exceeded. It is, therefore, advisable to establish some measure for the elimination of immediate danger to the pipes.

For the judgment of the damage attributed to a railroad system the density of the current leaving the pipes and returning to the railroad system is indicative.

The density of the current at the pipe can be measured only after the completion of the plant. These measurements must be made during the time of operation, as per schedule, and as described in Section 3. The average density is important and is obtained from the computation of the results of several measurements, each of which follows a whole period of service.

Measurements of current density can be made, for instance, by means of a milliammeter and non-polarizable frame as designed by Prof. Haber. This frame contains two copper plates which are insulated from each other and which for the prevention of polarization are covered with a paste of copper sulphate and 20% sulphuric acid, over which a parchment, soaked with sodium sulphate is laid. The frame is filled with dirt except between the plates, and placed alongside the pipe at right angles to the assumed direction of the current and then covered with dirt. A very sensitive ammeter connected to the copper plates will indicate the current passing through the frame and the density of this current can readily be calculated by taking into account the surface of the copper plates inside the frame. Inasmuch as here also only average readings are to be considered, it is advisable to use an instrument with very slow period.

According to investigations made so far, absolute danger to the pipes results whenever the density of the currents leaving the pipes reaches the average value of 0.75 milliampere per square dcm. For railroads with small periods of operation an excess up to double and quadruple, respectively, the above value is permissible according to the rules laid down in Section 3.

Wherever the direction of the current changes, the currents entering the pipes are not to be considered in the calculations of the average density, inasmuch as it is not as yet established that such currents will add to the metal of the pipes. Wherever the average values are exceeded, especial precautionary measures are to be taken, the nature of which can be determined only by the local conditions. In many cases it is sufficient to protect a very limited section of the rail network, to which end the further reduction of the drop in the rails may not be necessary, but which may be attained by other means as, for instance, the re-location of short sections of tracks or pipes, or the artificial increase of the resistances between rails and pipes at such points.

In all cases the question arises whether the railroad is to be considered as the only cause of current concentration, as other causes may be found to be responsible for a part of the current on the pipes; for instance, bare neutrals or poor insulation in other electrical systems, the natural electrical elements resulting from the use of different metals in the pipe lines, or from different chemicals in solution in the ground. That part of the current which is attributable to the influence of the railroad can be determined by comparison with the measurements of the current during the period of no operation. In many cases the influence of the railroad can be judged from contemporaneous measurements of current density and the potential between pipe and rail. Under certain circumstances it is possible to find the degree of influence of the railroad and of other electrical plants operating at the same time, by establishing the course of the current in the ground. For this investigation electrodes that cannot be polarized are used as contacts from the test line to the ground. The measurements should preferably be made by the potentiometer method in order to eliminate drop at the electrodes due to the current flow, but this method is difficult in practice on account of the rapid fluctuations of the voltage. It will be sufficient in most cases to make the measurements with a voltmeter of very high resistance so that the current passing through the electrodes will be very small. It should be emphasized that such measurements should be made by experts only, as deviations from the right method which seem of no importance often give useless results.

SECTION 6. CONTROL.

In order to be able to test the potential at the return points of the rail system of a given territory, pilot wires are to be connected to these points and carried to a central testing place.

Before a service may be increased the potential distribution in the rail network must be retested.

The rail bonds and bridge connections are to be retested once yearly by means of a suitable rail joint tester and must be arranged so that they fulfill the rules of Sections 1 and 2. Connections the resistance of which has been found greater than that of an uninterrupted rail of 10 meters length must be repaired to comply with these rules.

EXPLANATION.

The control of the drop in potential in the whole network would be best assured by the installation of test wires from one of the buses to all points of probable highest and lowest rail potential, which arrangement admits of immediate measurement of potential between these points.

In certain cases, especially in existing plants, the installation of such test wires would involve great cost. Such test wires from all of the important rail points were not required; but it has been ruled that all points of the rail network, to which cables of the same district are now connected, are to be provided with test wires which have to run to some central point where readings of the differences of potentials between the return points can be taken.

Wherever the expense involved permits, it is recommended to install test wires not only to the return points but also to the points of highest rail potentials.

After permanent changes in the operation, the distribution of the potential in the rail network is to be investigated in the same way as after the inauguration of the plant, in order to ascertain whether the new conditions still correspond to the rules.

In case of temporary changes of short duration in the whole network or parts of the same as, for instance, occasionally some festival, change or repair of tracks, fairs, exhibits, etc., no special measures are to be taken because the short duration of the influence will cause no noticeable damage even when the limits of these rules are exceeded.

The yearly investigation of the rail joints, as required by the rules, is also to be recommended with regard to the reduction of losses of energy. For these measurements an apparatus may be used which allows of the comparison of the drop in potentials across the joint with one of the adjoining uninterrupted rails so that the measurement may be taken during the operation. Joints of a resistance higher than that of an uninterrupted rail of 10 m. length are immediately to be repaired. The total resistance, as found by the measurement of the single joints, must not exceed the value which has been assumed during the projection of the plant (compare Section 2, paragraph 2).

Should it result during operation that rail joints are of a higher resistance than that assumed in the designing it is permissible to abstain from a re-construction of the joints as long as the permissible difference of potentials in the rails is not exceeded, even with these higher resistances. The established limits of 20% increase of the resistance of the uninterrupted rail by the bonds must not be exceeded in any case.

79. France—Regulations by Minister of Public Works Circular and order of the Minister of Public Works (France) of March 21, 1911, establishing the technical conditions which electrical distribution systems must satisfy in order to conform to the law of June 15, 1906. (Pages 25-27)

Section III. Regulations Relative to the Construction of Structures for Electric Railways using Direct Current.[1]

DISTRIBUTION POTENTIAL FOR RAILWAYS.

Art. 27. The requirements of art. 3, paragraph 4; of art. 5 paragraph 26; 4 and 6 of art. 25, and of the first two sections of paragraph 3 of art. 31 do not refer to trolley wires, nor their supports, nor the other lines placed upon these supports, nor those not upon the public highway, nor those inaccessible to the public, if the potential between these conductors and ground is not greater than 1000 volts.

1. Electric traction projects using alternating current should be submitted to the Minister of Public Works in all cases where distribution is upon the public highway.

RIGHT OF WAY.

ART. 28. When the rails are used as conductors, all necessary measures should be taken to guard against the harmful action of stray currents, on metallic structures, such as the tracks of railways, the water and gas pipes, the telegraph or telephone lines and all other electric conductors, etc.

To this end the following regulations shall be applied:

1. The conductance of the tracks shall be known to be in the best possible condition, especially in regard to the joints, whose resistance should not exceed, in each case, that of 10 meters of the normal track.

The management is required to verify periodically this conductance and to place the results obtained on file, which shall be accessible to the administration upon demand.

2. The drop in potential in the rails, measured upon a length of track of 1 kilometer taken arbitrarily upon any section of the system, should not exceed an average value of 1 volt for the operating period of the normal car schedule.

3. The feeders tied into the track shall be insulated.

4. Where the tracks contain switches or crossings, the conductance shall be maintained by special work.

5. When the track crosses a metallic structure, it should be electrically insulated, as much as possible, throughout the length of the structure.

6. As long as no metallic structure is in the neighborhood of the tracks, a drop in potential greater than that fixed in paragraph 2 may be allowed, upon the condition that no damage will result, and particularly no trouble to telegraphic or telephonic communication, and none to railway signals.

7. The owner of the distribution system shall be required to make the installations necessary to enable the administration to verify the fulfillment of the provisions of this article; it should particularly provide, whenever necessary, for pilot

wires to be installed between designated points of the distribution system.

PROTECTION OF NEIGHBORING AERIAL LINES.

ART. 29. At all points where the lines feeding the traction system cross other distribution lines, or telegraph or telephone lines, the supports should be established with a view to protect mechanically these lines against contact with the aerial conductors feeding the traction system.

In all cases, measures shall be taken to prevent the trolley wire touching the neighboring lines.

80. England.—British Board of Trade Regulations. Regulations made by the Board of Trade under the provisions of Special Tramways Acts or Light Railway Orders authorizing " lines " on public roads; for regulating the use of electrical power; for preventing fusion or injurious electrolytic action of or on gas or water pipes or other metallic pipes, structures or substances; and for minimising as far as is reasonably practicable injurious interference with the electric wires, lines, and apparatus of parties other than the Company, and the currents therein, whether such lines do or do not use the earth as a return.

First made, March, 1894.
Revised, April, 1903.
Further revised, August, 1904.
Further revised, May, 1908.
Further revised, April, 1910.
Further revised, September, 1912.

REGULATIONS.

1. Any dynamo used as a generator shall be of such pattern and construction as to be capable of producing a continuous current without appreciable pulsation.

2. One of the two conductors used for transmitting energy from the generator to the motors shall be in every case insulated from earth, and is hereinafter referred to as the "line"; the other may be insulated throughout, or may be uninsulated in such parts and to such extent as is provided in the following regulations, and is hereinafter referred to as the "return."

> The Board of Trade will be prepared to consider the issue of regulations for the use of alternating currents for electrical traction on application.

3. Where any rails on which cars run or any conductors laid between or within three feet of such rails form any part of a return, such part may be uninsulated. All other returns or parts of a return shall be insulated, unless of such sectional area as will reduce the difference of potential between the ends of the uninsulated portion of the return below the limit laid down in Regulation 7.

4. When any uninsulated conductor laid between or within three feet of the rails forms any part of a return, it shall be electrically connected to the rails at distances apart not exceeding 100 feet by means of copper strips having a sectional area of at least one-sixteenth of a square inch, or by other means of equal conductivity.

5. (a) When any part of a return is uninsulated it shall be connected with the negative terminal of the generator, and in such case the negative terminal of the generator shall also be directly connected, through the current-indicator hereinafter mentioned, to two separate earth connections which shall be placed not less than 20 yards apart.

(b) The earth connections referred to in this regulation shall be constructed, laid and maintained, so as to secure electrical contact with the general mass of earth, and so that, if possible, an electromotive force, not exceeding four volts, shall suffice to produce a current of at least two amperes from one earth connection to the other through the earth, and a test shall be made once in every month to ascertain whether this requirement is complied with.

(c) Provided that in place of such two earth connections the Company may make one connection to a main for water supply of not less than three inches internal diameter, with the consent of the owner thereof and of the person supplying the water, and provided that where, from the nature of the soil or for other reasons, the Company can show to the satisfaction of the Board of Trade that the earth connections herein specified cannot be constructed and maintained without undue expense the provisions of this regulation shall not apply.

(d) No portion of either earth connection shall be placed within six feet of any pipe except a main for water supply of not less than three inches internal diameter which is metallically connected to the earth connections with the consents hereinbefore specified.

(e) When the generator is at a considerable distance from the tramway the uninsulated return shall be connected to the negative terminal of the generator by means of one or more insulated return conductors, and the generator shall have no other connection with earth; and in such case the end of each insulated return connected with the uninsulated return shall be connected also through a current indicator to two separate earth connections, or with the necessary consents to a main for water supply, or with the like consents to both in the manner prescribed in this regulation.

(f) The current indicator may consist of an indicator at the generating station connected by insulated wires to the terminals of a resistance interposed between the return and the earth connection or connections, or it may consist of a suitable low-resistance maximum demand indicator. The said resistance, or the resistance of the maximum demand indicator, shall be such that the maximum current laid down in Regulation 6 (I) shall produce a difference of potential not exceeding one volt between the terminals. The indicator shall be so constructed as to indicate correctly the current passing through the resistance when connected to the terminals by the insulated wires before-mentioned.

6. When the return is partly or entirely uninsulated the Company shall in the construction and maintenance of the tramway (a) so separate the uninsulated return from the general mass of earth, and from any pipe in the vicinity; (b) so connect together the several lengths of the rails; (c) adopt such means for reducing the difference produced by the current between the potential of the uninsulated return at any one point and the potential of the uninsulated return at any other point; and (d) so maintain the efficiency of the earth connections specified in the preceding regulations as to fulfill the following conditions, viz.:

(I) That the current passing from the earth connections through the indicator to the generator or through the resistance to the insulated return shall not at any time exceed either two amperes per mile of single tramway line or five per cent of the total current output of the station.

(II) That if at any time and at any place a test be made by connecting a galvanometer or other current-indicator to the uninsulated return and to any pipe in the vicinity, it shall always be possible to reverse the direction of any current indicated by interposing a battery of three Leclanche cells connected in series if the direction of the current is from the return to the pipe, or by interposing one Leclanche cell if the direction of the current is from the pipe to the return.

The owner of any such pipe may require the Company to permit him at reasonable times and intervals to ascertain by test that the conditions specified in (II) are complied with as regards his pipe.

7. When the return is partly or entirely uninsulated a continuous record shall be kept by the Company of the difference of potential during the working of the tramway between points on the uninsulated return. If at any time such difference of potential between any two points exceeds the limit of *seven volts*, the Company shall take immediate steps to reduce it below that limit.

8. The current density in the rails shall not exceed nine amperes per square inch of the cross sectional area.

9. Every electrical connection with any pipe shall be so arranged as to admit of easy examination, and shall be tested by the Company at least once in every three months.

10. The insulation of the line and of the return when insulated, and of all feeders and other conductors, shall be so maintained that the leakage current shall not exceed one hundredth of an ampere per mile of tramway. The leakage current shall be ascertained not less frequently than once in every week before or after the hours of running when the line is fully charged. If at any time it should be found that the leakage current exceeds one-half of an ampere per mile of tramway the leak shall be localised and removed as soon as practicable, and the running of the cars shall be stopped unless the leak is localised and removed within 24 hours. Provided that where both line and return are placed within a conduit this regulation shall not apply.

11. The insulation resistance of all continuously insulated cables used for lines, for insulated returns, for feeders, or for other purposes, and laid below the surface of the ground, shall not be permitted to fall below the equivalent of 10 megohms for a length of one mile. A test of the insulation resistance of all such cables shall be made at least once in each month.

12. Any insulated return shall be placed parallel to and at a distance not exceeding three feet from the line when the line and return are both erected overhead, or eighteen inches when they are both laid underground.

13. In the disposition, connections, and working of feeders, the Company shall take all reasonable precautions to avoid injurious interference with any existing wires.

14. The Company shall so construct and maintain their system as to secure good contact between the motors and the line and return respectively.

15. The Company shall adopt the best means available to prevent the occurrence of undue sparking at the rubbing or rolling contacts in any place and in the construction and use of their generator and motors.

16. Where the line or return or both are laid in a conduit the following conditions shall be complied with in the construction and maintenance of such conduit:

(a) The conduit shall be so constructed as to admit of examination of and access to the conductors contained therein and their insulators and supports.

(b) It shall be so constructed as to be readily cleared of accumulation of dust or other debris, and no such accumulation shall be permitted to remain.

(c) It shall be laid to such falls and so connected to sumps or other means of drainage, as to automatically clear itself of water without danger of the water reaching the level of the conductors.

(d) If the conduit is formed of metal, all separate lengths shall be so jointed as to secure efficient metallic continuity for the passage of electric currents. Where the rails are used to form any part of the return they shall be electrically connected to the conduit by means of copper strips having a sectional area of at least one-sixteenth of a square inch, or other means of equal conductivity, at distances apart not exceeding 100 feet. Where the return is wholly insulated and contained within the conduit, the latter shall be connected to earth at the generating station or sub-station through a high resistance galvanometer suitable for the indication of any contact or partial contact of either the line or the return with the conduit.

(e) If the conduit is formed of any non-metallic material not being of high insulating quality and impervious to moisture throughout, the conductors shall be carried on insulators the supports for which shall be in metallic contact with one another throughout.

(f) The negative conductor shall be connected with earth at the station by a voltmeter and may also be connected with earth at the generating station or sub-station by an adjustable resistance and current-indicator. Neither conductor shall otherwise be permanently connected with earth.

(g) The conductors shall be constructed in sections not exceeding one-half a mile in length, and in the event of a leak occurring on either conductor that conductor shall at once be connected with the negative pole of the dynamo, and shall remain so connected until the leak can be removed.

(h) The leakage current shall be ascertained daily, before or after the hours of running, when the line is fully charged, and if at any time it shall be found to exceed one ampere per mile of tramway the leak shall be localised and removed as soon as practicable, and the running of the cars shall be stopped unless the leak is localised and removed within 24 hours.

17. The Company shall, so far as may be applicable to their system of working, keep records as specified below. These records shall, if and when required, be forwarded for the information of the Board of Trade.

Number of cars running.

Number of miles of single tramway line.

DAILY RECORDS.

Maximum working current.

Maximum working pressure.

Maximum current from the earth plates or water-pipe connections(vide Regulation 6 (I)) where the indicator is at the generating works.

Fall of potential in return (vide Regulation 7).

Leakage current (vide Regulation 16 (h)).

WEEKLY RECORDS.

Leakage current (vide Regulation 10).

Maximum current from the earth plates or water-pipe connections (vide Regulations 6 (I)) where a maximum demand indicator is used.

MONTHLY RECORDS.

Condition of earth connections (vide Regulation 5).

Minimum insulation resistance of insulated cables in megohms per mile (vide Regulation 11).

QUARTERLY RECORDS.

Conductance of connections to pipes (vide Regulation 9).

OCCASIONAL RECORDS.

Specimens of tests made under provisions of Regulation 6 (II.)

Board of Trade,
7, Whitehall Gardens, S. W.
September, 1912.

81. Spain—Electric Legislation. Law of March 23, 1900.

ARTICLE 50. To prevent the return current of electric tramway lines from exercising any electrolytic effects, the following measures shall be taken:

(1) The rails of each one of the tracks are bonded by welding or by connections formed of short copper cables, or of equivalent cables made of some other metal, the section of which having to exceed 100 square millimeters per track, and shall be made as large as possible.

(2) At intervals of 100 meters, or at shorter distances, the tracks shall be cross-bonded.

(3) In case the official inspector should deem it necessary, a cable will have to be stretched in every line, which will have to be intimately connected with both tracks; and

(4) The dimensions of all cables and wires constituting such system will have to be calculated upon a basis that the potential difference between the generator terminals and the point of the tracks remotest from them will not exceed an amount of seven volts.

H. SUMMARY OF EUROPEAN CONDITIONS.

Conditions in Germany, Italy, France and England as Reported to the Visiting Committee by Various Authorities in these Countries.

82. Present Electrolysis Conditions.

Germany. Considerable damage was found in many cities prior to the application of the Earth Current Commission's Regulations; in one case service pipe trouble occurred as often as once a month. Generally, however, extensive damage was not known until it was revealed by investigation; thus, many of the cities which were surveyed by the Commission, and where more or less corrosion was found, had previously reported no damage.

In general, the pipe owning interests stated that the situation was such that the work of the Earth Current Commission was urgently needed. Some railway engineers held that a considerable amount of corrosion ascribed to stray railway current was in fact due to other sources, or to self-corrosion.

Many very thorough tests have been made in Germany, and a large majority of these have shown that corrosion was being produced by stray railway currents.

The more prosperous companies and municipalities spent money for improvements after the publication of the Regulations of the Earth Current Commission. Exact information was not available regarding the number of places where changes had been made, but the best information indicated that the number was between 20 and 30. Of these, about 100,000 marks each was spent in Danzig, Strassburg and Erfurt, re-arranging the resistances in existing return conductors, and Dresden was engaged in insulating the existing bare conductors, and generally, the most important cities were rapidly improving their return circuit conditions.

The present conditions in Germany are considered satisfactory where the electric railways have conformed to the Commission Regulations, or where conditions were already equally good; in other cases the conditions are considered to be unsatisfactory. No cases of extensive damage to cable sheaths were found.

Italy. Very little damage, if any, is known in Italy, and the conditions are said to be satisfactory. This favorable report is based on the absence of complaints.

France. Outside of Paris, there is little damage caused by tramway systems, which generally observe a one volt per kilometer rail drop limit, contained in regulations issued by the Ministry of Public Works. No adequate or complete tests have been made in France, although some testing has been done in Paris following the development of trouble.

In Paris, 60 to 70 cases of damage to pipes have been found in a year, and the actual minimum cost of repairs was estimated to be 60,000 francs; however, it was held that the paramount consideration was the danger to security of service, since nearly all cases caused losses in buildings, although there were no explosions.

At least 30 to 35 per cent of the total number of cases reported were due to re-arrangement of the Edison two-wire and three-wire mains; such troubles are local and temporary, while in other cases the troubles are persistent.

A very considerable amount of damage in Paris is due to the " Metropolitan" subway system, which claims exemption from the one-volt per km. rule, not being a tramway system. With this exception, conditions in France are said to be generally satisfactory.

England. Considerable damage is said to have occurred in the early days of electric traction in England, although such damage was apparently insignificant compared to conditions familiar in America. Practically no damage has occurred in recent years, and certainly no extensive damage. Two or three cases, local in character and of small extent, have occurred in localities where the Board of Trade regulations were complied with.

In England there is very little good evidence in the way of tests, and the general statements of immunity are based on the absence of trouble. The Post Office and the South Metropolitan Gas Company (London) both make systematic tests and find no trouble, with the exception that the Post Office has from time to time encountered difficulties due to stray currents, which were however generally quite local in character.

While it is generally stated in England that there is little actual damage to piping systems, and that the problem is not an important issue with the owners of gas piping systems, there is considerable feeling among the privately owned gas companies that they are not adequately protected by the Board of Trade Regulations, since they cannot recover damages in case corrosion occurs where the Regulations are complied with. This has led to numerous applications to Parliament for special clauses in Acts granting powers to electric railway undertakings; most of these have been refused, but some have been granted.

It is generally admitted that the Board of Trade Regulations, as originally drawn, were empirical, and that they might be remodelled with advantage. but since the only feature of the regulations actually rigidly enforced: namely, the limit for overall rail drop, results in substantial immunity, the great difficulty attending revision does not seem justified.

83. Protective Measures in Vogue.

Feeders.

Germany. Insulated return feeders are used almost universally in Germany. In Berlin and Hamburg these return feeders are of the same number and size as the positive feeders, but generally in other towns the return feeders are of smaller cross-section. Separate feeders are generally used, but not exclusively, as feeders with resistance taps are used in some cases. Formerly there were cases of feeders tapping at several points, but important cases have been corrected by the insertion of resistances. (The distinction between copper which merely parallels the rails, and feeders intended to maintain equi-potential points in the rail net-work, is clearly understood in Germany).

Negative boosters are used in several cases, but the general practice is not to use them. The tramway in Danzig, operated by a private company, and having a maximum load of 600 kw., has used boosters since 1906.

Return feeder systems are carefully calculated in recent installations; the same grade of insulation is generally provided for both positive and negative feeders. No design data for feeder resistances were obtained.

England. Insulated return feeders are used in England, wherever return feeders are necessary to bring the rail drop within the B.O.T. regulations Separate feeders are generally used. (As in Germany, the feeders are intended to maintain the rail taps at the same potential throughout the system).

Negative boosters are more extensively used than in Germany. They are very commonly used in the larger systems, although in one large city their use was abandoned after they had been in operation for some time. They are considered more economical than resistances in the return feeders, and also to provide better regulation where the load centers shift.

Return feeder systems are only calculated in the larger, well supervised systems, elsewhere they are installed on "cut-and-try" methods. The same grade of insulation is usually provided for both positive and negative feeders.

Italy. Return feeders are not used for tramways in Italy.

France. Insulated return feeders are used for the conduit tramways in Paris, but little elsewhere. Most systems have but one feeding point to the rails. Boosters are very little used, the only system found to be equipped with boosters was that of the Cie. des Tramways de Paris et du Dept. de la Seine.

Voltage and Current Conditions.

Germany. Where return circuits have not been remodelled in accordance with the Commission Regulations, overall voltage limits vary greatly, but in the majority of cases they are between 5 and 10 volts. Other systems will be from 2 to 5 volts. Negative feeders are designed for equal drop.

England. Overall rail drops for tramways in England are generally very much lower than the B.O.T. requirement, averaging probably 2.5 to 3 volts, with the exception of occasional drops, which may be as high as 15 or 20 volts, due to extraordinary traffic at foot-ball matches, etc. The railways probably have higher overall voltages than the tramways. Glasgow, which voluntarily adopted a 2 volt rail drop limit, Manchester, and other large towns, have extraordinarily low rail drops. Electrolysis conditions throughout the United Kingdom are generally said to be satisfactory, although some private gas companies do not agree to this. Potential differences between pipes and rails are said to be generally less than 1 volt.

Negative feeders are designed for equal drop.

France. It is stated that the tramways in France generally endeavor to observe the 1 volt per km. limit. Potential differences between pipes and rails rarely exceed 1 volt (However we observed a 6 volt potential in Paris).

MISCELLANEOUS PROTECTIVE MEASURES.

Drainage System. Electrical drainage was formerly applied in one or two cases in Germany, notably in Aachen, but it was abandoned on account of damage produced by it, first, due to joint corrosion, and second, damage to other underground structures. It is condemned by the engineers of the Earth Current Commission.

Electrical drainage is not employed in Italy or France.

In England, it is not approved as a general measure to afford relief from stray current, although there are a few special instances of its application to the Railway Company's own lead covered cables, where the common practice is to bond to the rails at many points. One engineer thought that it might be applied where currents were small, except to gas pipes on account of the danger from sparking, he also thought that it would be undesirable in America where large currents are carried.

Negative Trolley or Periodic Reversal. The trolley wire was originally made negative in Nürnberg, and in St. Gall, Switzerland, but not periodically reversed. The scheme has been abandoned in both places.

This connection has not been used for tramways in Italy, France or England.

Three-Wire System. The three wire system has been applied to electric railways in a few cases in Germany. In each case the distribution of load between polarities was by districts, that is, certain entire sections will have the trolley wire positive, and others will have the trolley wire negative. Under these conditions the systems may become considerably unbalanced.

In France, the Nord-Sud Chemin de Fer employs a three-wire system with two motors per car, positive and negative, the running rails acting as a grounded neutral.

In England the three-wire system has not been applied to tramways. The City and South London Underground Railway employs it, but this will be discontinued following consolidation with other systems.

Average Feeding Distances. In England, the average feeding distances are said to be from 2 to 3 miles.

Joints in Cast-Iron Mains. Cast-iron pipes in England and Germany are generally of the lead calked bell and spigot type In Germany flanged joints are frequently used for special fittings, valves, T's and hydrant taps for water mains. Cast-iron pipes are little used in France; pipe joints are either lead calked bell and spigot, or in large pipes flanged with rubber gaskets. Insulating joints are not used, except that in England it is said that they are occasionally used for water pipes in very special cases.

Insulating Coverings. In Germany it is held that insulating coverings do not afford protection against electrolysis, as their effect is merely to concentrate escaping stray currents, since perfect coverings cannot be maintained. They should only be used where protection against chemical corrosion is desired, due to the character of the soil.

In France, gas engineers stated that insulating coverings were being studied, but it was not believed that they would prove practicable.

In England, insulating coverings are not considered good protection against stray railway currents. High pressure gas pipes have been covered with pitch canvas, and the London Water Board pipes are provided with an asphalt dip coating, but more as protection against chemical corrosion.

Insulating Joints in Telephone Cables. Not used in Germany or England.

Double Trolley. The double trolley system is not in general use in any of the countries visited. One or two very special cases near Laboratories in Germany, the district within 2 or 3 miles of the Greenwich Observatory, and some conduit tramways of the London County Council System, were the only cases noted. The double trolley is also used in connection with a few miles of rail-less trolley in England.

Corrosive Effects of Soil. In Germany the possibility of chemical corrosion (that is, corrosion without an external supply of electricity) is recognized, and distinction is made between such corrosion and that produced by stray currents. Pipe corrosion has actually been found under conditions where it could not have been produced by stray currents. The resistance of soil is said to vary from 1 ohm to 2000 ohms per cubic meter, averaging about 100 ohms per cubic meter.

No definite information was obtained in England regarding the corrosive properties of soil, but it was stated that chemical corrosion was known to occur. Such corrosion does not, however, produce acute conditions, as in electrolysis; it is more like ordinary oxidation.

Effect of Roadbed Construction on Leakage Current. The authorities consulted in Germany were of the opinion that the road-bed constructions used did not effect a reduction of leakage from the tracks. A similar opinion was held in England. (See Fig. 10-13).

Rail-Weights. In Germany the common rail weights are 50-60 Kg. per meter for tramways, and 30-40 Kg. per meter for interurban lines. In France the ordinary rail-weights are 46 to 51 Kg. per meter. In England rail-weights vary from 70 to 100 lbs. per yard, in the majority of cases. (See Fig. 14).

Welded Rail-Joints. In Germany Thermit welds are used to some extent, they are becoming more common. In France the rails of the System Cie. de Omnibus Thomson-Houston, are welded.

In England Thermit welds have been very extensively used, giving good results electrically, but having short life due to mechanical weakness where traffic is heavy. A type of electrically welded continuous rail, very extensively used in Leeds, and to an increasing extent in Manchester and Glasgow, is giving excellent results, being mechanically strong and providing good electrical conductivity.

Rail-bonds. Solid copper pin type bonds, usually 1 meter long, are most commonly used in Germany, and also in France. The Metropolitan System in Paris places the bonds under the base flange of the rail.

In England, solid copper pin type bonds, protected bonds inside of fish plates, and other types familiar in America, are generally used. (See Fig. 15).

Cross-bonds. In Germany, cross-bonds are used about every 10 rails, *i.e.*, every 100 meters. In France, cross-bonds are placed every 50-100 meters, they have the same area as the rail-bonds. In England cross-bonds are placed generally every 40 yards, they have the same area as the rail-bonds. (See Fig. 16).

Depth of Pipes etc. Below Surface. In Germany, gas pipes are generally laid 0.8-1. meter, and water pipes 1-1,5 meters, below the surface. In France, gas pipes are laid where possible 0.6 meter below the surface, L.T. cables 0.7 meter, and H.T. cables 1.3 meters. In England 1 foot is said to be dangerous; 2 feet was given by one authority as an average and 2.5 to 5 feet by another. In all cases the above depths are only typical, the practice varies widely.

Mains on Both Sides of Streets. In Germany, France and England, mains are laid on both sides of principal streets, or streets wider than 14 meters (Paris) or in streets with wood or asphalt pavements, and generally in the larger towns. In narrow streets or in unimportant places, one main is used.

84. Economic Aspects of the Electrolysis Problem. About 40 per cent of the electric railway systems in Germany, and about 70 per cent in England, are municipally owned. In Germany one authority thought that municipalities were more ready than private companies to spend money for the purpose of improving their return circuits, but in England it was thought that there was no difference in this respect.

Opinions differed in Germany as to whether or not the prevailing regulations constituted a financial hardship. In England, the Board of Trade regulations are nowhere considered a hardship, and when inquiry was made as to whether the existing regulations had retarded the development of electric railways, the authorities consulted uniformly stated that this was not the case. It appears that in fact a saturation point has been reached, and busses are being used where tramways would not pay. Traffic conditions are said to be quite as heavy in England as in the United States. Only one authority in England ventured an estimate of the average load factor for English electric railway systems, he estimated it to be 35 per cent.

There is very little overhead feeder line construction in Germany, and almost none in England.

85. Regulations and Tests. The German Earth Current Commission Regulations only attain the force of law when incorporated in the contracts between civil authorities and the railroad companies, or, as in the case of many cities, where it is provided that new work be done in accordance with "existing technical standards." The Commission regulations are being generally incorporated in contracts for new enterprises or extensions. Also, other undertakings not subject to its provisions are changing over voluntarily for reasons of policy or economy, or as the result of compromise to avoid litigation; this is said to be the case in 30 or 40 important towns.

So far as could be ascertained, no local ordinances exist in Germany regarding electrolysis. In England, there are no local ordinances which have the effect of modifying the Board of Trade regulations. Certain gas companies have obtained special statutory orders, fixing the responsibility for damage, but these do not modify the Board of Trade regulations.

In applying the Earth Current Commission Regulations in Germany, the term "average schedule traffic" is interpreted to mean the average for the entire period of operation which is usually 18 or 19 hours per day. If the measurements are not actually taken over the entire period, they are corrected to obtain a figure corresponding to this average.

In England, measurements are based on an average for about 20 minutes at peak load. The "average" is obtained as the mean between the average of the maxima during this period, disregarding unusually high swings, and the actual average of all measurements. This quantity is usually obtained in practice from inspection of recording instrument charts.

The British Board of Trade makes inspections on its own initiative, because it is responsible for its rules, which have substantially the force of law; they also investigate complaints. There are no regular inspections, on account of the lack of a proper appropriation; most of its information is obtained by means of circular returns, provided for in the Regulations. The latest call for a return was issued in 1906.

In Germany, permanent means for measuring overall potentials are very generally provided, but the methods of doing this vary widely. Pilot wires are usually provided for new installations in France.

In England, pilot wires are universally used in connection with recording instruments. The practice varies widely, but the most common method employs 14 or 16 gauge wires laid with the main cables, and extended beyond them.

Bond testing is generally done in Germany on some systematic basis, more often annually, but in some large systems semi-annually. The bond testing devices are generally of the three contact type with differential galvanometer. Some of these are said to be undesirable on account of the form of the contact, others because the rail joint points span too short a length, or on account of the type of galvanometer employed, etc. In England, it is stated that there is practically no systematic bond testing except in the large, well supervised systems.

I. GENERAL REMARKS.

86. Germany. Where municipalities own the water, gas and street railway systems, they may prefer to assume the cost of damage rather than making larger expenditure for protection of their pipes. There are cases in dispute pending in Essen and Aachen. In Aachen the drainage system was formerly used, but gave trouble; changes are under study or under way.

Recently the case of Mansfeld was decided against the gas company as the railway existed before the gas plant.

Hamburg, prior to the forming of the commission, installed return insulated feeders which gave valuable information in guiding the recommendations of the commission.

Strassburg found in summer 50 % greater leakage than in winter when measurements were made in cold weather and the ground frozen. In snow storms, however, the leakage was increased as the cars were using more current.

The Prussian Law protects railway companies against suits for damages caused by stray currents whenever the pipe owning concerns did not apply for protection against these possible damages before the original franchise to the Railway Company was granted.

Similar laws apply in other States.

When the municipality assumes the operation of a railway it does not assume responsibility to protect the pipe owning companies against damages due to stray currents.

87. France. In Paris pipes for water are located in sewers and therefore remote from trouble.

Telephone cable troubles are few in Paris. In the suburbs all underground pipe systems are more or less affected.

Twenty suits are now in litigation between the gas companies and the railways.

J. STATISTICAL—OPERATING—STRUCTURAL AND TECHNICAL DATA.

TABLE 1.

88. Magnitude of Electric Railway Undertakings in German Empire and United Kingdom.

	German Empire 1911	United Kingdom 1912
Number of undertakings	258	262
Miles of single track	4,920	4,202
No. of cars of all kinds	26,078	12,860
Capital expended £	54,354,625	77,087,944
Car miles	430,512,031	326,688,674
No. of passengers	2,631,892,678	3,145,805,137
Gross income £	13,237,024	14,593,052

TABLE 2.

89. Tramways not Operated by Electricity.

	Miles of single track.			
	Horse	Steam locomotive	Cable	Petrol motors, etc.
German Empire, 1911	45.1	49.8	4.1	10.0
United Kingdom.1912	38.7	42.3	50.1	4.8

TABLE 3.

90. Ownership of Electric Railway Undertakings

A—German Empire, 1911.

	Private corporations	Local authorities	Public ownership operated by private corporations
No. of undertakings	112	110	36
Miles of single track	2,711	1,646	563
No. of cars of all kinds	16,390	7,756	1,932
Capital expended £	32,685,120	16,232,025	5,437,480
Car miles	260,729,075	134,466,975	35,315,981
No. of passengers	1,519,571,662	899,127,262	213,193,754
Gross income £	8,095,757	4,118,873	1,022,394

B—United Kingdom, 1912.

	Private corporations	Local authorities
No. of undertakings	94	168
Miles of single track	1,115	3,078
No. of cars of all kinds	3,444	9,416
Capital expended £	22,648,596	54,439,348
Car miles	81,191,368	245,497,306
No. of passengers	621,546,806	2,524,358,331
Gross income £	3,534,873	11,058,179

TABLE 4.
91. Statistics of Tramways in Large Cities.
A—German Empire.

	Max. load kw.		Avg. car miles per diem		Avg. pass. per diem		Annual gross Income-marks	
	Actual	Per 10,000 Popul.	Actual	Per 10,000 Popul.	Actual	Per 10,000 Popul.	Actual	Per capita.
Hamburg (935,000)	..	..	91,450	981	460,000	4940	12,208,781	12.97
Leipzig (590,000)	2,145	36.5	59,910	1020	328,500	6590	11,129,573	18.95
Dresden (550,000)	3,300	60.3	59,410	1085	345,800	6320	12,324,054	22.55
Dusseldorf (360,000)	1,386	38.8	27,040	756	183,000	5120	5,524,714	15.45
Nürnberg (330,000)	880	26.5	18,860	569	108,600	3280	3,543,810	10.69
AVERAGE........	..	40.5	....	882	..	5050	....	M16.12 $ 3.85

B—United Kingdom.

	Max. load kw.		Avg. car miles per diem		Avg. pass. per diem		Annual gross Income-pounds	
	Actual	Per 10,000 Popul.	Actual	Per 10,000 Popul.	Actual	Per 10,000 Popul.	Actual	Per capita.
Manchester 1,250,000)	11,000	88	51,400	411	510,400	4082	887,647	0.710
Glasgow (1,150,000)	11,500	100.	63,950	556	854,000	7422	1,070,175	0.932
Birmingham (900,000)	..	..	36,000	400	368,000	4088	581,566	0.646
Leeds (450,000)	4,500	100.	24,100	536	245,800	5460	411,531	0.914
Dublin (390,000)	4,500	115.4	19,650	504	147,700	3790	293,748	0.752
AVERAGE........	..	100.9	....	481	....	4968	....	£ 0 791 $ 3 84

TABLE 7.

94. Use of Negative Boosters.
United Kingdom.

	Number	Miles of single track
Total number of undertakings	183	3835.
Number of undertakings using negative boosters	39	1152.
Per cent using negative boosters	21.3%	30. %

Relation between Booster Capacity and Plant Capacity

Average, for 25 cases: Booster Capacity—3.9% of plant capacity.

Highest— 9 % for plant of 500 kw. capacity
12 % " " " 800 " "
Lowest —0.8 % " " " 5725 " "
0 9 % " " " 3500 " "

TABLE 8.

95. Distribution Systems for Tramway Feeders.
United Kingdom.

	No. of undertakings	Miles of single track
Solid system, all types	80	1888.2
Conduit " " "	63	1839.2
Solid and conduit	21	626 1
Overhead, wholly or partly	6	40 9
	170	4394 9
Not reported	11	
	181	

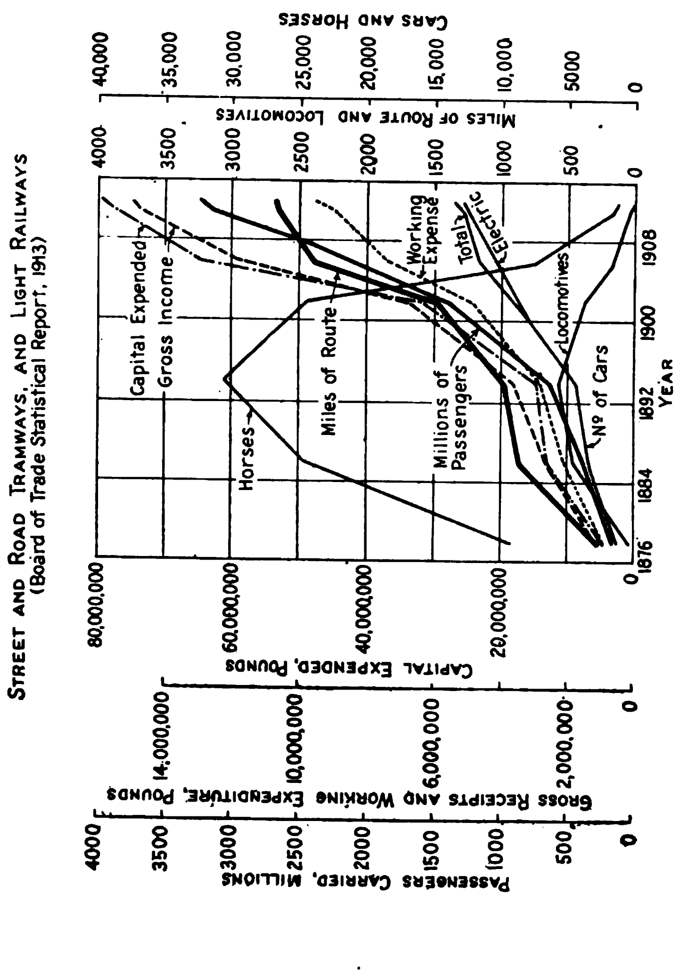

STREET AND ROAD TRAMWAYS, AND LIGHT RAILWAYS
(Board of Trade Statistical Report, 1913)
CARS AND HORSES
MILES OF ROUTE AND LOCOMOTIVES
CAPITAL EXPENDED, POUNDS
GROSS RECEIPTS AND WORKING EXPENDITURE, POUNDS
PASSENGERS CARRIED, MILLIONS
YEAR
Capital Expended
Gross Income
Horses
Miles of Route
Millions of Passengers
Working Expense
Total
Electric
Locomotives
Nº of Cars
1876
1884
1892
1900
1908

Figure 9

TRACK CONSTRUCTION - UNITED KINGDOM

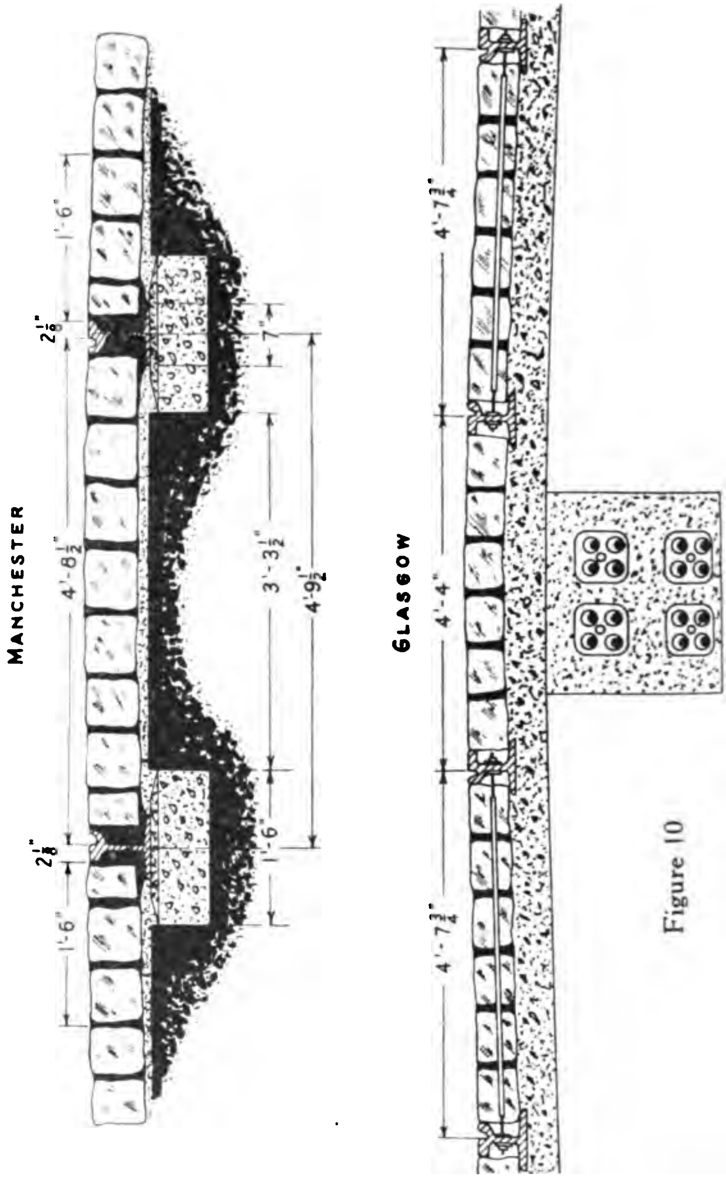
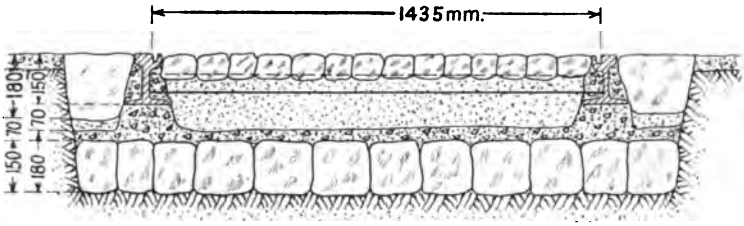


Figure 10

TRACK CONSTRUCTION AND RAILS - GERMANY



Typical Construction for paved street

STRASSBURG
Haarman 3 piece Rail, and foot plate

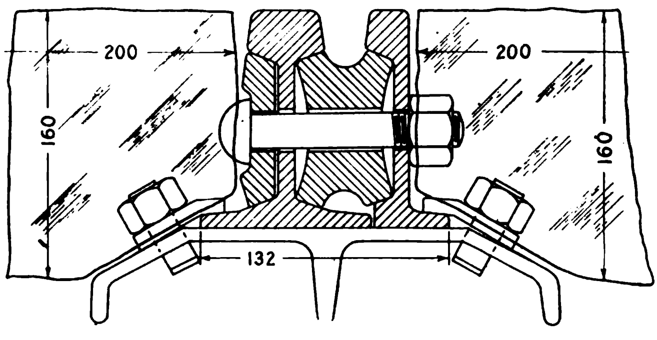


Figure 11

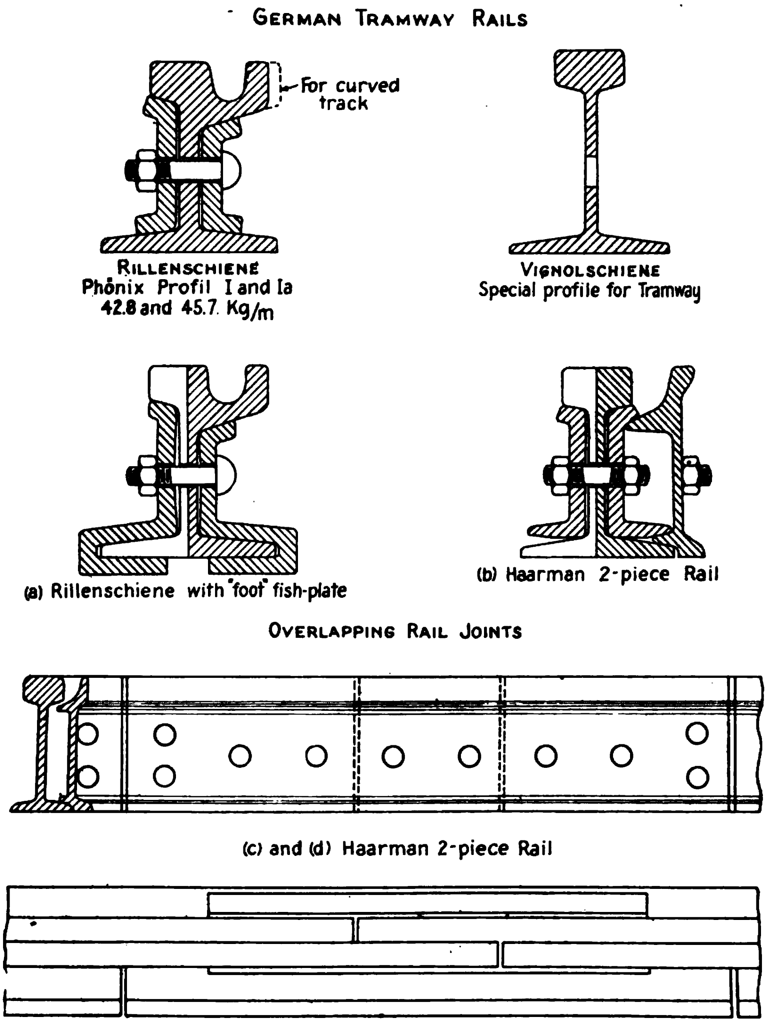

GERMAN TRAMWAY RAILS
For curved track
RILLENSCHIENE
Phönix Profil I and Ia
42.8 and 45.7 Kg/m
VIGNOLSCHIENE
Special profile for Tramway
(a) Rillenschiene with "foot" fish-plate
(b) Haarman 2-piece Rail
OVERLAPPING RAIL JOINTS
(c) and (d) Haarman 2-piece Rail

Figure 12

British Tramway Rails

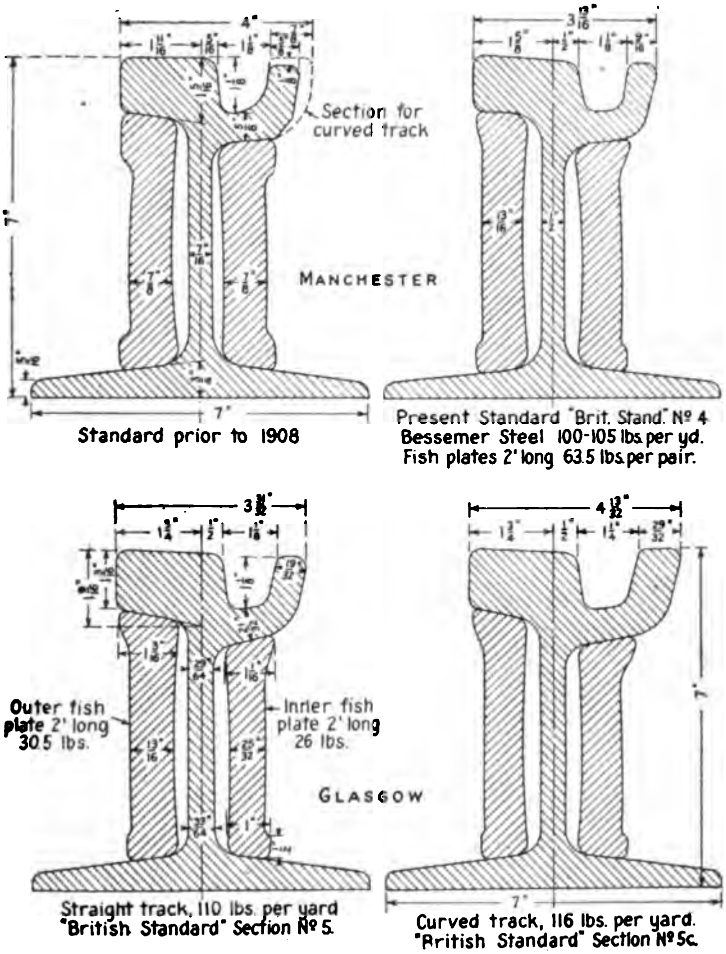


Figure 13

RAIL WEIGHT DATA

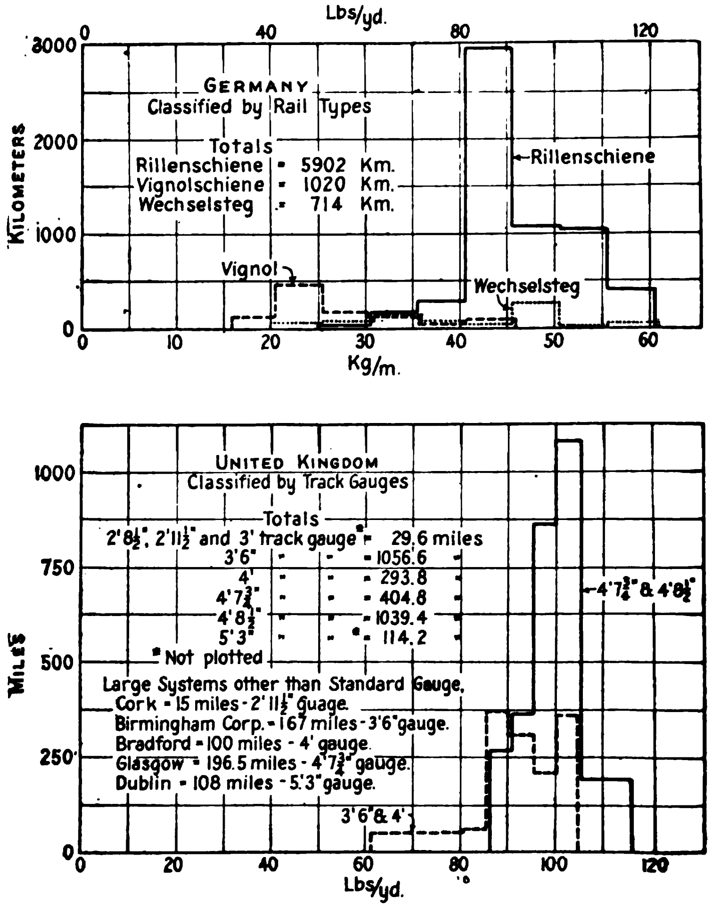


Figure 14

Typical Rail Bonds - United Kingdom

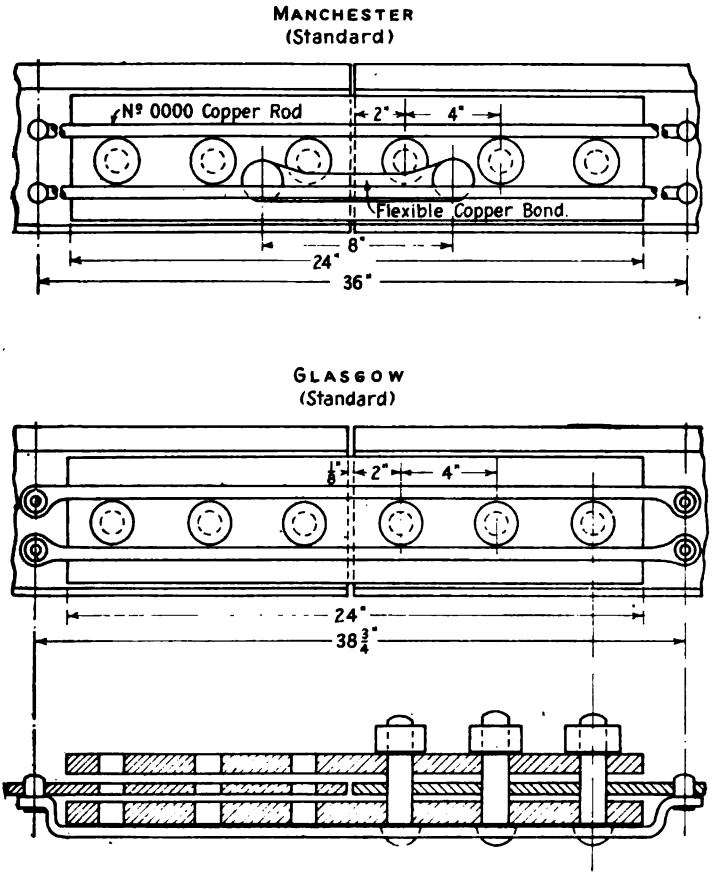


Figure 15

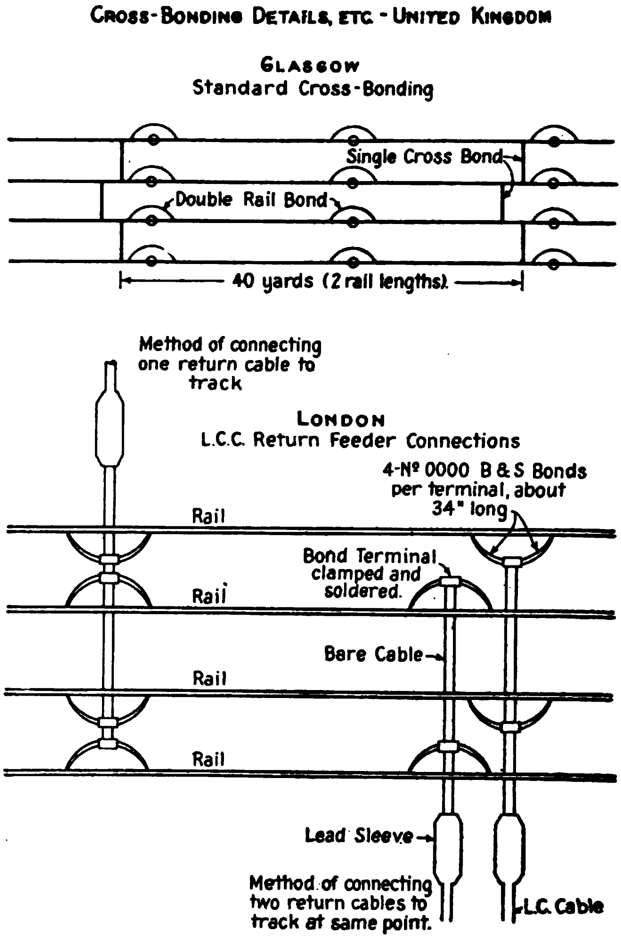

Cross-Bonding Details, etc. - United Kingdom
Glasgow
Standard Cross-Bonding
Single Cross Bond
Double Rail Bond
40 yards (2 rail lengths).
Method of connecting one return cable to track
London
L.C.C. Return Feeder Connections
4-No 0000 B & S Bonds per terminal, about 34" long
Rail
Bond Terminal clamped and soldered.
Rail
Bare Cable
Rail
Rail
Lead Sleeve
Method of connecting two return cables to track at same point.
L.C. Cable

Figure 16

96. Electrolysis Testing Methods. The surveys made by the engineers of the Earth Current Commission of Germany are systematically planned. They start with a general investigation of geological conditions, the character of the soil, ground water, and so forth, continuing with a general survey of the present condition of the railway property, including distribution of load, track and rail resistance, location and loading of supply and return circuit cables, and any other electrical data relating to the investigation. The surveys then take up the specific measurements relating to stray current, such as potential differences between pipes and rails, current in pipes, and so forth. The surveys conclude generally with recommendations for betterments where such are needed, and often include estimates of the cost of such improvements.

In England very little testing is done to investigate electrolysis questions and no technique has been developed for such work. The only extensive work in recent years is that of the Cunliffe brothers, and their work was directed mainly toward the investigation of certain theoretical questions rather than toward the systematic investigation of any railway system. The work of the Cunliffes appears in two papers presented by them before the British Institution of Electrical Engineers.

97. Abstract of Laws and Regulations or Recognized Standards in European Countries.

(See next page.)

Country	England	France	Germany	Italy	Spain.
Nature of Regulations,	Board of Trade Regulations. Original issue March 1894, last revision Sept. 1912.	Ministerial Decree of Mar. 21, 1911.	No laws, but the Recommendations of the German Earth Current Commission are recognized as Standards.	No laws or Municipal Regulations	Law of Mar. 23, 1900.
Maximum Rail Drop, (See text as to how determined in different countries)	7 volts total.	1 volt per km.	2.5 volts total in central district; 1.0 volt per km. in outer districts.		7 volts total.
Return Feeders,	May be uninsulated unless drop exceeds 7 volts.	Must be insulated.	Must be insulated.		
Rail Bonds: Tested,		Periodically and record kept.	Yearly		
Resistance not to exceed		10 meters of rail	10 meters of rail		Section must exceed 100 sq. mm. per rail.
Connections to pipes,	For test purposes may connect to water mains of 3 in. or more diameter with owner's permission.		Prohibited.		
Pilot wires,		Must be provided.	To be provided.		

L. MISCELLANEOUS NOTES.

98. Plan of German Earth Current Commission Reports. In abstracting these reports we have selected at random characteristic studies which would illustrate the method pursued in the investigations. We have not made any attempt at all to select studies for direct comparison with any specific American condition. In interpreting these results, the above qualifications should, therefore, be kept in mind.

The reports are quite uniform in character and contain in general the following data:

I. Maps showing the location and extent of the tramway, water pipe and gas pipe systems, location of the generating station or stations, points of connection of the supply and return feeders.

II. Soil—kind (clay, sand, loam, etc.) moisture content, chemical composition, resistance per cubic meter.

III. Pavements—(in some cases only).

IV. Piping systems—both water and gas pipes. Total length, diameter, material, age, depth below surface, kind of joints, resistance of pipe only and of pipe including joints.

V. Tramway system.

(a) General details of ownership and operation, car schedule, maximum and average loads.

(b) Track and rails—total miles of single and double tracks, gauge, rail profile and cross section, standard length, resistance of rail alone and including bonds.

(c) Rail bonds and cross bonds, type, cross section, per cent increase in rail resistance caused by bonds.

(d) Feeders, both supply and return feeders—length each, cross section, total weight of copper, current—maximum and average, return feeders bare or insulated and with or without regulating resistance.

VI. Tests.

(a) Voltage between pipes and rails, maximum, minimum and average, with polarity, determined at numerous points on the system.

(b) Voltage drop per kilometer on pipes and on rails and calculated current flowing on pipes.

(c) Determination by means of telephone wires of the relative potential of various points on the piping and on the rail systems.

VII. Excavations in likely places to determine the existence and extent of the electrolytic damage.

VIII. Plates accompany the reports, giving graphically many of the above data, frequently on transparent paper so that when placed over the city map the details of streets, railroads, etc. can be observed.

Reasoning from the data contained in the body of the report, recommendations are made for improving conditions, sometimes accompanied by an estimate of cost. In some cases a supplementary report is made which shows the conditions after the changes recommended had been made, in whole or in part.

99. General Comments on Reports. The electrolysis troubles in all cases were confined to a few localities, and in no case was the yearly cost of repairs of such amount that, on the surface, would justify large expenditure of money for improvements. The Commission, however, while recognizing the importance of the financial aspect of the problem, still recommended the adoption of the relatively expensive remedies for the reason they state "that the repairs will certainly become more frequent with lapse of time, and besides the increased expense so caused, there is the liability of service interruption, disturbance of traffic, pavement replacement and even danger of explosion to be considered."

V. BIBLIOGRAPHY

This committee has made a complete search of the American literature on the subject of electrolysis, but in compiling the following bibliography no attempt has been made to list this literature in its entirety. This bibliography may be considered a selected list of such contributions to the subject known to the committee, as, in its opinion, are of permanent value.

Bureau of Standards Publications: The following Technologic Papers upon electrolysis have been published by the Bureau of Standards at Washington, D. C.

No. 15. Surface Insulation of Pipes as a Means of Preventing Electrolysis.

No. 18. Electrolysis in Concrete.

No. 25. Electrolytic Corrosion of Iron in Soils.

No. 26. Earth Resistance and its Relation to Electrolysis of Underground Structures.

No. 27. Special Studies in Electrolysis Mitigation.

No. 28. Methods of Making Electrolysis Surveys.

No. 32. Special Studies in Electrolysis Mitigation, No. 2, Electrolysis from Electric Railway Currents and its Prevention—Experimental Test on a System of Insulated Negative Feeders in St. Louis.

No. 52. Electrolysis and Its Mitigation.

No. 54. Special Studies in Electrolysis Mitigation, No. 3. A Report on Conditions in Springfield, Ohio, with Insulated Feeder System Installed.

No. 55. Special Studies in Electrolysis Mitigation in Elyria, Ohio, with Recommendations for Mitigation.

No. 62. Modern Practice in the Construction and Maintenance of Rail Joints and Bonds in Electric Railways.

No. 63. Leakage of Current from Electric Railways.

No. 72. Influence of Frequency of Alternating or Infrequently Reversed Current on Electrolytic Corrosion.

No. 75. Data on Track Leakage.

Deiser, George F. "The Law Relating to Conflicting Uses of Electricity and Electrolysis," T. & J. W. Johnson Co., Philadelphia, Pa., 1911.

Farnham, Isiah H. "Destructive Effect of Electric Currents on Subterranean Metal Pipes," *Trans.* A. I. E. E., 1894.

This paper probably covers the first investigation undertaken of real scientific value. The discussion of the paper is also important and interesting.

"Means for Preventing Electrolysis of Buried Metal Pipes," *Cassiers Magazine,* August, 1895.

This article is of particular interest, in that it shows that at a very early date the value of the insulated negative feeder system as a means of mitigating electrolysis was recognized.

Ganz, Albert F. "Electrolytic Corrosion of Iron by Direct Current in Street Soils," *Trans.* A. I. E. E., Vol. XXXI, p. 1167, 1912.

This paper gives the results of a laboratory investigation of considerable scientific value and interest.

"Electrolysis from Stray Electric Currents," *Proc. New England Association of Gas Engineers,* 1913.

This paper treats the subject in a popular, but nevertheless scientifically correct manner, and leads to the conclusion that the insulated negative feeder system is the logical one to employ for the purpose of mitigating electrolysis.

"Effects of Electrolysis on Engineering Structures," Trans. Inter. Eng. Congress, San Francisco, Cal., 1915.

This paper gives a review of electrolysis conditions and of mitigating methods in America with a brief statement of the electrolysis situation in Europe.

Haber, F., and Goldschmidt, F. "Der Anodische Angriff des Eisens Durch Vagabundierende Strome im Erdreich und die Passivitat des Eisens." (The Corrosion of Iron by Stray Currents in the Ground and the Passivity of Iron.) *Zeitschrift fur Electrochemie,* January 26, 1906. Breslau.

A paper of considerable scientific value, particularly with respect to the electrochemistry of the subject. In so far as is known no English translation exists.

Harper, Robert B. "Comparative Values of Various Coatings and Coverings for the Prevention of Soil and Electrolytic

Corrosion of Iron Pipe," *Proc. Illinois Gas Association*, Vol. 5, 1909.

A paper based upon a rather elaborate series of tests carried out in a thoroughly scientific manner on many coatings and coverings, leading to the conclusion that no coatings or coverings are of permanent value in positive areas. Of all coatings investigated, dips of coal tar pitch applied hot, were found to be best. Paints were found to be practically useless.

Hayden, J. L. R. "Alternating-Current Electrolysis," *Trans.* A. I. E. E., 1907. Vol. 26, Part I.

A report of a laboratory investigation tending to show that alternating current electrolysis is small as compared with direct current electrolysis. The tests also bring out the inhibiting effect of the superposition of a small direct current.

Jackson, Dugald C. "Corrosion of Iron Pipes by Action of Electric Railway Currents." *Journal of Association of Engineering Societies*, September, 1894.

An account of some early laboratory investigations carried out at the University of Wisconsin, in which it was definitely proven that corrosion due to electrolysis could take place at very low voltages—considerably lower voltages than are required to decompose water.

Michalke, Carl. "Stray Currents from Electric Railways." Translated and edited by Otis Allen Kenyon, McGraw Publishing Company, New York City, 1906.

A relatively non-mathematical, though scientific and valuable treatment of the subject.

Rhodes, George I. "Some Theoretical Notes on the Reduction of Earth Currents from Electric Railway Systems, by Means of Negative Feeders." *Trans.* A. I. E. E., Vol. XXVI, p. 247, 1907.

A mathematical paper showing quantitatively the difference in effectiveness of copper paralleling the rails and insulated negative feeders in reducing stray currents.

Schaffer, Guy F. "Corrosion of Iron Embedded in Concrete." *Engineering Record*, July 30, 1910.

This is a report of a series of tests made at the Massachusetts

Institute of Technology, carried out with the view of obtaining some data on the effect of currents of low potential on steel embedded in concrete. The study included the effect on steel in both the stressed and unstressed condition, also the effect of setting cement on paint films. It was shown (a), that concrete does not act as an insulator; (b), that iron under stress does not go into solution as rapidly as unstressed iron; and (c), that the paints used to-day for structural work embedded in concrete do not fulfill the conditions of proper protection from electrolytic action, and it is doubtful whether they are of use for protection in any sense after a lapse of some months.

Sever, George F. "Electrolysis of Underground Conductors." *Trans. International Electrical Congress*, St. Louis, Vol. 3, p. 666, 1904.

This is a summary in tabular form, consisting of street railway practice, municipal reports, ordinances and letters in force in the United States at the time the report was prepared, 1904. The discussion which followed the presentation of this report is of interest.

Stone, Charles A. and Howard C. Forbes. "Electrolysis of Water Pipes." *New England Water Works Association*, Vol. 9, 1894-95.

This is the report of the results of an investigation of electrolysis conditions in Boston. It is one of the best early papers on the subject. The discussion of this paper is interesting.

Topical Discussion on Electrolysis. *Proc. New England Water Works Association*, Vol. XX, 1905.

This is the report of a discussion entered into by various New England Water Works superintendents. Several phases of the discussion are instructive.

VI. APPENDICES.

100. Resistance of Standard Cast Iron Pipe.

Note: The values given in this table are for one assumed specific resistance for cast iron, wrought iron and steel, respectively. For exceedingly accurate work, measures should be taken to determine the actual specific resistance of the metal under test. Experience has shown that this may vary widely from that assumed in the tables; in other words, the table values can only be used for approximate results unless definite information is at hand as to the specific resistance of the metal under test.

From pages 379 and 386, 1913, *Proceedings American Electric Railway Engineering Association.*

TABLE FOR DETERMINATION OF CURRENT FLOW ON PIPING FROM MILLI-VOLT DROP ALONG CONTINUOUS LENGTH OF PIPE BETWEEN JOINTS.

L = Distance between contacts in feet
E = Instrument reading in milli-volts,
K = Constant from table.

$$\frac{KE}{L} = \text{Current flow in amperes.}$$

TABLE 9

STANDARD CAST IRON PIPE.

(Based on a resistance of 0.00144 ohm per lb. ft.)

Classification					Actual Dimensions			
Nominal. Dia. in.	*Association Standard	Class Letter†	Head Feet	Press. lbs. per sq. in.	Outs. dia. in.	Ins. dia. in.	Weight per ft. exclusive of hub-lb.	K = current for one milli-volt drop per ft. of continuous pipe. Amperes.
4	N	A	...	...	4.80	4.12	14.9	10.3
4	N	C	...	...	4.80	4.08	15.7	10.9
4	N	E	...	...	4.80	4.02	16.9	11.7
4	G	..	...	...	4.80	4.00	17.2	12.0
4	W	A	100	43	4.80	3.96	18.0	12.5
4	N	G	...	...	5.00	4.16	18.9	13.1
4	N	I	...	...	5.00	4.10	20.0	13.9
4	W	B	200	86	5.00	4.10	20.0	13.9
4	N	K	...	...	5.00	4.04	21.3	14.8

*W = American Water Works Association Standard.
N = New England Water Works Association Standard.
G = American Gas Institute Standard.
† = As used by the American Water Works Association and the New England Water Works Association.

TABLE FOR DETERMINATION OF CURRENT FLOW ON STANDARD CAST IRON PIPE FROM MILLI-VOLT DROP ALONG CONTINUOUS LENGTH OF PIPE BETWEEN JOINTS. (*Continued.*)

Classification					Actual Dimensions			
Nominal. Dia. in.	*Association Standard	Class Letter †	Head Feet	Press. lbs. per sq. in.	Outs. dia. in.	Ins. dia. in.	Weight per ft. exclusive of hub-lb.	K = current for one milli-volt drop per ft. of continuous pipe. Amperes.
4	W	C	300	130	5.00	4.04	21.3	14.8
4	W	D	400	173	5.00	3.96	22.8	15.8
6	N	A	...	...	6.90	6.14	24.3	16.9
6	N	C	...	...	6.90	6.06	26.7	18.5
6	G	..	...	...	6.90	6.04	27.2	18.9
6	W	A	100	43	6.90	6.02	27.8	19.3
6	N	E	...	...	6.90	5.98	29.1	20.2
6	W	B	200	86	7.10	6.14	31.1	21.6
6	N	G	...	...	7.10	6.10	32.4	22.5
6	W	C	300	130	7.10	6.08	32.9	22.8
6	N	I	...	...	7.10	6.02	34.8	24.2
6	W	D	400	173	7.10	6.00	35.3	24.5
6	W	E	500	217	7.22	6.06	37.7	26 2
6	W	F	600	260	7.22	6.00	39.6	27.4
6	W	G	700	304	7.38	6.08	42.8	29.7
6	W	H	800	347	7.38	6 00	45.2	31 4
8	N	A	...	...	9.05	8.21	35 5	24.7
8	G	..	...	...	9.05	8.15	37.9	26.3
8	W	A	100	43	9.05	8.13	38.7	26.9
8	N	C	...	...	9.05	8.09	40.3	28.0
8	W	B	200	86	9.05	8.03	42.7	29.6
8	N	E	...	...	9.05	7.99	44.3	30.7
8	W	C	300	130	9.30	8.18	47.9	33.3
8	N	G	...	...	9.30	8 14	49.6	34.5
8	W	D	400	173	9.30	8.10	51.2	35.5
8	N	I	...	...	9.30	8.04	53.6	37 2
8	W	E	500	217	9.42	8.10	56 7	39.4
8	W	F	600	260	9.42	8.00	60.6	42.1
8	W	G	700	304	9.60	8.10	65.0	45.1
8	W	H	800	347	9.60	8.00	69.0	48.0
10	N	A	...	..	11.10	10 16	49 0	34.0
10	G	..	...	...	11.10	10.12	51 0	35.4
10	N	B	...	...	11.10	10.10	51.9	36.1

TABLE FOR DETERMINATION OF CURRENT FLOW ON STANDARD CAST IRON PIPE FROM MILLI-VOLT DROP ALONG CONTINUOUS LENGTH OF PIPE BETWEEN JOINTS. (*Continued*)

Classification					Actual Dimensions			
Nominal. Dia.in.	*Association Standard	Class Letter †	Head Feet	Press. lbs. per sq. in.	Outs. dia. in.	Ins. dia. in.	Weight per ft. exclusive of hub-lb.	K-current for one milli-volt drop per ft. of continuous pipe. Amperes.
10	W	A	100	43	11.10	10.10	51.9	36.1
10	N	C	...	...	11.10	10.04	54.9	38.1
10	N	D	...	...	11.10	9.98	57.9	40.2
10	W	B	200	86	11.10	9.96	58.9	40.9
10	N	E	...	...	11.40	10.20	63.6	44.1
10	W	C	300	130	11.40	10.16	65.5	45.5
10	N	F	...	...	11.40	10.14	66.5	46.2
10	N	G	...	...	11.40	10.06	70.5	49.0
10	W	D	400	173	11.40	10.04	71.5	49.7
10	N	H	...	...	11.40	10.00	73.5	51.1
10	W	E	500	217	11.60	10.12	78.7	54.6
10	W	F	600	260	11.60	10.00	84.6	58.8
10	W	G	700	304	11.84	10.12	92.4	64.1
10	W	H	800	347	11.84	10.00	98.5	68.4
12	N	A	...	...	13.20	12.22	61.1	42.5
12	N	B	...	...	13.20	12.14	65.9	45.7
12	G	..	...	...	13.20	12.12	67.0	46.5
12	W	A	100	43	13.20	12.12	67.0	46.5
12	N	C	...	...	13.20	12.06	70.6	49.0
12	N	D	...	...	13.20	11.98	75.3	52.3
12	W	B	200	86	13.20	11.96	76.4	53.0
12	N	E	...	...	13.50	12.20	81.9	56.8
12	W	C	300	130	13.50	12.14	85.5	59.4
12	N	F	...	...	13.50	12.12	86.6	60.2
12	N	G	...	...	13.50	12.04	91.5	63.6
12	W	D	400	173	13.50	12.00	93.8	65.1
12	N	H	...	...	13.50	11.96	96.2	66.8
12	W	E	500	217	13.78	12.14	104.0	72.3
12	W	F	600	260	13.78	12.00	112.0	77.9
12	W	G	700	304	14.08	12.14	125.0	86.7
12	W	H	800	347	14.08	12.00	133.0	92.4
14	N	A	...	...	15.30	14.24	76.8	53.4
14	N	B	...	...	15.30	14.16	82.3	57.1
14	W	A	100	43	15.30	14.16	82.3	57.1

TABLE FOR DETERMINATION OF CURRENT FLOW ON STANDARD CAST IRON PIPE FROM MILLI-VOLT DROP ALONG CONTINUOUS LENGTH OF PIPE BETWEEN JOINTS. (*Continued.*)

Classification					Actual Dimensions			
Nominal. Dia. in.	*Association Standard	Class Letter †	Head Feet	Press. lbs. per sq. in.	Outs. dia. in.	Ins. dia. in.	Weight per ft. exclusive of hub-lb.	*K* = current for one milli-volt drop per ft. of continuous pipe. Amperes.
14	N	C	...	...	15.30	14.08	87.9	61.0
14	N	D	...	...	15.30	13.98	94.8	65.8
14	W	B	200	86	15.30	13.98	94.8	65.8
14	N	E	...	...	15.65	14.25	103.0	71.4
14	W	C	300	130	15.65	14.17	108.0	75.0
14	N	F	...	...	15.65	14.15	109.0	76.2
14	N	G	...	...	15.65	14.07	115.0	80.0
14	W	D	400	173	15.65	14.01	119.0	82.8
14	N	H	...	...	15.65	13.99	121.0	83.9
14	W	E	500	217	15.98	14.18	133.0	92.4
14	W	F	600	260	15.98	14.00	145.0	101.0
14	W	G	700	304	16.32	14.18	160.0	111.0
14	W	H	800	347	16.32	14.00	172.0	120.0
16	N	A	...	...	17.40	16.30	90.9	63.1
16	N	B	...	...	17.40	16.20	98.9	68.6
16	W	A	100	43	17.40	16.20	98.9	68.6
16	G	..	...	...	17.40	16.16	102.0	70.7
16	N	C	...	...	17.40	16.10	107.0	74.1
16	N	D	...	...	17.40	16.00	115.0	79.6
16	W	B	200	86	17.40	16.00	115.0	79.6
16	N	E	...	...	17.80	16.30	125.0	87.1
16	N	F	...	...	17.80	16.20	133.0	92.6
16	W	C	300	130	17.80	16.20	133.0	92.6
16	N	G	...	...	17.80	16.10	141.0	98.2
16	W	D	400	173	17.80	16.02	147.0	102.3
16	N	H	...	...	17.80	16.00	149.0	103.5
16	W	E	500	217	18.16	16.20	165.0	114.5
16	W	F	600	260	18.16	16.00	181.0	125.5
16	W	G	700	304	18.54	16.18	201.0	139.5
16	W	H	800	347	18.54	16.00	215.0	149.0
18	N	A	...	...	19.25	18.11	104.0	72.5
18	N	B	...	...	19.25	17.99	115.0	79.8
18	W	A	100	43	19.50	18.22	118.0	82.2
18	N	C	...	...	19.50	18.12	127.0	88.5
18	N	D	...	...	19.50	18.00	138.0	95.8
18	W	B	200	86	19.50	18.00	138.0	95.8

TABLE FOR DETERMINATION OF CURRENT FLOW ON STANDARD CAST IRON PIPE FROM MILLI-VOLT DROP ALONG CONTINUOUS LENGTH OF PIPE BETWEEN JOINTS. (*Continued.*)

Classification					Actual Dimensions			K = current for one milli-volt drop per ft. of continuous pipe. Amperes.
Nominal. Dia. in.	*Association Standard	Class Letter †	Head Feet	Press. lbs. per sq. in.	Outs. dia. in.	Ins. dia. in.	Weight per ft. exclusive of hub-lb.	
18	N	E	...	...	19.70	18.10	148.0	103.0
18	N	F	...	...	19.70	17.98	159.0	110.4
18	W	C	300	130	19.92	18.18	162.0	113.0
18	W	D	400	173	19.92	18.00	178.0	123.8
18	W	E	500	217	20.34	18.20	202.0	140.5
18	W	F	600	260	20.34	18.00	220.0	152.6
18	W	G	700	304	20.78	18.22	245.0	170.0
18	W	H	800	347	20.78	18.00	264.0	183.3
20	N	A	...	..	21.30	20.10	122.0	84.6
20	N	B	...	...	21.30	19.98	134.0	93.0
20	W	A	100	43	21.60	20.26	137.0	95.4
20	G	..	...	...	21.60	20.24	140.0	97.0
20	N	C	...	...	21.60	20.16	147.0	102.5
20	N	D	...	...	21.60	20.02	161.0	112.0
20	W	B	200	86	21.60	20.00	163.0	113.0
20	N	E	...	...	21.90	20.20	175.0	122.0
20	N	F	...	...	21.90	20.06	189.0	131.0
20	W	C	300	130	22.06	20.22	191.0	132.0
20	W	D	400	173	22.06	20.00	212.0	148.0
20	W	E	500	217	22.54	20.24	241.0	167.0
20	W	F	600	260	22.54	20.00	265.0	184.0
20	W	G	700	304	23.02	20.24	295.0	205.0
20	W	H	800	347	23.02	20.00	319.0	221.0
24	N	A	...	...	25.40	24.12	156.0	108.0
24	N	B	...	...	25.40	23.96	174.0	121.0
24	G	..	...	...	25.80	24.28	187.0	130.0
24	W	A	100	43	25.80	24.28	187.0	130.0
24	N	C	...	...	25.80	24.20	196.0	136.0
24	N	D	...	...	25.80	24.04	215.0	149.0
24	W	B	200	86	25.80	24.02	217.0	151.0
24	N	E	...	...	26.10	24.20	234.0	163.0
24	N	F	...	...	26.10	24.04	253.0	176.0
24	W	C	300	130	26.32	24.24	258.0	179.0
24	W	D	400	173	26.32	24.00	286.0	198.0
24	W	E	500	217	26.90	24.28	328.0	228.0
24	W	F	600	260	26.90	24.00	362.0	251.0

TABLE FOR DETERMINATION OF CURRENT FLOW ON STANDARD CAST IRON PIPE FROM MILLI-VOLT DROP ALONG CONTINUOUS LENGTH OF PIPE BETWEEN JOINTS. (*Continued.*)

Classification					Actual Dimensions			K = current for one milli-volt drop per ft of continuous pipe. Amperes.
Nominal. Dia. in.	*Association Standard	Class Letter †	Head Feet	Press. lbs. per sq. in.	Outs. dia. in.	Ins. dia. in.	Weight per ft. exclusive of hub-lb.	
30	N	A	...	...	31.60	30.18	215 0	149.0
30	N	B	...	...	31.60	29.98	245.0	170.0
30	G	..	...	...	31.74	30.04	257 0	179.0
30	W	A	100	43	31.74	29.98	266.0	185 0
30	N	C	...	...	32.00	30.18	277.0	192.0
30	N	D	...	...	32.00	29.98	306.0	213.0
30	W	B	200	86	32.00	29.94	312.0	217.0
30	N	E	...	..	32.40	30.20	337.0	231.0
30	N	F	...	...	32.40	30.00	367.0	255.0
30	W	C	300	130	32.40	30.00	367.0	255.0
30	W	D	400	173	32.74	30.00	422.0	292 0
30	W	E	500	217	33.10	30.00	479.0	333.0
30	W	F	600	260	33.46	30.00	537.0	373.0
36	N	A	...	...	37.80	36.22	287.0	199.0
36	N	B	...	...	37.80	36.00	326.0	226.0
36	G	..	...	...	37.96	36.06	315.0	239 0
36	W	A	100	43	37.96	35.98	358.0	248.0
36	N	C	...	...	38.30	36.26	373.0	259.0
36	N	D	...	...	38.30	36.04	412.0	286.0
36	W	B	200	86	38.30	36.00	418.0	290.0
36	N	E	...	...	38.70	36.20	459.0	319.0
36	W	C	300	130	38.70	35 98	497.0	346.0
36	N	F	...	...	38.70	35.96	502.0	349 0
36	W	D	400	173	39.16	36.00	581.0	404 0
36	W	E	500	217	39.60	36.00	666.0	463 0
36	W	F	600	260	40 04	36.00	753.0	523.0
42	N	A	...	...	44.00	42.26	368 0	256.0
42	N	B	...	...	44 00	42 00	422.0	293.0
42	G	..	...	...	44 20	42 06	452.0	314.0
42	W	A	100	43	44 20	42.00	465 0	323.0
42	N	C	...	...	44.50	42 24	480.0	333.0
42	N	D	..	...	44.50	41 96	538.0	374.0
42	W	B	200	86	44.50	41.94	542 0	376.0
42	N	E	...	..	45.10	42.30	600.0	416.0
42	N	F	...	...	45.10	42.04	651 0	451.0

TABLE FOR DETERMINATION OF CURRENT FLOW ON STANDARD CAST IRON PIPE FROM MILLI-VOLT DROP ALONG CONTINUOUS LENGTH OF PIPE BETWEEN JOINTS. *(Continued.)*

Classification					Actual Dimensions			K = current for one milli-volt drop per ft. of continuous pipe. Amperes.
Nominal dia. in.	*Association Standard	Class Letter †	Head Feet	Press. lbs. per sq. in.	Outs. dia. in.	Ins. dia. in.	Weight per ft. exclusive of hub-lb.	
42	W	C	300	130	45.10	42.02	657.0	456.0
42	W	D	400	173	45.58	42.02	763.0	530.0
48	N	A	...	...	50.20	48.30	459.0	319.0
48	N	B	...	...	50.20	48.00	529.0	367.0
48	N	C	...	...	50.80	48.30	608.0	422.0
48	G	..	...	...	50.50	47.98	608.0	422.0
48	W	A	100	43	50.50	47.98	608.0	422.0
48	N	D	...	...	50.80	48.00	678.0	471.0
48	W	B	200	86	50.80	47.96	686.0	477.0
48	N	E	...	...	51.40	48.30	757.0	526.0
48	N	F	...	...	51.40	48.00	828.0	575.0
48	W	C	300	130	51.40	47.98	832.0	578.0
48	W	D	400	173	51.98	48.06	961.0	667.0
54	N	A	...	...	56.40	54.34	559.0	388.0
54	N	B	...	...	56.40	54.00	650.0	452.0
54	W	A	100	43	56.66	53.96	731.0	508.0
54	N	C	...	...	57.10	54.36	750.0	521.0
54	N	D	...	...	57.10	54.02	840.0	583.0
54	W	B	200	86	57.10	54.00	845.0	586.0
54	N	E	...	...	57.80	54.26	946.0	657.0
54	N	F	...	...	57.80	54.00	1041.0	723.0
54	W	C	300	130	57.80	54.00	1041.0	723.0
54	W	D	400	173	58.40	53.94	1230.0	854.0
60	N	A	...	...	62.60	60.40	664.0	460.0
60	N	B	...	...	62.60	60.00	782.0	543.0
60	W	A	100	43	62.80	60.02	836.0	581.0
60	N	C	...	...	63.40	60.40	910.0	632.0
60	W	B	200	86	63.40	60.06	1010.0	701.0
60	N	D	...	...	63.40	60.00	1028.0	714.0
60	N	E	...	...	64.20	60.40	1160.0	806.0
60	W	C	300	130	64.20	60.20	1220.0	848.0
60	N	F	...	...	64.20	60.00	1280.0	889.0
60	W	D	400	173	64.82	60.06	1455.0	1010.0
72	W	A	100	43	75.34	72.08	1178.0	819.0
72	W	B	200	86	76.00	72.10	1415.0	983.0
72	W	C	300	130	76.88	72.10	1745.0	1212.0
84	W	A	100	43	87.54	84.10	1445.0	1005.0
84	W	B	200	86	88.54	84.10	1878.0	1304.0

101. Resistance of Standard Steel or Wrought Iron Pipe.

TABLE 10

STANDARD STEEL (Or Wrought Iron) PIPE.

(Based on Resistance of steel 0.00021 ohms per lb. ft. Based on resistance of wrought iron 0.000181 ohm per lb. ft.)

Nominal dia. in.	Classification	Actual Dimensions		Weight per ft. plain ends-steel-lb.	K = current for one millivolt drop per ft. of continuous pipe-amperes.	
		Outside diameter inches	Inside diameter inches		Steel	Wrought iron
1/8	S	0.405	0.269	0.244	1.16	1.32
1/8	X	0.405	0.215	0.314	1.50	1.70
1/4	S	0.540	0.364	0.424	2.02	2.30
1/4	X	0 540	0.302	0.535	2.55	2.90
3/8	S	0.675	0.493	0.567	2.70	3.07
3/8	X	0.675	0.423	0.738	3.51	4.00
1/2	S	0.840	0.622	0.850	4.05	4.60
1/2	X	0.840	0.546	1.09	5.18	5.88
1/2	XX	0.840	0.252	1.71	8.16	9.28
3/4	S	1.050	0.824	1.13	5.38	6.11
3/4	X	1.050	0.742	1.47	7.03	7.98
3/4	XX	1.050	0.434	2.44	11.6	13.2
1	S	1.315	1.049	1.68	7.99	9.09
1	X	1.315	0.957	2.17	10.3	11.8
1	XX	1.315	0.599	3.66	17.4	19.8
1 1/4	S	1.660	1.380	2.27	10.8	12.3
1 1/4	X	1.660	1.278	3.00	14.3	16.2
1 1/4	XX	1.660	0.896	5.21	24.8	28.2
1 1/2	S	1.900	1.610	2.72	12.9	14.7
1 1/2	X	1.900	1.500	3.63	17.3	19.6
1 1/2	XX	1.900	1.100	6.41	30.5	34.7
2	S	2 375	2.067	3.65	17.4	19.8
2	X	2.375	1.939	5.02	23.9	27.2
2	XX	2.375	1.503	9.03	43.0	48.8
2 1/2	S	2.875	2.469	5.79	27.6	31.4
2 1/2	X	2.875	2.323	7.66	36.5	41.5
2 1/2	XX	2.875	1.771	13.69	65.2	74.2
3	S	3.500	3.068	7.57	36.0	41.0
3	X	3.500	2.900	10.2	48.8	55.6
3	XX	3.500	2.300	18.6	88.5	101.0
3 1/2	S	4.000	3.548	9.11	43.4	49.3
3 1/2	X	4.000	3.364	12.5	59.6	67.8
3 1/2	XX	4.000	2.728	22.8	109.0	124.0
4	S	4.500	4.026	10.8	51.4	58.4
4	X	4.500	3.826	15.0	71.3	81.1
4	XX	4.500	3.152	27.5	131.0	149.0

STANDARD STEEL (OR WROUGHT IRON) PIPE. *Continued.*

Nominal dia. in.	Classification	Actual Dimensions: Outside diameter inches	Actual Dimensions: Inside diameter inches	Weight per ft. plain ends-steel-lb.	K = current for one millivolt drop per ft. of continuous pipe-amperes. Steel	Wrought iron
4 1/2	S	5.000	4.506	12.5	59.8	67.9
4 1/2	X	5.000	4.290	17.6	83.9	95.3
4 1/2	XX	5.000	3 580	32.5	155.0	176.0
5	S	5.563	5.047	14.6	69.7	79.2
5	X	5.563	4.813	20.8	98.9	112.0
5	XX	5.563	4.063	38.5	183.0	209.0
6	S	6.625	6.065	19.0	90.3	103.0
6	X	6.625	5.761	28.6	136.0	155.0
6	XX	6.625	4.897	53.2	253.0	288 0
7	S	7.625	7 023	23.5	112.0	127.0
7	X	7.625	6.625	38.0	181.0	206.0
7	XX	7.625	5.875	63.1	300.0	342.0
8	S	8.625	8.071	24.7	118.0	134.0
8	S	8.625	7.981	28.5	136.0	155.0
8	X	8.625	7.625	43.4	206.0	235.0
8	XX	8.625	6.875	72.4	345.0	392.0
9	S	9 625	8.941	33 9	161.0	184.0
9	X	9.625	8.625	48.7	232.0	264.0
10	S	10.750	10.192	31.2	149.0	169.0
10	S	10.750	10.136	34.2	163.0	185.0
10	S	10.750	10.020	40.5	192.0	219.0
10	X	10.750	9.750	54.7	261.0	297.0
11	S	11.750	11.000	45.6	217.0	247.0
11	X	11.750	10.750	60.1	286.0	326.0
12	S	12.750	12.090	43 8	208.0	237.0
12	S	12.750	12.000	49.6	236.0	269.0
12	X	12.750	11.750	65.4	311.0	354.0
13	S	14.000	13.250	54.6	260.0	296.0
13	X	14 000	13.000	72 1	343 0	391.0
14	S	15.000	14.250	58 6	279.0	317.0
14	X	15.000	14.000	77 4	369.0	420.0
15	S	16.000	15.250	62.6	298.0	339.0
15	X	16.000	15.000	82.8	394.0	149.0

S = Standard pipe.
X = Extra strong pipe.
XX = Double extra strong pipe.

102. Resistance of Lead Cable Sheaths

TABLE 11.

TABLE FOR DETERMINING CURRENT ON LEAD CABLE SHEATHS FROM VOLTAGE DROP IN MEASURED LENGTH OF SHEATH.

Resistivity, 1 ft. length, 1 sq. in. sectional area = 0.00010 ohm

Outside diam. of lead sheath (in.)	Thickness of lead sheath (64th in.)	Resistance of lead sheath (ohm per ft.)	Current for 1 millivolt per ft. (amp.)
0.50	4	0.001163	0.860
0.50	5	0.000965	1.036
0.50	6	0.000836	1.196
0.625	4	0.000906	1.104
0.625	5	0.000745	1.343
0.625	6	0.000640	1.563
0.75	4	0.000741	1.350
0.75	5	0.000606	1.650
0.75	6	0.000518	1.931
0.875	4	0.000627	1.594
0.875	5	0.000511	1.957
0.875	6	0.000435	2.300
1.00	5	0.0004419	2.263
1.00	6	0.0003750	2.668
1.00	7	0.0003268	3.061
1.00	8	0.0002913	3.437
1.125	5	0.0003892	2.569
1.125	6	0.0003294	3.037
1.125	7	0.0002866	3.491
1.125	8	0.0002547	3.926
1.25	5	0.0003476	2.876
1.25	6	0.0002939	3.404
1.25	7	0.0002552	3.918
1.25	8	0.0002265	4.415
1.375	5	0.0003142	3.183
1.375	6	0.0002650	3.773
1.375	7	0.0002299	4.35
1.375	8	0.0002038	4.91
1.50	6	0.0002416	4.14
1.50	7	0.0002092	4.78
1.50	8	0.0001853	5.40
1.625	6	0.0002218	4.51
1.625	7	0.0001920	5.21
1.625	8	0.0001698	5.89
1.75	6	0.0002051	4.88
1.75	7	0.0001772	5.64
1.75	8	0.0001567	6.38
1.875	6	0.0001906	5.25
1.875	7	0.0001648	6.07
1.875	8	0.0001456	6.87
2.00	6	0.0001781	5.61
2.00	7	0.0001538	6.50
2.00	8	0.0001359	7.36
2.125	6	0.0001672	5.98
2.125	7	0.0001443	6.93
2.125	8	0.0001273	7.86
2.25	6	0.0001575	6.35
2.25	7	0.0001359	7.36
2.25	8	0.0001198	8.35
2.375	6	0.0001488	6.72
2.375	7	0.0001284	7.79
2.375	8	0.0001132	8.83
2.50	7	0.0001217	8.22
2.50	8	0.0001073	9.32
2.50	9	0.0000959	10.43
2.625	7	0.0001156	8.65
2.625	8	0.0001019	9.81
2.625	9	0.0000911	10.98
2.75	7	0.0001102	9.08
2.75	8	0.0000971	10.30
2.75	9	0.0000868	11.53
2.875	7	0.0001050	9.51
2.875	8	0.0000927	10.79
2.875	9	0.0000828	12.08
3.00	8	0.0000887	11.28
3.00	9	0.0000792	12.62
3.00	10	0.0000716	13.96
3.125	8	0.0000849	11.77
3.125	9	0.0000758	13.18
3.125	10	0.0000686	14.58
3.25	8	0.0000815	12.27
3.25	9	0.0000728	13.74
3.25	10	0.0000659	15.19
3.375	8	0.0000783	12.77
3.375	9	0.0000700	14.29
3.375	10	0.0000633	15.83
3.50	8	0.0000755	13.24
3.50	9	0.0000674	14.84
3.50	10	0.0000609	16.42

103. Typical Report Sheets.

TIME	DATE ... TESTED BY ... LOCATION ... AVE. OR ST. ...	POTENTIAL, CABLE TO												DIRECTION OF CURRENT ON CABLE	ELECTROLYSIS PITTINGS ON CABLES?	CABLES BONDED TOGETHER?	WATER IN MANHOLE?	DUCT MATERIAL?	CABLES PROTECTED?	CABLES SUPPORTED?
				DUCT		WATER		GAS		TRACK										
		+	−	+	−	+	−	+	−	+	−	+	−							
1130																				

CURRENT MEASUREMENTS

(This shows a condensed form in convenient size for a field notebook).

DATE AND TIME		Dura-tion of Test Min.	Dist. betw. Cont. Feet	Amp. per Milli. K	Drop—Millivolts			Current—Amperes			DIREC-TION.
					Max.	Min.	Ave.	Max.	Min.	Ave.	

POTENTIAL MEASUREMENTS

DATE AND TIME		Duration of Test Min.	Potential—Volts Max.	Potential—Volts Min.	Potential—Volts Ave.	Momentary bond Current Amp.

FORM NO. 1

POTENTIAL SURVEY:—

CITY:— DATE:— OBSERVER:—

Time	Location	Measurements		Duration of Test Min.	Volts Polarities Refer To (A)			Max. Momentary Current Through Temporary Bond	Remarks
		From (A)	To (B)		Max.	Min.	Ave.		

FORM NO. 2

CURRENT SURVEY:—

CITY:— DATE:— OBSERVER:—

Time	Location	Size and Kind of Pipe	Dist. Bet. Contacts Feet	Duration of Test Min.	Direction of Current Flow	Drop in Millivolts			Calculated Current Amperes			Remarks
						Max.	Min.	Ave.	Max.	Min.	Ave.	

FORM No. 3

DATA SHEET FOR ELECTROLYSIS SURVEY.

TESTS ON EXPOSED PIPE

City:— Date:— Time:— Observer:—

Location:—

Size and kind of pipe:—

Pavement:— Soil:—

Location of nearest trolley tracks:—

" " " " power station:—

Approximate age and condition of pipe:—

	Max.	Min.	Aver.
Duration of each test........minutes			
Potential, pipe to rails, volts	......	......	......
Current through temporary bond connection, amperes			......
Distance between contacts on pipe = ... feet			
Drop on pipe, millivolts	......	......	......
Current on pipe, amperes	......	......	......

Direction of current flow:—

SIMULTANEOUS DROP MEASUREMENTS FOR RESISTANCE OF JOINTS.

		Equivalent Resistance	
		Feet of pipe.	Ohms.
Drop in...... feet of pipe =	millivolts		
Drop across first joints	"	....	....
" " second joint =	"	....	....

POTENTIAL TO OTHER PIPES, ETC.:—

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

REPORT OF THE BOARD OF DIRECTORS FOR THE FISCAL YEAR ENDING APRIL 30, 1916

The Board of Directors of the American Institute of Electrical Engineers presents herewith to the membership its Thirty-Second Annual Report, for the fiscal year ending April 30, 1916. A General Balance Sheet showing the financial condition of the Institute on April 30, 1916, together with other financial statements, is included herein.

The Board has endeavored, as far as possible, to keep the membership informed of its proceedings by publishing monthly in the Institute PROCEEDINGS a resumé of the business transacted at each meeting. These notices, however, are necessarily incomplete, as many important matters are considered which cannot be disposed of at one meeting and which must be held over for future consideration and action. Eventually such matters are dealt with in subsequent issues.

Directors' Meetings.—During the year the Board of Directors held 10 regular meetings, one adjourned meeting, and one special meeting. The adjourned meeting was held on December 11, 1915, for the purpose of considering the report of the Constitutional Revision Committee. The special meeting was held on January 21, 1916, for the purpose of acting upon an invitation from President Wilson to President Carty to nominate from the Institute's membership, candidates for appointment by the Secretary of the Navy upon the Organization for Industrial Preparedness, referred to elsewhere in this report.

Eleven of these meetings were held in New York, and one in Deer Park, Md., during the Annual Convention.

Annual Convention.—The Thirty-Second Annual Convention was held in Deer Park, Maryland, June 29-July 2, 1915. The total attendance was 202, which included 43 ladies. Although the attendance was small, due possibly to the location being somewhat remote from the larger membership centers, the convention was very successful from a technical and social standpoint. Thirty-one papers were presented at the seven technical sessions.

Panama-Pacific Convention.—The Panama-Pacific Convention was held in San Francisco September 16-18, 1915. It was arranged chiefly to provide an Institute meeting in San Francisco for Pacific coast members during the Panama-Pacific Exposition in place of the International Electrical Congress, which had been scheduled to be held on the same dates, but which had been postponed. The convention was unusually successful. Three hundred and fifty-five members registered, of which a considerable number were eastern members visiting the Exposition and attending the International Engineering Congress. Twenty-six papers were presented on a variety of engineering subjects.

Midwinter Convention, New York.—The Fourth Midwinter Convention was held in New York on February 8 and 9, 1916. The total registered attendance was 671, of which number 380 were members. The 291 guests included 175 ladies. Eleven papers were presented and four technical sessions were held. A subscription dinner-dance was held at the Hotel Astor on the evening of February 8, which was attended by 425 members and guests. The proceeds from the sale of tickets to this function covered all of the expenses and provided a surplus which will be available towards defraying the expenses of future midwinter social functions.

Philadelphia Meeting.—An Institute meeting was held in Philadelphia, Pa., on October 11, 1915, under the auspices of the Philadelphia Section. Three papers were presented and the total attendance was 200. This is the third annual meeting of this kind to be held in Philadelphia at the opening of the active season.

St. Louis Meeting.—On October 19 and 20, 1915, Institute members in the middle west were given an opportunity to attend a two-day Institute meeting which was held in St. Louis, Mo., under the auspices of the St. Louis Section, on the occasion of the 100th meeting of that Section. Eleven papers were presented, and the total attendance was 201. Members of the Associated Engineering Societies of St. Louis, with which the Section is affiliated, participated in this meeting.

Water Power Meeting, Washington, D. C.—This meeting was held in Washington on April 26, 1916, under the auspices of the Washington Section and the Committee on Development of Water Power. Five very carefully prepared papers were presented on the general subject of the relation of water power to the industrial advancement of the country. Two-hundred and fifty members and invited guests attended the meeting.

National Meeting, May 16, 1916.—An event unique in the history of the Institute and one which is attracting widespread interest will take place on May 16, 1916. This is a National Meeting which will be held simultaneously through the medium of the long distance telephone in six different cities; namely, San Francisco, Chicago, Atlanta, Philadelphia, New York and Boston. The purpose of the meeting is to commemorate the achievements of Institute members in the fields of communication, transportation, lighting and power. Incidentally it is being held on the date of the Annual Meeting of the Institute, and although the business coming before the Annual Meeting will be transacted in the afternoon at the business meeting, it is planned to reserve a part of it for the National Meeting in the evening.

Other Meetings.—In addition to these special meetings, held in various parts of the country for the benefit of the membership at large, eight regular monthly meetings were held in New York, with an average attendance of 300.

The Sections and Branches have also continued active and have held a large number of regular monthly meetings as shown by the tabulated statement in the report of the Sections Committee.

President.—President Carty has presided at all meetings of the Institute held during the year, with the exception of the meeting in St. Louis, and also at all meetings of the Board of Directors. During the year he has attended the following meetings: Detroit, September 9, 1915, Joint Session of A. I. E. E. at Convention of Association of Iron and Steel Electrical Engineers: Panama-Pacific Convention, San Francisco, September 16-18, 1915; Institute Meeting, Philadelphia, October 11, 1915; Schenectady Section, October 12, 1915; Boston Section, October 13, 1915; Pittsburgh Section, December 4, 1915; Ithaca Section, March 25, 1916; Water Power Meeting, Washington, April 26, 1916.

International Engineering Congress.—The International Engineering Congress has already received such wide publicity through its Committee of Management that no extended reference to it is necessary in this report. The Institute was one of the five national engineering societies which planned the Congress and which was interested in its success. It was held in San Francisco on the dates scheduled, September 20-25, 1915, and was eminently successful in every way.

The total registered attendance at the Congress was 851, of which number 71 were from 20 foreign countries. Fifty-two technical sessions were held, and over 200 papers were presented on a wide range of engineering subjects. In addition to the registered attendance over 600 cards of admission were issued so that the attendance at the various sessions was well over 1,500. The Committee of Management is still acting, principally with the publication and distribution of the volumes of the transactions, which it is estimated will be in the neighborhood of 10,000 to 12,000. A full report will be submitted by the committee to the participating societies in the near future.

National Preparedness.—The Institute has taken an active part in a number of the movements which have been organized recently in the interest of adequate national preparedness. Chief among these are the National Engineer Reserve, the Naval Consulting Board, and the Organization for Industrial Preparedness.

National Engineer Reserve.—The suggestion for the organization of a National Engineer Reserve was first made early in 1915, and shortly thereafter a joint committee was formed of representatives of the American Society of Civil Engineers, the American Society of Mechanical Engineers, the American Institute of Mining Engineers, the American Institute of Electrical Engineers, and the American Institute of Consulting Engineers, to cooperate with the war department in the organization of such a reserve. The members of this committee being widely separated geographically, making full attendance at meetings difficult and impracticable a smaller working committee was formed consisting of the five chairman of the individual committees of each society constituting the joint committee. This arrangement greatly facilitated the work. The committee has held conferences with Major General Leonard Wood, officers of the General Staff of the U. S. Army and of the War College, and with the chairmen of the House and Senate legislative committees on military affairs. The result of this work is that several of the military measures before Congress embody provisions for an Officers Reserve Corps under which the engineers of the country may take service. The committee is now waiting for the Navy Department to formulate its plan for an increase of the naval forces, and as soon as a decision has been reached by that Department, the committee will take up the question of an engineer reserve for the Navy similar to that contemplated for the Army.

U. S. Naval Consulting Board.—On July 19, 1915, the Institute was invited by the Hon. Josephus Daniels, Secretary of the U. S. Navy Department, to select two members for appointment by Secretary Daniels upon a proposed advisory committee to be presided over by Mr. Thomas A. Edison and to be composed of men recognized throughout the country for their inventive genius and engineering achievements, to assist the Navy Department, both instructively and critically, in the development of such new ideas for naval advance as might be presented and found worthy of consideration. The underlying idea was to make available the latent inventive and engineering genius of our country to improve the navy, and to bring the officers of the service into more intimate contact with the industrial resources of the country. Similar invitations were extended to ten other scientific and engineering organizations. The two members officially selected for this service by the Institute were Mr. Frank Julian Sprague, of New York, and Mr. Benjamin G. Lamme, of Pittsburgh, Pa., both of whom were appointed by Secretary Daniels as members of the Naval Consulting Board. The excellent work of the Board has already received so much attention from the public press that no further statement regarding it is necessary in this report. Recently its usefulness has been greatly enlarged by the organization of representatives from each state in the Union to assist in the work of collecting data regarding the manufacturing resources of the country.

Organization for Industrial Preparedness.—This movement was inaugurated as the result of the valuable service rendered by the Naval Consulting Board. Its purpose, as expressed in President Wilson's letter to President Carty inviting the Institute to nominate representatives, is to assist the Naval Consulting Board in the work of collecting data for use in organizing the manufacturing resources of the country for the public service in time of emergency. The Institute was invited to nominate, for the approval of the Secretary of the Navy, a representative from its membership from each state in the Union to act in conjunction with representatives of the American Society of Civil Engineers, the American Society of Mechanical Engineers, the American Institute of Mining Engineers and the American Chemical Society. At the call of President Carty the Board of Directors of the Institute held a special meeting on January 21, 1916, to act upon this invitation, and at this meeting President Carty was empowered to select the nominees on behalf of the Institute. A list of these nominees was subsequently submitted to the Secretary of the Navy and the appointments were made. The state representatives are officially known as the *State Directors of the Organization for Industrial Preparedness, and Associate Members of the Naval Consulting Board of the United States*, and it will be the duty of these directors to make a canvass of the industrial establishments in their respective States and have them fill out a confidential form giving in detail data regarding their manufacturing and producing resources. On April 20, 1916, President Carty issued a letter to all Institute members in the United States appealing to them to assist in the work.

Representatives.—In addition to its regular representation upon the various joint committees and other local and national bodies with which it has been affiliated in past years, the Institute has also appointed special representatives on numerous occasions during the year in connection with matters of interest to the Institute and to the engineering profession, especially in civic affairs and matters pertaining to legislation affecting the profession.

Committees.—There has been no change in the number and character of the standing, technical and special committees, but a committee has been investigating the fields of the respective technical committees, and it is probable that there will be some additions next year. With one or two exceptions all of the committees have been more or less active. Abstracts of the reports of the chairmen of many of the Institute committees to the Board of Directors are included herein as follows:

Sections Committee.—The Sections Committee is able to report a gratifying increase in activity and interest on the part of the Sections and Branches during the year.

Although the number of meetings has not greatly increased, the attendance has been considerably larger, notwithstanding the fact that two Sections have necessarily been inactive during the present year; namely, Mexico and Toronto. The Toronto Section is inactive only temporarily.

Two new Sections were organized during the year: one at Denver, Colo., on May 18, 1915, and the other at Kansas City, Mo., on April 14, 1916. The Denver Section has made an excellent start and is doing good work. The Kansas City section was just organized a month ago and has therefore not yet had an opportunity to become active. The officers, however, are enthusiastic and the Section will doubtless be of great usefulness to the membership.

New Branches were organized at the Carnegie Institute of Technology, Clarkson College of Technology, and the Brooklyn Polytechnic Institute.

On April 14, 1916, the Board of Directors, acting upon the recommendation of the Sections Committee authorized a conference of Branch delegates at the Annual Convention, similar to the conference of Section delgates which of late years has become such a prominent feature of the annual conventions. It was considered inexpedient, however, to recommend that the transportation expenses of the Branch delegates be paid from the Institute treasury.

In accordance with Section 60 A of the Institute by-laws, which was adopted upon recommendation of the committee, the Chairman is receiving suggestions of questions for discussion at the coming conference of Section delegates at the Cleveland Convention.

A tabulated table showing the activity of the Sections and Branches during the past five years follows:

	For Fiscal Year Ending				
	May 1 1912	May 1 1913	May 1 1914	May 1 1915	May 1 1916
Sections					
Number of Sections	28	29	30	31	32
Number of Section meetings held	231	244	233	246	251
Total Attendance	19,800	22,825	22,626	23,507	28,553
Branches					
Number of Branches	42	47	47	52	54
Number of Branch meetings held	281	357	306	328	360
Attendance	10,255	11,808	11,617	12,712	15,166

Meetings and Papers Committee.—The Meetings and Papers Committee has held regular monthly meetings throughout its term of office, at which meetings the disposition of all manuscripts submitted has been attended to and the regular Institute meetings and conventions decided upon. In addition to the monthly meetings in New York, meetings have been arranged for by this committee in St. Louis, Philadelphia and Washington. The Panama-Pacific Convention, the Midwinter Convention, the Annual Convention, Cleveland, and the Pacific Coast Convention at Seattle, have also been arranged for by this committee. Following its practise in previous years all manuscripts which have been submitted have first been passed upon by one of the special technical committees before being finally acted upon by the main committee.

Standards Committee.—The 1915 edition of the Standardization Rules, representing the work of the Standards Committee of 1914-1915, was presented to and approved by the Board of Directors at the Deer Park Convention meeting, July 1, 1915. The revision was not radical, but rather a completion and clarification of the radical revision of December 1, 1914.

The present committee has held monthly meetings for the consideration of amendments and additions. The work has been largely carried on through the medium of 20 sub-committees charged with various parts of the field, whose reports have been reviewed by the whole committee. No final action will be taken on the proposed amendments until the May meeting, which will probably last for several days.

The changes to be considered at the May meeting are for the most part not radical, although they constitute distinct improvements. These will be presented to the Board of Directors at the Cleveland Convention in June, and if approved will be incorporated in the 1916 edition which will become effective on August 1.

In order to insure greater continuity of policy and method in the work of the Standards Committee from year to year the committee will present to the Board of Directors for its approval a set of by-laws with the recommendation that any future changes thereto can be made only with the sanction of the Board.

During the year a number of additions have been made to the list of cooperating societies, which includes several foreign societies.

Code Committee.—The Code Committee has continued to represent the Institute on the Electrical Committee of the National Fire Protection Association. Only one meeting was held, in Boston, and nothing transpired at this meeting of sufficient importance to merit special mention.

A sub-committee of the Code Committee spent much time cooperating with the U. S. Bureau of Standards during the year, working on the National Safety Code which the Bureau is formulating and which it expects to issue sometime in the near future. This was a continuation of the kind of work carried on last year, and represents the real activity of the Code Committee for the year.

Library Committee.—The united libraries of the founder societies and the United Engineering Society are now controlled and administered as one joint library by the Library Board of the United Engineering Society under an agreement which took effect on January 1, 1915, and in accordance with the by-laws of that society. The first annual report of the Library Board, for the year 1915, was issued and published in pamphlet form in January 1916. A synopsis of the report appeared in the Institute PROCEEDINGS for February 1916. It includes many interesting statistics of the accessions to the library, its utilization, its finances, and a list of the donors of books and pamphlets.

Railway Committee.—The Railway Committee this year has cooperated with the Standards Committee in respect to the revision of Rule No. 418 of the Standardization Rules, and has made suggestions regarding the rule for incorporation in the final edition of the Rules. Some consideration has been given to a more standard terminology for electric railway devices and the standardization of voltages for railroad purposes.

Transmission Committee.—The Transmission Committee has this year continued its practise of securing a consensus of opinion of the best informed engineers and operating men on some selected subject or subjects and either reproducing or digesting the material for the benefit of the membership. This year the committee will make reports at the Annual Convention on experiences in the effect of altitude in the operating temperature of electrical apparatus, and in the use of the grounded neutral in high tension systems.

Electric Lighting Committee.—The Electric Lighting Committee has held several meetings during the year at which the principal subject of discussion was the arrangement of circuits for street lighting purposes. A paper on this subject will be presented at the Annual Convention.

Industrial Power Committee.—As in previous years, the Industrial Power Committee cooperated with the Sections and Branches in arranging meetings on the subject of industrial power. The Cleveland Section appointed a local industrial power committee and later a considerable number of Sections and Branches followed its example. Each Section and Branch was requested to hold at least one meeting during the year on the subject of industrial power, and the local committees were of great assistance in arranging for these meetings. The Industrial Power Committee was also able to obtain for the use of the Sections and Branches a number of lantern slide lectures. The committee has been assigned one session of the Annual Convention. Four meetings were held during the year.

Electrochemical Committee.—The Electrochemical Committee has confined its work to efforts to obtain suitable papers on electrochemical subjects which the committee considered might be of general interest to the membership. The committee arranged for the joint meeting with the New York Section of the American Electrochemical Society held in New York on March 10, 1916.

Electrophysics Committee.—The work of the Electrophysics Committee has been directed chiefly to obtaining and reviewing, for the Meetings and Papers Committee, papers on subjects relating to the physical theory underlying the application of electricity to electrical engineering. Six papers have thus far been obtained and two others promised. Of the six, three have already been presented, one will be presented at the Annual Convention, and two will be offered for future meetings.

Iron and Steel Industry Committee.—This committee has arranged for a joint session between the A.I.E.E. and the Association of Iron and Steel Electrical Engineers, for Wednesday, September 20, 1916, during the annual convention of the Association to be held in Chicago, September 18-22, 1916.

Committee on Use of Electricity in Mines.—A session of the Panama-Pacific Convention held in San Francisco in September 1915 was devoted to mining work and a number of papers were presented dealing particularly with metal mine problems. Some work was also done by the committee in conjunction with the U. S. Bureau of Mines regarding rules for electrical installation in mines, but owing to business conditions it has not been possible to get the members of the committee together for a thorough discussion of the subject.

Committee on Use of Electricity in Marine Work.—The work of this committee has been directed, first, to obtaining papers dealing with electrical installations on shipboard, and, second, to continuing the work carried on during the previous two years in securing standard rules for various types of marine installations. A paper on this subject was presented at the Panama-Pacific Convention, and several papers are in view dealing with auxiliary power plants on shipboard for lighting, and for power for radio telegraph sets in cases of emergencies.

A sub-committee of this committee is now at work in conjunction with Lloyds and the American Bureau of Shipping in an endeavor to bring up to date and standardize the rules of the various building and insurance societies.

Protective Apparatus Committee.—The work of the Protective Apparatus Committee during the year might be divided into five categories, as follows: 1. An endeavor to standardize lightning arresters and similar protective devices. 2. Consideration and discussion of the factors involved in attempting to standardize the rating of oil switches. 3. An analysis of the protective problems connected with relays, split conductor cables, and like protective means. 4. Collection of data on partially solved problems relating to protective devices and continuity of service in the transmission of electrical energy. 5. Presentation of data in the form of papers; four dealing with operating experiences with protective devices, three on pressing problems relating to line insulators, and one on the theory of parallel grounded wires.

Committee on Records and Appraisals of Properties.—The geographical distribution of the committee has made it necessary to carry on its work through the medium of correspondence. One of the results of the committee's work was the presentation of several very important papers on various phases of appraisal work at the Panama-Pacific Convention.

A considerable number of conferences have been held by members of the committee, as a result of which it is planned to present at the October meeting in New York a number of papers on appraisal work and a topical discussion on methods of keeping inventories and appraisals up to date.

In view of the wide variety of opinions concerning inventory and appraisal work, the committee believes that it is not wise to attempt to present anything in the nature of a complete report but recommends the continuance of the committee in order that further study and investigation may be made of this important subject.

Educational Committee.—The Educational Committee has decided to begin the preparation of a list of topics suitable for advanced study, research and invention in electrical engineering. This was considered to be a piece of work which might be of benefit to colleges of engineering, and at the same time of such a technical nature as to be outside of the scope of activity of various educational associations. It is felt that work of this kind might well be made a part of the regular duties of the Educational Committee or one of its sub-committees. The committee would thus in time establish closer relations with colleges of engineering, research laboratories and individual investigators, and would become a center of information and a source of wholesome inspiration for electrical research in this country. A list of topics for research with some suggestions, compiled by the chairman of the committee, has been accepted for presentation at the Annual Convention.

Editing Committee.—The Editing Committee has had general supervision over the discussions in the PROCEEDINGS and the contents of the TRANSACTIONS published during its incumbency. The method of handling this material has been the same as in the previous two or three years and it appears to have met with general satisfaction. The only important typographical changes which have been adopted for the current year have been the new style for the cover and the combination of the Section I and Section II tables of contents on the first page of the PROCEEDINGS immediately inside the cover.

Committee on Development of Water Power.—During the past year this committee, through its members, has endeavored to keep informed respecting the progress of legislation affecting water power development and other allied questions. The committee has held several meetings, a large number of informal conferences, and has exchanged much correspondence.

In the fall of 1915 the committee accepted an invitation from Governor James Withycombe of the State of Oregon to send a delegate to address a Western Water Power Conference held at Portland, Oregon, September 21, 22 and 23. Mr. John H. Finney, a member of the committee, was appointed and presented to the conference a brief which had been prepared by the committee.

Acting jointly with the Meetings and Papers Committee, this committee arranged for the special Institute meeting held in Washington, D. C., under the auspices of the Washington Section, on April 26, at which various aspects of the water power situation were treated through the medium of a carefully prepared program.

Public Policy Committee—The Public Policy Committee has held four meetings during the year, at which various matters referred to the committee were considered and discussed. Among the more important questions reported upon by the committee to the Board of Directors were the following: Legislation providing for federal support for engineering experiment stations in each state; water power legislation; engineering cooperation; translation of standardization rules into foreign languages: legislation affecting the engineering profession.

Committee on Relations of Consulting Engineers.—On May 13, 1915, the committee submitted to the Board of Directors a proposed schedule of fees as a general guide for consulting engineers. No other matters have developed requiring the attention of the committee.

U. S. National Committee of the International Electrotechnical Commission—The War has naturally interfered with the international activities of the Commission, but nevertheless a considerable amount of work has been carried on among the individual national committees.

In America, electrical engineering standardization has been confined to the work of the A. I. E. E. Standards Committee. The British Standardization Rules for Electrical Machinery have been published during the year, and are believed to be in substantial conformity with the last edition (1915) of the A. I. E. E. Standardization Rules, as well as with the international rules thus far adopted by the I. E. C.

The Annual Report of the Honorary Secretary of the Commission, dated January 1916, which has been received from the Central Office, indicates that the work of the Commission, in abeyance for the present, should be expected to recontinue as soon as the peace of the world shall have been restored.

The U. S. National Committee held one meeting, in New York, in November 1915.

Constitutional Revision Committee.—The Constitutional Revision Committee was appointed at the beginning of the administrative year, and immediately began work upon the revision of the constitution. All suggestions which had been received since the last amendment to the constitution in 1912 were considered by the committee. Requests for further suggestions were made to each member of the present Board of Directors, each past-president, and each Section chairman. As the result of the suggestions received and those made by the members of the committee the proposed amendments were agreed upon and submitted to the Board of Directors in December 1915. The amendments are now being voted upon by the membership and the result of the vote will be made known at the Annual Meeting.

Employment Department.—The usefulness of the Employment Department has increased greatly during the year. A considerable number of Institute members have been helped to positions, and employers are more and more taking advantage of the facilities offered by the Institute for placing them in touch with desirable technical men. The Institute continues to publish without charge in the monthly PROCEEDINGS announcements of vacancies and men available.

Board of Examiners.—The Board of Examiners has held 11 meetings during the year. It has considered and referred to the Board of Directors with its recommendations a total of 1,419 applications of all kinds. In addition to these, the Board has reviewed 29 applications for a second and third time. Although the total number of applications is less than last year, the amount of time devoted to the work by the Board was considerably greater this year. The reason for this is that there were less applications for admission as Associates, which require very little detailed examination, but more applications for the higher grades, to which much time must necessarily be devoted. In considering applications for admission and transfer to the grade of Fellow the Board has adhered rigidly to its interpretation of the constitutional requirements, as may be inferred from the following figures showing that only 10 applicants were recommended for this grade, and 20 were not recommended.

APPLICATIONS FOR ADMISSION.

Recommended for grade of Associate	624	
Not recommended for grade of Associate	1	625
Recommended for grade of Member	44	
Not recommended for the grade of Member	14	58
Recommended for grade of Fellow	3	
Not recommended for Fellow	5	8
Recommended for enrolment as students	643	643

APPLICATIONS FOR TRANSFER.

Recommended for grade of Member	54	
Not recommended for grade of Member	9	63
Recommended for grade of Fellow	7	
Not recommended for grade of Fellow	15	22
Total number of applications considered		1419
Applications reconsidered		29
Admission and transfer all grades		1448

Membership Committee.—The work of the Membership Committee began early last fall when plans were formulated assigning a definite portion of the work to each member of the committee. This, based upon well established precedent, aimed to increase the membership without the employment of undignified methods. Later it was decided to extend operations in the same and new fields.

The work of the committee, into which the individual members entered with considerable interest and activity, resulted in the filing of 777 applications for membership, and the laying of a foundation for the work of the succeeding committee.

The Membership Committee, believing its duty to be the retention of existing as well as the acquisition of new members, has during the year cooperated with the Secretary of the Institute in securing the payment of dues in arrears, and, in general, seeking and endeavoring to remove the cause of difficulty. So much has been accomplished that it is urgently recommended that this function be delegated to the Membership Committee each year.

The following tabulated statement shows the number of members in each grade, the total membership, and the additions and deductions that have been made during the year:

	Honorary Member	Fellow	Member	Associate	Total
Membership, April 30, 1915.	5	448	1079	6522	8054
Additions:					
Elected	....	4	41	584	....
Transferred	....	6	47	....	....
Reinstated	....	....	7	46	....
Deductions:					
Died	....	2	7	27	....
Resigned	....	....	13	206	....
Dropped	....	2	13	254	....
Transferred	....	....	4	49	....
Membership, April 30, 1916	5	454	1137	6616	8212

Net increase in membership during the year 158

Deaths.—The following deaths have occurred during the year:

Fellows.—Henry A. Mavor, Louis Duncan.

Members.—Fred S. Pearson, Max Hebgen, C. E. Hogle, R. A. McKee, James I. Ayer, W. W. Cole, W. C. Robinson.

Associates.—J. A. Culverwell, I. W. Moore, O. C. F. Hague, J. F. McElroy, E. J. Correa, R. W. Farr, Eugene Fischer, W. J. Henry, Geo. F. Kenyon, Joseph Herzog, John W. Barnett, R. C. Watson, Wm. F. Endress, Roy N. Wooster, Crellin Cartwright, W. C. Andrews, James S. Anthony, W. G. Roome, Frank Zencak, W. E. Dickinson, F. H. Varney, E. F. Cannon, J. Ray Wilson, C. J. H. Woodbury, John C. Manley, Chas. F. Baldwin, George H. Stockbridge. Total deaths, 36.

Finance Committee.—The following correspondence and financial statements form a complete summary of the work of the Finance Committee for the year.

Board of Directors, New York, May 12, 1916
American Institute of Electrical Engineers.

Gentlemen:

Your Finance Committee respectfully submits the following report for the year ending April 30, 1916.

During the past year the committee has held monthly meetings, has passed upon the expenditures of the Institute for various purposes and otherwise performed the duties prescribed for it in the Constitution and By-Laws. Haskins & Sells, certified public accountants, have audited the books, and their certification of the Institute finances follows.

In company with your Treasurer, Secretary, and a member of the firm of accountants, the committee has examined the securities held by the Institute and finds them to be as stated in the accountants' report.

In accordance with the recommendation of your committee in their report dated May 11, 1915, the Board of Directors instructed the Finance Committee to liquidate the mortgage upon the lands on which the Engineering Societies Building stands. This mortgage, amounting to **$54,000.00**, was paid June 25, 1915, and therefore the Institute is now free from all indebtedness save for current liabilities as shown in the accompanying report.

Respectfully submitted,

(Signed) J. Franklin Stevens,
Chairman, Finance Committee.

HASKINS & SELLS

CERTIFIED PUBLIC ACCOUNTANTS
30 BROAD STREET
NEW YORK

CABLE ADDRESS "HASKSELLS"

WATERTOWN
BALTIMORE
PITTSBURGH
CLEVELAND
CHICAGO
ST. LOUIS
ATLANTA
DENVER
SAN FRANCISCO
LONDON, E. C.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

CERTIFICATE

We have audited the books and accounts of the American Institute of Electrical Engineers for the year ended April 30, 1916, and

WE HEREBY CERTIFY that the accompanying General Balance Sheet properly sets forth the financial condition of the Institute on April 30, 1916, that the Statement of Income and Profit & Loss for the year ended that date is correct, and that the books of the Institute are in agreement therewith.

HASKINS & SELLS
Certified Public Accountants.

NEW YORK.
May 12, 1916.

AMERICAN INSTITUTE OF

General Balance Sheet

Exhibit A.

Assets.

Land and Building:			
Interest in United Engineering Society's Real Estate No. 25 to 33 West 39th Street:			
Building		$353,346.61	
Land (One-third of Cost)		180,000.00	
Total Land and Building			$533,346.61
Equipment:			
Library—Volumes and Fixtures		$ 39,217.30	
Works of Art, Paintings, etc.		3,001.35	
Office Furniture and Fixtures		11,229.48	
Total		$ 53,448.13	
Less Reserve for Depreciation		6,989.01	
Remainder—Equipment			$ 46,459.12
Investments:			
Bonds—City of Wilmington, Delaware, 4½%, 1934, Par $15,000			$ 15,938.83
Working Assets:			
Publications entitled "Transactions," etc.		$ 10,908.50	
Badges		602.95	
Total Working Assets			$ 11,511.45
Current Assets:			
Cash		$ 6,740.09	
Accounts Receivable:			
Members, for Entrance Fees and Past Dues		7,750.00	
Advertisers		446.70	
Miscellaneous		580.94	
Interest Accrued—Investments		56.25	
Interest Accrued—Bank Balances		107.73	
Total Current Assets			$ 15,681.71
Funds:			
Life Membership Fund:			
Cash	$ 349.89		
Chicago, Burlington & Quincy Railroad Company, 4%, 1958, Par $5,000.00	4,868.75		
Interest Accrued	33.33	$ 5,251.97	
International Electrical Congress of St. Louis—Library Fund:			
Cash	$ 756.39		
New York City Bonds, 4½%, 1957, Par $2,000.00	2,261.47		
Interest Accrued	45.00	3,062.86	
Mailloux Fund:			
Cash	$ 104.10		
New York Telephone Company Bond, 4½%, 1939	1,000.00		
Interest Accrued	22.50	1,126.60	
Midwinter Convention Fund—Cash		158.93	
Total Funds			9,600.36
Total			$632,538.08

ELECTRICAL ENGINEERS

April 30, 1916

Liabilities

Current Liabilities:		
Accounts Payable—Subject to Approval by the Finance Committee	$ 7,146.64	
Dues Received in Advance	1,322.97	
Entrance Fees and Dues Advanced by Applicants for Membership	455.50	
Total Current Liabilities		$ 8,925.11
Fund Reserves:		
Life Membership Fund	$ 5,251.97	
International Electrical Congress of St. Louis—Library Fund	3,062.86	
Mailloux Fund	1,126.60	
Midwinter Convention Fund	158.93	
Total Fund Reserves		9,600.36
Surplus: Per Exhibit " B "		614,012.61
Total		$63,2538.08

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

Statement of Income and Profit and Loss

For the Year Ended April 30, 1916

Exhibit B.

Revenue:			
Entrance Fees		$ 3,565.00	
Dues		87,605.28	
Student's Dues		4,621.50	
Transfer Fees		520.00	
Advertising		8,049.43	
Subscriptions		2,688.38	
Sales of " Transactions," etc.		2,323.86	
Badges Sold	$1,684.00		
Less Cost	1,475.05		
		208.95	
Interest on Investments		965.97	
Interest on Bank Balances		533.92	
Exchange		27.53	
Total			$111,199.82
Expenses:			
Meetings and Papers Committee:			
Salaries		$ 5,425.00	
Binding and Mailing Proceedings		6,426.13	
Printing Proceedings		11,121.75	
Engraving Proceedings		2,349.12	
Paper and Cover Paper		6,320.34	
Envelopes		786.83	
Stationery and Miscellaneous Printing		89.95	
General Expenses		128.23	
Meetings		5,983.43	
Volume No. 32		5.90	
Volume No. 33		12,422.92	
Volume No. 34		1,476.64	
Total		$ 52,536.24	
Deduct Increase in Inventory of Publications:..			
May 1, 1915	$ 9,650.75		
April 30, 1916	10,908.50	1,257.75	$ 51,278.49
Executive Department:			
Salaries		$ 16,448.50	
General Expenses		1,980.06	
United Engineering Society—Assessments		4,800.00	
Express		412.59	
Postage		2,710.56	
Advertising		2,035.76	
Stationery and Miscellaneous Printing		3,111.67	
Year Book and Catalogue		2,750.85	
Interest on Bond and Mortgage		360.00	34,609.99
Forward		$	$ 85,888.48
Revenue—(Forward)			$111,199.82

Revenue—(Forward)		$111,199.82
Expenses—(Forward)		$ 85,888.48
Sections Committee:		
Section Meetings	$ 5,338.94	
Branch Meetings	162.33	
Delegates' Convention Expenses	1,574.05	
Salaries, New York Office	2,340.00	
Stationery and Printing, New York Office	647.00	
Express on Advance Copies	43.94	
		10,106.26
General:		
Library Committee	$ 3,999.99	
Membership Committee	890.55	
Finance Committee	150.00	
Standards Committee	368.41	
Code Committee	73.45	
International Engineering Congress, 1915	750.00	
Reception Committee, International Engineering Congress 1915	224.17	
Constitutional Revision Committee	695.50	
Library Research Department	250.00	
Salary and Traveling Expenses, Honorary Secretary	4,440.17	11,837.24
Total		$107,831.98
Add:		
Increase in Accounts Payable—Subject to Approval of Finance Committee, Expenses Undistributed at:		
May 1 1915, not including liability for badges sold or on hand, $70.00	$ 4,979.41	
April 30, 1916	7,146.64	2,167.23
Total Expenses		$109,999.21
Net Revenue:		$1,200.61
Profit & Loss Credits—Accessions to Library Volumes and Fixtures	$ 681.25	
Land, Building, and Endowment Fund Transferred to the General Fund	7,807.10	
Charged to Mailloux Fund on Account of Payment from General Fund in December, 1914, which should have been paid from Mailloux Fund	50.75	
Payment Received for Tickets to Annual Function, February 1915	10.50	
Adjustment of Office Furniture and Fixtures, Applicable to Prior Period	466.50	9,016.10
Gross Surplus for the Year		$ 10,216.71
Profit & Loss Charges:		
Uncollectible Dues Written Off	$ 3,403.00	
Provision for Depreciation of Furniture and Fixtures	1,267.06	
Loss on Sale of Securities	1,763.85	
Amortisation of Premium on City of Wilmington, Delaware, 4½% Bonds of 1934	58.67	
Total		6,492.58
Net Surplus for the Year		$ 3,724.13
Surplus, May 1, 1915		610,288.48
Surplus, April 30, 1916		$614,012.61

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

Statement of Cash Receipts and Donations for Designated Purposes. Also Disbursements, for the Year Ended April 30, 1916.

Exhibit C.

Receipts:	
Land, Building and Endowment fund—Interest	$104.62
Life Membership Fund—Interest	206.63
International Electrical Congress of St. Louis Library Fund—Interest and Royalties	97.65
Mailloux Fund—Interest	45.00
Midwinter Convention Fund	158.93
Total	$612.83
Disbursements:	
Land Building and Endowment Fund—Account payment of mortgage on land, 25-33 West 39th Street, New York City	$7807.10
Life Membership Fund	269.38
Mailloux Fund	54.95
Total	$8131.43

RECEIPTS AND DISBURSEMENTS PER YEAR PER MEMBER.

During each fiscal year for the past eight years.

Year ending April 30	1909	1910	1911	1912	1913	1914	1915	1916
Membership, April 30, each year	6400	6681	7117	7459	7654	7876	8054	8212
Receipts per Member	$13.21	$13.35	$13.37	$13.19	$13.45	$14.08	$14.06	$13.62
Disbursements per Member	10.49	12.03	11.03	12.44	15.57	12.86	13.54	13.74
Credit Balance per Member	$2.72	$1.32	$2.34	$ .75	*$2.12	$1.22	$ .52	*$ .12

*Deficit.

Respectfully submitted for the Board of Directors,

F. L. HUTCHINSON, *Secretary.*

New York, May 16, 1916.

INDEX

Note: For complete topical and synoptical index see end of Part II

PAPERS AND DISCUSSIONS

INDEX TO AUTHORS

SYNOPTICAL AND TOPICAL

INDEX

OF

A. I. E. E. TRANSACTIONS

Vol. XXXV, Parts I and II

The main headings under which these synopses are classified were arrived at by a careful study of all the papers contributed since the organization of the Institute.

The method of making this classification may be called the automatic method, since it is created by sorting the papers themselves into groups and then naming the groups.

Many papers fall naturally into several different groups and in such cases they are inserted under as many different heads as it is thought they rightfully belong.

The classified synopses are designed for those searching for comprehensive information on any given topic, while the subject index is intended for those looking up specific and definite data or information.

MAIN SECTIONS OF SYNOPTICAL INDEX

1. EDUCATION

THE RELATION OF PURE SCIENCE TO INDUSTRIAL RESEARCH

President's Address

J. J. Carty **Vol. xxxv—1916, pp. 479-488**

SUGGESTIONS FOR ELECTRICAL RESEARCH IN ENGINEERING COLLEGES

V. Karapetoff **Vol. xxxv—1916, pp. 895-910**

This paper gives a list of topics in electrical engineering suitable for thesis, research and advanced study. A plea is made for systematic research, each college specializing year after year in only a few topics. Cooperation is urged with individual inventors and investigators. Various types of investigation are enumerated, such as invention, experimental study, theoretical study, library search, and compilation of data.

Discussion, pages 911-923, by Messrs. J. B. Whitehead, A. E. Flowers, C. E. Skinner, F. C. Caldwell, E. E. Creighton, D. D. Ewing, C. F. Harding, N. S. Diamant, J. J. Carty, D. H. Braymer, A. A. Nims and A. Gray.

A general discussion from the viewpoints of the college professor, inventor and manufacturer.

2. GENERAL THEORY

OUTLINE OF THEORY OF IMPULSE CURRENTS

C. P. Steinmetz **Vol. xxxv—1916, pp. 1-20**

In Part I it is shown how, from the integral of the general differential equation of the electric circuit, which has been discussed in a previous paper, all types of electric currents are derived as special cases, corresponding to particular values of the integration constants.

In Part II an outline of the theory of impulse currents is given. They comprise two classes, the non-periodic and the periodic. The equations of both are given in different form, by exponential and by hyperbolic or trigonometric functions.

A few special cases are discussed.

Discussion, pages 20-31, by Messrs. C. P. Steinmetz, M. I. Pupin, H. Pender, H. Lippelt and A. E. Kennelly.

A discussion of the advantages of the synthetic and analytic methods of studying engineering phenomena. A development of the special case under impulse currents of the circuit having capacity in series.

APPLICATION OF A POLAR FORM OF COMPLEX QUANTITIES TO THE CALCULATION OF ALTERNATING-CURRENT PHENOMENA

N. S. Diamant **Vol. xxxv—1916, pp. 957-978**

In the calculation of a-c. phenomena by means of complex quantities, as a rule, the rectangular components of the vector are used. A simple method for dealing directly with the vectors themselves is described and consists in introducing the operator j^n, where n, contrary to ordinary usage, may be any positive or negative fraction. For convenience of reference a summary of formulas is given and also a very short bibliography.

Discussion, pages 979-981, by Messrs. A. Gray, E. E. F. Creighton, J. B. Whitehead, E. H. Colpitts and N. S. Diamant.

A general discussion of the various mathematical determinations.

3. UNITS, MEASUREMENTS AND INSTRUMENTS

CREST VOLTMETERS

C. H. Sharp and E. D. Doyle **Vol. xxxv—1916, p. 99-107**

The paper shows how a voltmeter which will read directly the maximum or crest values obtained in high-voltage testing may be constituted by a combination of an electrostatic voltmeter and an electric valve. Diagrams of connection are shown and results of test given to indicate the validity of the method.

Discussion incorporated with that of paper by W. R. Work on "Notes on the Measurement of High Voltage".

THE VOLTMETER COIL IN TESTING TRANSFORMERS

A. B. Hendricks, Jr. **Vol. xxxv—1916, p. 117**

The advantages of the voltmeter coil in the determination of the high-tension voltage in testing transformers.

Discussion incorporated with that of paper by W. R. Work on "Notes on the Measurement of High Voltage".

THE CREST VOLTMETER

L. W. Chubb **Vol. xxxv—1916, pp. 109-116**

This paper mentions and compares some of the methods of high-voltage measurement and describes in more detail the crest voltmeter with its construction, operation, accuracy and application. The summary states that spark gaps should be only a calibrating standard and a more practical instrument, such as described, the preferred working standard.

Discussion incorporated with that of paper by W. R. Work on "Notes on the Measurement of High Voltage".

NOTES ON THE MEASUREMENT OF HIGH VOLTAGE

W. R. Work **Vol. xxxv—1916, pp. 119-126**

A brief account of some of the experiments made to determine the relative accuracy of certain methods used in measuring high voltage. The methods comprise the use of a tertiary (or voltmeter) coil in the high-tension transformer, the crest voltmeter and the derivation of the high-tension pressure from the primary voltage.

Discussion (including that of papers by Sharp and Doyle, L. W. Chubb and A. B. Hendricks), pages 127-146, by Messrs. E. E. Creighton, F. W. Peek, Jr., F. M. Farmer, F. Bedell, C. A. Adams, W. I. Middleton, J. R. Craighead, C. L. Dawes, J. B. Whitehead, L. W. Chubb, C. H. Sharp, C. F. Harding, W. D. Peaslee, M. G. Newman and A. B. Hendricks, Jr.

A general discussion with particular reference to the oscillograph and visual corona methods of measuring crest voltage.

A METHOD OF DETERMINING THE CORRECTNESS OF POLYPHASE WATT-METER CONNECTIONS

W. B. Kouwenhoven **Vol. xxxv—1916, pp. 183-206**

A description of a method of checking the correctness of the connections of a polyphase watt-hour meter and proof that the methods most commonly used are unreliable. Rules are worked out that make the rectification of incorrect connections simple. Another method is described which may be used on balanced or unbalanced three-phase circuits at any power factor, providing the opening of one phase at a time is permissible.

Discussion, pages 207-211, by Messrs. W. H. Pratt, G. A. Sawin, L. W. Chubb, C. A. Adams and W. B. Kouwenhoven.

A general discussion.

IRON LOSSES IN DIRECT-CURRENT MACHINES

B. G. Lamme **Vol. xxxv—1916, pp. 261-286**

It is shown that no great accuracy is practicable in the calculation of actual iron losses, except in special cases. A brief explanation of several causes of variation in losses is given.

The four principal sources of core loss are considered, namely—armature-ring loss, armature-tooth loss, eddy currents in buried conductors, and pole-face losses. Under eddy current losses an explanation is given of certain losses not usually taken into account with a crude method of calculation and some tabulated results.

Under pole-face losses an empirical formula is given, also tabulated results.

The effect of load on losses is discussed and some of the effects of flux distortion on losses are shown.

Discussion, pages 287-299, by Messrs. H. F. T. Erben, W. S. Moody, W. B. Potter, F. H. Kierstead, H. M. Hobart, W. J. Foster, J. L. Burnham, L. T. Robinson, A. S. Langsdorf and B. G. Lamme.

A general discussion of iron losses in d-c. machines and transformers.

STANDARDIZATION

C. Le Maistre **Vol. xxxv—1916, pp. 489-496**

A general review of development of standardization committees and organizations here and abroad. A citation of the many advantages of proper standardization and an appeal for universal cooperation. Particular reference is given to standardization of electrical machinery with emphasis laid on the adoption of a standard temperature rise basis.

Discussion, pages 497-500, by Messrs. C. H. Sharp, F. Osgood, C. P. Steinmetz, C. Le Maistre and C. A. Adams.

A general discussion.

REPORT OF THE TRANSMISSION COMMITTEE

Percy H. Thomas, Chairman **Vol. xxxv—1916, pp. 555-583**

I. Data from Operating Plants on the Effect of Altitude on the Operating Temperature Rise of Electrical Apparatus.

II. Experience with Grounded Neutral on High-Tension Transmission Lines.

Discussion, pages 584-597, by Messrs. N. A. Carle, M. O. Troy, P. Junkersfeld, E. E. F. Creighton, D. B. Rushmore, J. T. Lawson, J. B. Taylor, P. H. Chase, H. R. Woodrow, E. C. Stone, F. L. Hunt, L. N. Crichton, R. F. Schuchardt, E. T. Street, H. Goodwin, Jr., W. A. Carter and B. Price.

A general discussion of experience with systems, grounded and ungrounded. Very complete description of the Victoria Falls and Transvaal Power Company, Ltd., and the Rand Mines Power Supply Co., Ltd.

EFFECT OF BAROMETRIC PRESSURE ON TEMPERATURE RISE OF SELF-COOLED STATIONARY INDUCTION APPARATUS

V. M. Montsinger **Vol. xxxv-1916, pp. 599-626**

This paper is divided into three parts, as follows; (1) A general review of the principal laws of the dissipation of heat,—radiation, conduction and convection. (2) The development of a simple formula for the effect of altitude on the cooling of surfaces of different shapes. (3) A general discussion of the method of conducting experimental observations at different altitudes on three different shaped surfaces.

Discussion, pages 627-633, by Messrs. R. W. Sorensen, A. Gray and V. M. Montsinger.

A general discussion of methods and results obtained.

MEGGER AND OTHER TESTS ON SUSPENSION INSULATORS

F. L. Hunt **Vol. xxxv—1916, pp. 735-738**

This paper gives the results of megger tests made on disk insulators on a 66,000-volt transmission line in Massachusetts after 2.5 years operation. The percentage of failures in different positions in the string is given on both strain and suspension towers. The actual cost of making these tests under different conditions of weather and of service requirements is given per insulator on the line, per bad insulator and per tower.

Discussion incorporated with that of paper by R. H. Marvin on "A New Method of Grading Suspension Insulators".

EXPERIENCES IN TESTING PORCELAIN

E. E. F. Creighton **Vol. xxxv—1916, pp. 739-744**

The results of numerous experiences in testing porcelain insulators particularly in regard to porosity, absorption of water, surface leakage and dielectric losses. Considerable energy is required to drive moisture out of a porous insulator and it has been found best to restrict the oscillator testing to dry porcelain, whereas the wetter the porcelain the more effective is the 60-cycle test.

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A NEW METHOD OF GRADING SUSPENSION INSULATORS

R. H. Marvin **Vol. xxxv—1916, pp. 745-752**

Attention is drawn to the known disadvantages of the uneven distribution of voltage in long strings of disks. The general theory showing how the distribution is determined by the various capacities of the units is given. It is shown how the distribution can be improved by grading, or varying the internal capacity of the units.

The proposed method of grading consists in placing flat metal rings on the insulator, around cap and stud respectively, the porcelain disk being enlarged for this purpose.

A simple method of measuring the voltage distribution is described using a single needle gap.

The results of tests with and without grading are given, the graded strings showing a decidedly better distribution of voltage.

Discussion, pages 753-755, by Messrs. F. W. Peek, Jr., and E. E. F. Creighton.

A general discussion.

THE CORONA VOLTMETER

J. B. Whitehead and M. W. Pullen **Vol. xxxv—1916, pp. 809-833**

An instrument is described in which the first appearance of corona is used as a measure of the applied voltage. The electroscope, the galvanometer or the telephone are used to determine the first appearance of corona. Tests showing the constancy and permanence of the instrument are described.

Discussion, pages 834-843, by Messrs. L. W. Chubb, C. H. Sharp, J. R. Craighead, C. F. Harding, F. W. Peek, Jr., J. Kunz, J. B. Taylor and J. B. Whitehead.

Arguments for and against the corona voltmeter as compared with other methods of measuring high voltages.

TEMPERATURE RISE OF INSULATED LEAD-COVERED CABLES

Richard C. Powell **Vol. xxxv—1916, pp. 1017-1042**

After a brief historical note, the factors that determine the rate of temperature rise of a cable are considered. The thermal conductivity is expressed in terms of volume thermal conductivity of the insulation, the surface thermal conductivity of the lead sheath, and the dimensions of the cable. A formula is given for calculating increased temperature due to stray currents in the lead sheath. Carrying capacity is also considered from the viewpoint of the thermal properties of the duct line. The overload or intermittent rating is calculated from a given formula. Variable air temperature is discussed. Various formulas given are developed in three appendixes.

Discussion, pages 1043-1050, by Messrs. M. T. Crawford, L. T. Merwin, J. B. Fisken, S. C. Lindsay, C. R. Collins, H. W. Buck, R. Howes, M. E. Cheney and W. A. Del Mar.

A general discussion with special emphasis on the effect on temperature rise of adjacent power lines and crossovers. Experiences of several large power companies.

TESTING FOR DEFECTIVE INSULATORS ON HIGH-TENSION TRANSMISSION LINES

B. G. Flaherty **Vol. xxxv—1916, pp. 1095-1109**

A discussion of the importance and necessity of field tests on high-tension insulators and three methods of making such tests, viz; with the oscillator, the megger, and the telephone receiver. The latter is described in detail and some data given on its development and use on a 60,000-volt-line. Laboratory checks on defective insulators are given. Figures of cost for locating and replacing defective units are given. A method of studying rate of depreciation is outlined.

Discussion, pages 1110-1129, by Messrs. H. J. Ryan, L. T. Merwin, E. A. Loew, J. B. Taylor, C. E. Magnusson, M. T. Crawford, W. D. Peaslee, R. W. Pope, C. P. Osborne, G. Harding, B. G. Flaherty, S. C. Lindsay, J. P. Jollyman, J. Mini, Jr., and E. E. Creighton.

Advantages and disadvantages of various methods of detecting and testing faulty insulators, question of removal, oil impregnation of porous insulators, value of grounded neutral, etc.

THE HIGH-VOLTAGE POTENTIOMETER

Harris J. Ryan **Vol. xxxv—1916, pp. 1131-1136**

Description of a high-voltage potentiometer which may be made at reasonable expense consisting of a water resistance potential distributor and a sparking probe potential difference detector. The results of an integrity trial are charted. The device is intended for investigations in which the results are not required to be known within 2 or 3 per cent of their actual value.

No discussion.

AN ARTIFICIAL TRANSMISSION LINE WITH ADJUSTABLE LINE CONSTANTS

C. Edward Magnusson and S. R. Burbank **Vol. xxxv—1916, pp. 1137-1149**

A description of an artificial transmission line which can be readily adjusted to represent 200 miles (321.86 km.) of commercial transmission lines of any spacing up to a maximum of 120 in. (3 m.) and of any size wire up to 4/0 copper. It can also be made to correspond to aerial or cable telephone lines and to power cables. The use of this line is illustrated by a number of typical experiments.

Discussion, pages 1150-1153, by Messrs. L. J. Corbett, W. D. Peaslee, J. D. Ross, S. R. Burbank, C. A. Whipple and C. E. Magnusson.

A general discussion of the value of artificial transmission lines.

CHARACTERISTICS OF ADMITTANCE TYPE OF WAVE-FORM STANDARD

Frederick Bedell **Vol. xxxv—1916, pp. 1155-1170**

A description of the characteristics of a certain type of standard for determining how near an actual wave is to a true sine wave and for prescribing allowable limits of deviation. An investigation to determine whether a standard can be specified that will be more suitable in its characteristics and more practical in its application.

Discussion, pages 1171-1186, by Messrs. H. S. Osborne, L. F. Curtis, C. E. Magnusson, L. W. Chubb, L. T. Merwin, L. J. Corbett, J. B. Fisken, W. D. Peaslee, H. J. Ryan, R. W. Mastick, F. Bedell and Report by Joint Committee on Inductive Interference.

A discussion of the various factors involved in the selection of a wave-shape standard and the penalizing of upper harmonics. An appeal for cooperation between power companies, telephone companies and manufacturers.

EXPERIMENTS ON PORCELAIN SUSPENSION INSULATOR UNITS

J. Cameron Clark Vol. xxxv-1916, pp. 1453-1486

A very complete description of experiments on porcelain suspension insulator units. Preliminary organization, scope of tests, unusual equipment required to measure very high resistance of sound dry insulators. Results tabulated when insulators were subjected to mechanical stress, voltages of 1,000 to 30,000, to temperature variation, also effect of moisture. Description of attempted methods of water-logging insulators.

No discussion.

TEMPERATURE DISTRIBUTIONS IN ELECTRICAL MACHINERY

B. G. Lamme Vol. xxxv—1916, pp. 1471-1488

The fundamental principles governing heat distribution and temperature in electrical apparatus. Heat generation, heat flow and heat dissipation and resultant temperature are discussed. Paths of heat flow and effects of heat resistance of such paths discussed. The effects of rapid head flow on equalization of temperatures and on their measurement. Fallacies in temperature guarantees and indications pointed out. Some of more common errors in methods of measurement described.

Discussion incorporated with that of paper by F. D. Newbury on "Rational Temperature Guarantees for Large A-C. Generators.

RATIONAL TEMPERATURE GUARANTEES FOR LARGE A.C. GENERATORS

F. D. Newbury Vol. xxxv—1916, pp. 1489-1502

An argument for the standardization of temperature guarantees when based on internal temperatures as measured by thermocouples. It is recommended that in all cases the maximum safe operating temperature of the insulation be used as temperature guarantee instead of a lower temperature. Arguments are presented from the stand-point of both operating and designing engineers. Curves are shown illustrating temperature conditions in stator and rotor of a large high-voltage turbo-generator. Examples are given showing that a low temperature rise guarantee for the stator does not necessarily result in overload margin. To be certain of overload margin specifications must call for maximum rating desired.

Discussion, pages 1503-1522, by Messrs. A. Gray, W. J. Foster, C. J. Fechheimer, V. M. Montsinger, P. Junkersfeld, P. M. Lincoln, W. C. Bauer, N. J. Conrad, C. A. Keller, M. M. Flower, B. G. Lamme, and F. D. Newbury.

A general discussion.

4. INSULATION AND DIELECTRIC PHENOMENA

STUDIES IN LIGHTNING PROTECTION ON 4000-VOLT CIRCUITS

D. W. Roper Vol. xxxv—1916, pp. 655-694

Investigations over a five-year period on a distributing system covering about 180 square miles of the city of Chicago, supplying about 250,000 customers through about 16,000 transformers. A number of theories were tried out in practise and results are given in detail. The conditions during the year 1915 and records obtained from lightning storms during the year are set forth by means of maps, drawings and tables. An analysis of results is followed by a list of conclusions.

Discussion incorporated with that of paper by O. O. Rider on "Protection of High-Voltage Distribution Systems by Isolating Transformers".

MEGGER AND OTHER TESTS ON SUSPENSION INSULATORS

F. L. Hunt **Vol. xxxv—1916, pp. 725-728**

This paper gives the results of megger tests made on disk insulators on a 66,000-volt transmission line in Massachusetts after 2.5 years operation. The percentage of failures in different positions in the string is given on both strain and suspension towers. The actual cost of making these tests under different conditions of weather and of service requirements is given per insulator on the line, per bad insulator and per tower.

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Discussion, pages 753-755, by Messrs. F. W. Peek, Jr., and E. E. F. Creighton.

A general discussion.

THE EFFECT OF HIGH CONTINUOUS VOLTAGES ON AIR, OIL AND SOLID INSULATIONS

F. W. Peek, Jr. **Vol. xxxv—1916, pp. 783-800**

This paper gives the results of experiments on the dielectric strength of air, oil and solid insulations determined for d-c. voltages up to 150 kv.

and compared with a-c. results. Visual corona voltage and variation of voltage with air density. Spark-over voltages in air and oil. D-c. breakdown voltages of solid insulations as compared with a-c. High-voltage direct current in cable testing.

Discussion, pages 801-808, by Messrs. J. B. Whitehead, W. Baum, S. Farwell, C. E. Skinner, C. L. Dawes, C. H. Sharp, J. B. Taylor, F. W. Peek, Jr., and L. T. Robinson.

A general discussion with amplification of certain features such as spark-over between concentric cylinders, the Thury high-tension d-c. system, etc.

TESTING FOR DEFECTIVE INSULATORS ON HIGH-TENSION TRANSMISSION LINES

B. G. Flaherty **Vol. xxxv—1916, pp. 1095-1109**

A discussion of the importance and necessity of field tests on high-tension insulators and three methods of making such tests, viz.: with the oscillator, the megger, and the telephone receiver. The latter is described in detail and some data given on its development and use on a 60,000-volt-line. Laboratory checks on defective insulators are given. Figures of cost for locating and replacing defective units are given. A method of studying rate of depreciation is outlined.

Discussion, pages 1110-1129, by Messrs. H. J. Ryan, L. T. Merwin, E. A. Loew, J. B. Taylor, C. E. Magnusson, M. T. Crawford, W. D. Peaslee, R. W. Pope, C. P. Osborne, G. Harding, B. G. Flaherty, S. C. Lindsay, J. P. Jollyman, J. Mini, Jr., and E. E. Creighton.

Advantages and disadvantages of various methods of detecting and testing faulty insulators, question of removal, oil impregnation of porous insulators, value of grounded neutral, etc.

INSULATOR FAILURES UNDER TRANSIENT VOLTAGES

W. D. Peaslee **Vol. xxxv—1916, pp. 1187-1194**

This paper presents the results of recent investigations on the failure of insulators under impact and combined impact and normal frequency voltages. Microphotographs are included. The breakdown of a dielectric involves energy which is a time function, and the importance of the duration of the stress in determining the magnitude of the voltage necessary to puncture an insulator are discussed. The importance of the elimination of air holes and defects in porcelain is shown. Some essential features of a successful line insulator are stated.

Discussion, pages 1195-1205, by Messrs. J. B. Fisken, W. D. Peaslee, R. Howes, L. T. Merwin, H. J. Ryan, R. W. Mastick, R. M. Boykin, A. A. Miller and E. E. F. Creighton.

A general discussion including experiences of certain power transmission lines.

CERAMICS IN RELATION TO THE DURABILITY OF PORCELAIN SUSPENSION INSULATORS

Harris J. Ryan **Vol. xxxv—1916, pp. 1437—1462**

The fundamental requirements in satisfactory high-voltage line insulators are summarized and particular emphasis is placed upon the need for coordinated study of service durability. The effect of porosity upon durability is explained in detail and an appeal made for the establishment of a practical porosity elimination test.

The manufacture and structure of electrical porcelain is studied from the viewpoint of the ceramist, with many quotations and illustrations taken from the Transactions of the American Ceramic Society.

The author briefly states the conclusions at which he has arrived and gives a very complete list of references and notes.

No discussion.

EXPERIMENTS ON PORCELAIN SUSPENSION INSULATOR UNITS

J. Cameron Clark **Vol. xxxv—1916, pp. 1453-1466**

A very complete description of experiments on porcelain suspension insulator units. Preliminary organization, scope of tests, unusual equipment required to measure very high resistance of sound dry insulators. Results tabulated when insulators were subjected to mechanical stress, voltages of 1,000 to 30,000, to temperature variation, also effect of moisture. Description of attempted methods of water-logging insulators.

No discussion.

INVESTIGATION OF SUSPENSION INSULATOR DETERIORATION

J. E. Woodbridge **Vol. xxxv—1916, pp. 1467-1470**

This paper gives an outline of an investigation of suspension insulator deterioration. It cites the origin of the investigation, the limiting factors encountered and methods employed to overcome them.

No discussion.

5. ELECTRIC CONDUCTORS

OUTLINE OF THEORY OF IMPULSE CURRENTS

C. P. Steinmetz **Vol. xxxv—1916, pp. 1-20**

In Part I it is shown how, from the integral of the general differential equation of the electric circuit, which has been discussed in a previous paper, all types of electric currents are derived as special cases, corresponding to particular values of the integration constants.

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A few special cases are discussed.

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A discussion of the advantages of the synthetic and analytic methods of studying engineering phenomena. A development of the special cases under impulse currents of the circuit having capacity in series.

TEMPERATURE RISE OF INSULATED LEAD-COVERED CABLES

Richard C. Powell **Vol. xxxv—1916, pp. 1017-1042**

After a brief historical note, the factors that determine the rate of temperature rise of a cable are considered. The thermal conductivity is expressed in terms of volume thermal conductivity of the insulation, the surface thermal conductivity of the lead sheath, and the dimensions of the cable. A formula is given for calculating increased temperature due to stray currents in the lead sheath. Carrying capacity is also considered from the viewpoint of the thermal properties of the duct line. The overload or intermittent rating is calculated from a given formula. Variable air temperature is discussed. Various formulas given are developed in three appendixes.

Discussion, pages 1043-1050, by Messrs. M. T. Crawford, L. T. Merwin, J. B. Fisken, S. C. Lindsay, C. R. Collins, H. W. Buck, R. Howes, M. E. Cheney and W. A. Del Mar.

A general discussion with special emphasis on the effect on temperature rise of adjacent power lines and crossovers. Experiences of several large power companies.

STEEL CONDUCTORS FOR TRANSMISSION LINES

H. B. Dwight **Vol. xxxv—1916, pp. 1237-1250**

This paper states that steel cables will not generally be economical on main transmission lines, except for long spans, and for high altitudes where corona is excessive. They may be advisable as bare conductors for d-c. railway feeders. They deteriorate more rapidly than copper conductors and have very low scrap value. Steel cables for alternating current should be finely stranded and different groups of wire should be spiraled in opposite directions. Medium grades of steel give better results with alternating currents than high priced grades. There is an opening for the profitable use of steel cables on branch lines of power systems of all voltages.

Discussion, pages 1251-1258, by Messrs. R. E. Doane, T. H. Worcester, D. B. Rushmore, S. C. Coey, W. T. Snyder and H. B. Dwight.

A general discussion.

6. MAGNETIC PROPERTIES AND TESTING OF IRON

IRON LOSSES IN DIRECT-CURRENT MACHINES

B. G. Lamme **Vol. xxxv—1916, pp. 261-286**

It is shown that no great accuracy is practicable in the calculation of actual iron losses, except in special cases. A brief explanation of several causes of variation in losses is given.

The four principal sources of core loss are considered, namely—armature-ring loss, armature-tooth loss, eddy currents in buried conductors, and pole-face losses. Under eddy current losses an explanation is given of certain losses not usually taken into account, with a crude method of calculation and some tabulated results.

Under pole-face losses an empirical formula is given, also tabulated results.

The effect of load on losses is discussed and some of the effects of flux distortion on losses are shown.

Dis ussion, pages 287-299, by Messrs. H. F. T. Erben, W. S. Moody, W. B. Potter, F. H. Kierstead, H. M. Hobart, W. J. Foster, J. L. Burnham, L. T. Robinson, A. S. Langsdorf and B. G. Lamme.

A general discussion of iron losses in d-c. machines and transformers.

8. TRANSFORMERS

THE VOLTMETER COIL IN TESTING TRANSFORMERS

A. B. Hendricks, Jr. **Vol. xxxv—1916, p. 117**

The advantages of the voltmeter coil in the determination of the high-tension voltage in testing transformers.

Discussion incorporated with that of paper by W. R. Work on "Notes on the Measurement of High Voltage."

EFFECT OF BAROMETRIC PRESSURE ON TEMPERATURE RISE OF SELF-COOLED STATIONARY INDUCTION APPARATUS

V. M. Montsinger **Vol. xxxv—1916, pp. 599-626**

This paper is divided into three parts, as follows: (1) A general review of the principal laws of the dissipation of heat, radiation, conduction and convection. (2) The development of a simple formula for the effect of altitude on the cooling of surfaces of different shapes. (3) A general discussion of the method of conducting experimental observations at different altitudes on three different shaped surfaces.

Discussion, pages 627-633, by Messrs. R. W. Sorensen, A. Gray and V. M. Montsinger.

A general discussion of methods and results obtained.

PROTECTION OF HIGH-VOLTAGE DISTRIBUTION SYSTEMS BY ISOLATING TRANSFORMERS

O. O. Rider **Vol. xxxv—1916, pp. 717-719**

This paper calls attention to the practicability of localizing line disturbances by means of transformers. Application is made to high-voltage distribution systems serving the rural communities which results in an interconnected net work of overhead lines.

Discussion, pages 720-734, by Messrs. E. E. F. Creighton, C. P. Steinmetz, P. H. Chase, J. T. Lawson, J. B. Taylor, J. O. Montignani, R. F. Schuchardt, P. Junkersfeld, D. B. Rushmore, D. W. Roper, N. S. Diamant, H. Mouradian and N. L. Pollard.

A general discussion with particular reference to the split-conductor principle and its relation to ideal relay protection.

9. ELECTRICAL MACHINERY AND APPARATUS

THE LIQUID RHEOSTAT IN LOCOMOTIVE SERVICE

A. J. Hall **Vol. xxxv—1916, pp. 167-171**

A description of the liquid rheostat in locomotive service giving in detail the arrangement of the mechanical parts and means of controlling it.

Discussion, pages 172-173, by Messrs. C. D. Knight and R. E. Hellmund.

A discussion mainly of the liquid rheostat used in mine-hoist service.

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B. G. Lamme **Vol. xxxv—1916, pp. 261-286**

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A general discussion of iron losses in d-c. machines and transformers.

ELECTRIC DRIVE FOR REVERSING ROLLING MILLS

Wilfred Sykes and David Hall **Vol. xxxv—1916, pp. 501-519**

This paper answers some of the questions which have arisen in the rapid displacement of steam drive by electric drive for reversing rolling mills, and describes the constructions which have been found desirable.

Discussion, pages 520-537, by Messrs. K. A. Pauly, E. S. Jeffries, D. M. Petty, R. Tschentscher, H. D. James, F. G. Liljenroth, B. Wiley, H. S. Page, P. Lindemann, A. Gray and W. Sykes.

A discussion of the relative merit of steam and electric drive for reversing mills. Statistics of installation at Steel Company of Canada. Comparison of European and American practise.

MOTOR EQUIPMENTS FOR THE RECOVERY OF PETROLEUM

W. G. Taylor **Vol. xxxv—1916, pp. 539-552**

This paper presents data covering the horse power requirements and kilowatt-hour consumption for the various operations in drilling and maintaining producing oil wells. The use of the slip-ring induction motor for drilling, pumping and cleaning wells. Special controllers and resistance. Pumping, cleaning and "pulling" rods by a Y-delta or two speed machine.

Discussion, pages 553-554, by Messrs. F. Woodbury and A. M. Dudley. General discussion.

EXPERIENCE AND RECENT DEVELOPMENTS IN CENTRAL STATION PROTECTION FEATURES

N. L. Pollard and J. T. Lawson **Vol. xxxv—1916, pp. 695-715**

The protective features described in this paper are some of those now in use on the system of the Public Service Electric Company, which serves a population of about 2,200,000.

The protective devices and schemes discussed are, as follows: Aluminum cell arresters; arcing ground suppressor; faulty cable localizer; cable testing; high-potential and high-frequency testing; generator bus connection scheme; exciter connection scheme; reactors; relays; multi-recorders; insulation resistance recorder; air washers; resistance bulbs and thermocouples; dampers on air-blast transformers; coherer alarm devices; potential indicating devices.

Discussion incorporated with that of paper by O. O. Rider on "Protection of High-Voltage Distribution Systems by Isolating Transformers."

ELECTRICAL MACHINERY TESTS AND SPECIFICATIONS BASED ON MODERN STANDARDS

H. M. Hobart **Vol. xxxv—1916, pp. 1259-1287**

Comparisons are made of the standardization rules for electrical machinery now in force in various countries showing that machinery built in conformance with the American rules will usually also conform with rules employed in other countries. Suggestion is made that 55 degrees could be employed as the ambient temperature of reference for tropical ratings. Attention is called to a series of acceptance tests on some large waterwheel generators and to the temperature results obtained by making cyclic heat runs on these machines.

No discussion.

TEMPERATURE DISTRIBUTIONS IN ELECTRICAL MACHINERY

B. G. Lamme **Vol. xxxv—1916, pp. 1471-1488**

The fundamental principles governing heat distribution and temperature in electrical apparatus. Heat generation, heat flow and heat dissipation and resultant temperature are discussed. Paths of heat flow and effects of heat resistance of such paths discussed. The effects of rapid heat flow on equalization of temperatures and on their measurement. Fallacies in temperature guarantees and indications pointed out. Some of more common errors in methods of measurement described.

Discussion incorporated with that of paper by F. D. Newbury on "Rational Temperature Guarantees for Large A-C. Generators.

RATIONAL TEMPERATURE GUARANTEES FOR LARGE A-C. GENERATORS

F. D. Newbury **Vol. xxxv—1916, pp. 1489-1502**

An argument for the standardization of temperature guarantees when based on internal temperatures as measured by thermocouples. It is recommended that in all cases the maximum safe operating temperature of the insulation be used as temperature guarantee instead of a lower temperature. Arguments are presented from the standpoint of both operating and designing engineers. Curves are shown illustrating temperature conditions in stator and rotor of a large high-voltage turbo-generator. Examples are given showing that a low temperature rise guarantee for the stator does not necessarily result in overload margin. To be certain of overload margin, specifications must call for maximum rating desired.

Discussion, pages 1503-1522, by Messrs. A. Gray, W. J. Foster, C. J. Fechheimer, V. M. Montsinger, P. Junkersfeld, P. M. Lincoln, W. C. Bauer, N. J. Conrad, C. A. Keller, M. M. Flower, B. G. Lamme and F. D. Newbury.

A general discussion.

RUPTURING CAPACITIES OF OIL CIRCUIT BREAKERS

Stephen Q. Hayes **Vol. xxxv—1916, pp. 1523-1580**

A series of notes on the rupturing capacity of oil breakers. Description of result obtained by root-mean-square of maximum peak of current wave that occurs while breaker is opening multiplied by root-mean-square of open-circuit voltage that occurs immediately after breaker opens. Attention called to different classes of ratings. Recommendations made as to most desirable method of rating and ability of breakers to be re-operative.

Discussion incorporated with that of paper by E. M. Hewlett on "Rating of Oil Circuit Breakers".

RATING OF OIL CIRCUIT BREAKERS

E. M. Hewlett — **Vol. xxxv—1916, pp. 1531-1533**

Paper points out several difficulties which are encountered in rating of actual circuit breakers, but generally favors that these ratings be on the basis of the current to be opened in the arc at the operating voltage of the system.

Discussion, pages 1534-1549, by Messrs. C. Lichtenberg, N. L. Pollard, G. A. Burnham, J. L. Harper, H. W. Buck, J. B. Taylor, K. C. Randall, L. E. Imlay, C. A. Adams, E. M. Hewlett, S. Q. Hayes, H. R. Summerhayes, P. M. Lincoln, L. W. Chubb and P. Lindemann.

A general discussion.

11. POWER PLANTS AND CENTRAL STATIONS

THE MUNICIPALLY-OPERATED ELECTRICAL UTILITIES OF WESTERN CANADA

A. G. Christie — **Vol. xxxv—1916, pp. 33-87**

The paper discusses a number of public utilities in various cities in Western Canada. The characteristics of these cities are reviewed and a brief outline of equipments of the various plants is given. The costs and methods of financing these utilities are discussed at considerable length and the charges for various services are summarized.

Discussion, pages 88-98, by Messrs. P. Betts, H. G. Stott, R. P. Bolton, E. J. Cheney, C. H. Sharp, A. Reid and A. G. Christie.

A general discussion of the advantages and disadvantages of municipal ownership of public utilities and methods of financing them.

THE POWER COMPANY'S PROBLEM IN THE ELECTRIC SUPPLY FOR LARGE SINGLE-PHASE LOAD

W. C. L. Eglin — **Vol. xxxv—1916, pp. 1289-1292**

A power company must be able to supply energy of uniform pressure, single-phase, two-phase or three-phase, at whatever voltage best suits customer. These conditions best met by polyphase units. When demand for single-phase current is heavy enough to produce unbalance, some means of balancing must be provided. Three methods are discussed. Correction for power factor on each individual large consumer's line is suggested.

Discussion incorporated with that of paper by Philip Torchio on "Supply of Single-Phase Loads from Central Stations".

SUPPLY OF SINGLE-PHASE LOADS FROM CENTRAL STATIONS

Philip Torchio — **Vol. xxxv—1916, pp. 1293-1301**

American central stations have extensively adopted single-phase distribution from polyphase stations. Individual regulators employed.

Generators with good single-phase characteristics or in certain cases generators with kilovolt ampere rating in excess of kilowatt capacity of steam unit are employed. Customers assist balancing by dividing load between phases. Question of power supply to N. Y., N. H. & H. RR. discussed. Equipment described.

Discussion, including that of paper by W. C. L. Eglin, pages 1302-1313. by Messrs. W. S. Murray, P. Junkersfeld, D. B. Rushmore, L. E. Imlay, H. R. Summerhayes, N. W. Storer, E. H. Martindale, E. F. W. Alexanderson, J. L. Harper, H. W. Buck, J. E. Kershner, C. F. Scott, W. C. L. Eglin, P. Torchio, F. Osgood and C. F. Harding.

General discussion.

SINGLE-PHASE POWER PRODUCTION

E. F. W. Alexanderson and G. H. Hill **Vol. xxxv—1916, pp. 1315-1327**

The general tendency of electric power supply is toward centralization of stations and to be consistent stations must be standardized. From this standpoint single-phase power can best be supplied from polyphase systems. Operation and theory of phase converters discussed.

Discussion incorporated with that of paper by Gilman and Fortescue on "Single-Phase Power Service from Central Stations".

SINGLE-PHASE POWER SERVICE FROM CENTRAL STATIONS

R. E. Gilman and C. L. Fortescue **Vol. xxxv—1916, pp. 1329-1347**

An outline of several methods by which single-phase power may be supplied from a polyphase system with advantages and disadvantages. Unbalance in voltage when single-phase power is supplied direct from polyphase circuit explained. Law of distribution of load in polyphase system deduced. Outline of theory of single-phase generator given. Essential requirements for phase balancing, requirements for control apparatus, behavior of balancer under short circuit.

Discussion, (including that of paper by Alexanderson and Hill), pages 1348-1368, by Messrs. R. E. Doherty, H. G. Reist, H. L. Wallau, H. R. Summerhayes, R. E. Gilman, W. C. L. Eglin, B. A. Behrend, C. A. Adams, D. W. Roper, G. H. Hill, P. Torchio, P. Junkersfeld, C. F. Scott, H. C. Albright, E. F. W. Alexanderson, and C. L. Fortescue.

A general discussion of the advantages of various methods of single-phase generation and operation with some facts relative to comparative costs.

12. PARALLEL OPERATION

ELECTRICAL MACHINERY TESTS AND SPECIFICATIONS BASED ON MODERN STANDARDS

H. M. Hobart **Vol. xxxv—1916, pp. 1269-1287**

Comparisons are made of the standardization rules for electrical machinery now in force in various countries showing that machinery built in conformance with the American rules will usually also conform with rules employed in other countries. Suggestion is made that 55 degrees could be employed as the ambient temperature of reference for tropical ratings. Attention is called to a series of acceptance tests on some large waterwheel generators and to the temperature results obtained by making cyclic heat runs on these machines.

No discussion.

13. TRANSMISSION LINES

OUTLINE OF THEORY OF IMPULSE CURRENTS

C. P. Steinmetz **Vol. xxxv—1916, pp. 1-20**

In Part I it is shown how, from the integral of the general differential equation of the electric circuit, which has been discussed in a previous paper, all types of electric currents are derived as special cases, corresponding to particular values of the integration constants.

In Part II an outline of the theory of impulse currents is given. They comprise two classes, the non-periodic and the periodic. The equations of both are given in different form, by exponential and by hyperbolic or trigonometric functions.

A few special cases are discussed.

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A discussion of the advantages of the synthetic and analytic methods of studying engineering phenomena. A development of the special cases under impulse currents of the circuit having capacity in series.

REPORT OF THE TRANSMISSION COMMITTEE

Percy H. Thomas, Chairman **Vol. xxxv—1916, pp. 555-583**

I. Data from Operating Plants on the Effect of Altitude on the Operating Temperature Rise of Electrical Apparatus.

II. Experience with Grounded Neutral on High-Tension Transmission Lines.

Discussion, pages 584-597, by Messrs. N. A. Carle, M. O. Troy, P. Junkersfeld, E. E. F. Creighton, D. B. Rushmore, J. T. Lawson, J. B. Taylor, P. H. Chase, H. R. Woodrow, E. C. Stone, F. L. Hunt, L. N. Crichton, R. F. Schuchardt, E. T. Street, H. Goodwin, Jr., W. A. Carter and B. Price.

A general discussion of experience with systems, grounded and ungrounded. Very complete description of the Victoria Falls and Transvaal Power Company, Ltd., and the Rand Mines Power Supply Co., Ltd.

THE RESTORATION OF SERVICE AFTER A NECESSARY INTERRUPTION

F. E. Ricketts **Vol. xxxv—1916, pp. 635-648**

The phenomenal growth during the last few years in the electrical industry has been due as much to the marked advances in the methods of maintaining a uniform service as to any other cause. Attention is called to that class of interruptions which so far have been and will likely continue to be unavoidable and a full description is given of certain means whereby the effect of unavoidable interruptions may be reduced to a minimum.

Discussion, pages 649-654, by Messrs. H. Goodwin, Jr., R. F. Schuchardt, H. R. Woodrow, E. T. Street, G. A. Burnham, J. B. Taylor, L. N. Crichton and J. T. Kelly, Jr.

A general discussion of protective features in use on various systems.

MEGGER AND OTHER TESTS ON SUSPENSION INSULATORS
F. L. Hunt **Vol. xxxv—1916, pp. 735-738**

This paper gives the results of megger tests made on disk insulators on a 66,000-volt transmission line in Massachusetts after 2.5 years operation. The percentage of failures in different positions in the string is given on both strain and suspension towers. The actual cost of making these tests under different conditions of weather and of service requirements is given per insulator on the line, per bad insulator and per tower.

Discussion incorporated with that of paper by R. H. Marvin, on "A New Method of Grading Suspension Insulators".

THEORY OF PARALLEL GROUNDED WIRES AND PRODUCTION OF HIGH FREQUENCIES IN TRANSMISSION LINES
E. E. F. Creighton **Vol. xxxv—1916, pp. 845-888**

An investigation of the value of the overhead grounded wire as used for lightning protection, mechanical support for towers, and a test circuit. The functions of the grounded wire are subdivided into four categories; first, the vertical grounded wire; second, the lightning rod extending above the ground; third, the electrostatic induction in the horizontally situated wires; and fourth, electromagnetic induction. The several factors determining the protective value of a ground wire are fully investigated. Equations expressing the protection of various arrangements of vertical and parallel grounded wires are developed.

Discussion, pages 889-893, by Messrs. H. S. Osborne, N. S. Diamant, J. B. Taylor, J. B. Whitehead, L. W. Chubb and E. E. F. Creighton.

A general discussion.

TESTING FOR DEFECTIVE INSULATORS ON HIGH-TENSION TRANSMISSION LINES
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Advantages and disadvantages of various methods of detecting and testing faulty insulators, question of removal, oil impregnation of porous insulators, value of grounded neutral, etc.

AN ARTIFICIAL TRANSMISSION LINE WITH ADJUSTABLE LINE CONSTANTS
C. Edward Magnusson and S. R. Burbank **Vol. xxxv—1916, pp. 1137-1149**

A description of an artificial transmission line which can be readily adjusted to represent 200 miles (321.86 km.) of commerical transmission lines of any spacing up to a maximum of 120 in. (3 m.) and of any size wire up to 4/0 copper. It can also be made to correspond to aerial or cable telephone lines and to power cables. The use of this line is illustrated by a number of typical experiments.

Discussion, pages 1150-1153, by Messrs. L. J. Corbett, W. D. Peaslee, J. D. Ross, S. R. Burbank, C. A. Whipple and C. E. Magnusson.

A general discussion of the value of artificial transmission lines.

STEEL CONDUCTORS FOR TRANSMISSION LINES

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CREST VOLTMETERS

C. H. Sharp and E. D. Doyle **Vol. xxxv—1916, pp. 99-107**

The paper shows how a voltmeter which will read directly the maximum or crest values obtained in high-voltage testing may be constituted by a combination of an electrostatic voltmeter and an electric valve. Diagrams of connection are shown and results of test given to indicate the validity of the method.

Discussion incorporated with that of paper by W. R. Work on "Notes on the Measurement of High Voltage."

THE VOLTMETER COIL IN TESTING TRANSFORMERS

A. B. Hendricks, Jr. **Vol. xxxv—1916, p. 117**

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THE CREST VOLMETER

L. W. Chubb **Vol. xxxv—1916, pp. 109-116**

This paper mentions and compares some of the methods of high-voltage measurement and describes in more detail the crest voltmeter with its construction, operation, accuracy and application. The summary states that spark gaps should be only a calibrating standard and a more practical instrument, such as described, the preferred working standard.

Discussion incorporated with that of paper by W. R. Work on "Notes on the Measurement of High Voltage."

NOTES ON THE MEASUREMENT OF HIGH VOLTAGE

W. R. Work **Vol. xxxv—1916, pp. 119-126**

A brief account of some of the experiments made to determine the relative accuracy of certain methods used in measuring high voltage. The methods comprise the use of a tertiary (or voltmeter) coil in the high-tension transformer, the crest voltmeter and the derivation of the high-tension pressure from the primary voltage.

Discussion (including that of papers by Sharp and Doyle, L. W. Chubb and A. B. Hendricks), pages 127-146, by Messrs. E. E. F. Creighton, F.W. Peek, Jr., F. M. Farmer, F. Bedell, C. A. Adams, W. I. Middleton, J. R. Craighead, C. L. Dawes, J. B. Whitehead, L. W. Chubb, C. H. Sharp, C. F. Harding, W. D. Peaslee, M. G. Newman and A. B. Hendricks, Jr.

A general discussion with particular reference to the oscillograph and visual corona methods of measuring crest voltage.

REPORT OF THE TRANSMISSION COMMITTEE

Percy H. Thomas, Chairman **Vol. xxxv—1916, pp. 565-583**

I. Data from Operating Plants on the Effect of Altitude on the Operating Temperature Rise of Electrical Apparatus.

II. Experience with Grounded Neutral on High-Tension Transmission Lines.

Discussion, pages 584-597, by Messrs. N. A. Carle, M. O. Troy, P. Junkersfeld, E. E. F. Creighton, D. B. Rushmore, J. T. Lawson, J. B. Taylor, P. H. Chase, H. R. Woodrow, E. C. Stone, F. L. Hunt, L. N. Crichton, R. F. Schuchardt, E. T. Street, H. Goodwin, Jr., W. A. Carter and B. Price.

A general discussion of experience with systems, grounded and ungrounded. Very complete description of the Victoria Falls and Transvaal Power Company, Ltd., and the Rand Mines Power Supply Co., Ltd.

THE RESTORATION OF SERVICE AFTER A NECESSARY INTERRUPTION
F. E. Ricketts **Vol. xxxv—1916, pp. 635-648**

The phenomenal growth during the last few years in the electrical industry has been due as much to the marked advances in the methods of maintaining a uniform service as to any other cause. Attention is called to that class of interruptions which so far have been and will likely continue to be unavoidable and a full description is given of certain means whereby the effect of unavoidable interruptions may be reduced to a minimum.

Discussion, pages 649-654, by Messrs. H. Goodwin, Jr., R. F. Schuchardt, H. R. Woodrow, E. T. Street, G. A. Burnham, J. B. Taylor, L. N. Crichton and J. T. Kelly, Jr.

A general discussion of protective features in use on various systems.

STUDIES IN LIGHTNING PROTECTION ON 4000-VOLT CIRCUITS
D. W. Roper **Vol. xxxv—1916, pp. 655-694**

Investigations over a five year period on a distributing system covering about 180 square miles of the city of Chicago, supplying about 250,000 customers through about 16,000 transformers. A number of theories were tried out in practise and results are given in detail. The conditions during the year 1915 and records obtained from lightning storms during the year are set forth by means of maps, drawings and tables. An analysis of results is followed by a list of conclusions.

Discussion, incorporated with that of paper by O. O. Rider on "Protection of High-Voltage Distribution Systems by Isolating Transformers."

EXPERIENCE AND RECENT DEVELOPMENTS IN CENTRAL STATIONS PROTECTION FEATURES
N. L. Pollard and J. T. Lawson **Vol. xxxv—1916, pp. 695-715**

The protective features described in this paper are some of those now in use on the system of the Public Service Electric Company, which serves a population of about 2,200,000.

The protective devices and schemes discussed are, as follows: Aluminum cell arresters; arcing ground suppressor; faulty cable localizer; cable testing; high-potential and high-frequency testing; generator bus connection scheme; exciter connection scheme; reactors; relays; multi-recorders; insulation resistance recorder; air washers; resistance bulbs and thermocouples; dampers on air-blast transformers; coherer alarm devices; potential indicating devices.

Discussion incorporated with that of paper by O. O. Rider on "Protection of High-Voltage Distribution Systems by Isolating Transformers."

PROTECTION OF HIGH-VOLTAGE DISTRIBUTION SYSTEMS BY ISOLATING TRANSFORMERS
O. O. Rider **Vol. xxxv—1916, pp. 717-719**

This paper calls attention to the practicability of localizing line disturbances by means of transformers. Application is made to high-voltage distribution systems serving the rural communities which results in an interconnected net work of overhead lines.

Discussion, pages 720-734, by Messrs. E. E. F. Creighton, C. P. Steinmetz, P. H. Chase, J. T. Lawson, J. B. Taylor, J. O. Montignani, R. F. Schuchardt, P. Junkersfeld, D. B. Rushmore, D. W. Roper, N. S. Diamant, H. Mouradian and N. L. Pollard.

A general discussion with particular reference to the split-conductor principle and its relation to ideal relay protection.

MEGGER AND OTHER TESTS ON SUSPENSION INSULATORS

F. L. Hunt **Vol. xxxv—1916, pp. 735-738**

This paper gives the results of megger tests made on disk insulators on a 66,000-volt transmission line in Massachusetts after 2.5 years operation. The percentage of failures in different positions in the string is given on both strain and suspension towers. The actual cost of making these tests under different conditions of weather and of service requirements is given per insulator on the line, per bad insulator and per tower.

Discussion incorporated with that of paper by R. H. Marvin on "A New Method of Grading Suspension Insulators."

THEORY OF PARALLEL GROUNDED WIRES AND PRODUCTION OF HIGH FREQUENCIES IN TRANSMISSION LINES

E. E. F. Creighton **Vol. xxxv—1916, pp. 845-888**

An investigation of the value of the overhead grounded wire as used for lightning protection, mechanical support for towers, and a test circuit. The functions of the grounded wire are subdivided into four categories: first, the vertical grounded wire; second, the lightning rod extending above the ground; third, the electrostatic induction in the horizontally situated wires; and fourth, electromagnetic induction. The several factors determining the protective value of a ground wire are fully investigated. Equations expressing the protection of various arrangements of vertical and parallel grounded wires are developed.

Discussion, pages 889-893, by Messrs. H. S. Osborne, N. S. Diamant, J. B. Taylor, J. B. Whitehead, L. W. Chubb and E. E. F. Creighton.

A general discussion.

INDUCTIVE INTERFERENCE AS A PRACTICAL PROBLEM

A. H. Griswold and R. W. Mastick **Vol. xxxv—1916, pp. 1061-1087**

A review of the factors which affect inductive interference in telephone circuits from high-voltage power transmission circuits, a presentation of practical considerations regarding the reduction of interference, and description of actual cases of the application of these means of reduction. Balanced and residual voltages and currents, wave shapes of voltages and currents, transposition schemes, three particular cases of parallels.

Discussion, pages 1088-1094, by Messrs. F. Bedell, L. T. Merwin, J. B. Fisken, W. D. Peaslee, R. F. Robinson, L. J. Corbett, C. A. Whipple and R. W. Mastick.

A discussion of effects of leaking insulators, charging electrolytic arresters, carelessness in making transpositions and an appeal for cooperation of telephone and power companies.

TESTING FOR DEFECTIVE INSULATORS ON HIGH-TENSION TRANSMISSION LINES

B. G. Flaherty **Vol. xxxv—1916, pp. 1095-1109**

A discussion of the importance and necessity of field tests on high-tension insulators and three methods of making such tests, viz; with the oscillator, the megger, and the telephone receiver. The latter is described in detail and some data given on its development and use on a 60,000-volt line. Laboratory checks on defective insulators are given. Figures of cost for locating and replacing defective units are given. A method of studying rate of depreciation is outlined.

Discussion, pages 1110-1129, by Messrs. H. J. Ryan, L. T. Merwin, E. A. Loew, J. B. Taylor, C. E. Magnusson, M. T. Crawford, W. D. Peaslee, R. W. Pope, C. P. Osborne, G. Harding, B. G. Flaherty, S. C. Lindsay, J. P. Jollyman, J. Mini, Jr. and E. E. Creighton.

Advantages and disadvantages of various methods of detecting and testing faulty insulators, question of removal, oil impregnation of porous insulators, value of grounded neutral, etc.

THE HIGH-VOLTAGE POTENTIOMETER

Harris J. Ryan **Vol. xxxv—1916, pp. 1131-1136**

Description of a high-voltage potentiometer which may be made at reasonable expense consisting of a water resistance potential distributor and a sparking probe potential difference detector. The results of an integrity trial are charted. The device is intended for investigations in which the results are not required to be known within 2 or 3 per cent of their actual value.

No discussion.

CHARACTERISTICS OF ADMITTANCE TYPE OF WAVE-FORM STANDARD

Frederick Bedell **Vol. xxxv—1916, pp. 1155-1170**

A description of the characteristics of a certain type of standard for determining how near an actual wave is to a true sine wave and for prescribing allowable limits of deviation. An investigation to determine whether a standard can be specified that will be more suitable in its characteristics and more practical in its application.

Discussion, pages 1171-1186, by Messrs. H. S. Osborne, L. F. Curtis, C. E. Magnusson, L. W. Chubb, L. T. Merwin, L. J. Corbett, J. B. Fisken, W. D. Peaslee, H. J. Ryan, R. W. Mastick, F. Bedell and Report by Joint Committee on Inductive Interference.

A discussion of the various factors involved in the selection of a wave-shape standard and the penalizing of upper harmonics. An appeal for cooperation between power companies, telephone companies and manufacturers.

INSULATOR FAILURES UNDER TRANSIENT VOLTAGES

W. D. Peaslee **Vol. xxxv—1916, pp. 1187-1194**

This paper presents the results of recent investigations on the failure of insulators under impact and combined impact and normal frequency voltages. Microphotographs are included. The breakdown of a dielectric involves energy which is a time function, and the importance of the duration of the stress in determining the magnitude of the voltage necessary to puncture an insulator are discussed. The importance of the elimination of air holes and defects in porcelain is shown. Some essential features of a successful line insulator are stated.

Discussion, pages 1195-1205, by Messrs. J. B. Fisken, W. D. Peaslee. R. Howes, L. T. Merwin, H. J. Ryan, R. W. Mastick, R. M. Boykin, A. A. Miller and E. E. F. Creighton.

A general discussion including experiences of certain power transmission lines.

STEEL CONDUCTORS FOR TRANSMISSION LINES

H. B. Dwight **Vol. xxxv—1916, pp.1237-1250**

This paper states that steel cables will not generally be economical on main transmission lines, except for long spans, and for high altitudes where corona is excessive. They may be advisable as bare conductors for d-c. railway feeders. They deteriorate more rapidly than copper conductors and have very low scrap value. Steel cables for alternating current should be finely stranded and different groups of wire should be spiraled in opposite directions. Medium grades of steel give better results with alternating currents than high priced grades. There is an opening for the profitable use of steel cables on branch lines of power systems of all voltages.

Discussion, pages 1251-1258, by Messrs. R. E. Doane, T. H. Worcester, D. B. Rushmore, S. C. Coey, W. T. Snyder and H. B. Dwight.

A general discussion.

15. DISTRIBUTION SYSTEMS

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A general discussion with particular reference to the split-conductor principle and its relation to ideal relay protection.

A DISTRIBUTION SYSTEM FOR DOMESTIC POWER SERVICE FROM COMMERCIAL AND ENGINEERING STANDPOINTS

Carl H. Hoge and Edgar R. Perry **Vol. xxxv—1916, pp. 983-990**

This paper endeavors to lay out a distribution system that will take care of the greatly increasing demand for power for heating and cooking. Units of load, consumption and revenue were taken from actual tests and applied to definite sections thought to be representative, as containing every class of house, with schools, churches, etc. Results obtained seem to indicate for this class of business a profit at a lower rate. The central station man is advised to make provision for this increased demand when rebuilding in the future.

Discussion, pages 991-1000, by Messrs. D. F. Henderson, E. R. Perry, J. B. Fisken, M. T. Crawford, F. D. Weber, C. R. Collins, W. D. Peaslee, E. G. Robinson, L. T. Merwin, H. W. Buck, S. M. Kennedy, W. L. Chrysler, J. R. King, H. J. Gille and R. Howes.

A general discussion with particular emphasis on the desirability of simpler rates and methods of metering.

UNDERGROUND DISTRIBUTION SYSTEMS

G. J. Newton **Vol. xxxv—1916, pp. 1207-1222**

This paper shows the importance of properly designing an underground distribution system for the district it serves and the particular service it is to supply. Simply placing the wires underground does not constitute an efficient system. Underground distribution is the ultimate solution of the distribution problem that confronts every electric light and power company operating in progressive towns and cities. The suggestions offered are based on many years experience and are aimed to aid particularly in the design and installation of the first system in the smaller cities.

Discussion, pages 1223-1235, by Messrs. T. E. Tynes, A. F. Hovey, F. D. Egan, S. C. Coey, C. A. Menk, H. B. Gear, B. G. Beck, B. W. Gilson, L. Hommel, G. T. Street and F. H. Woodhull.

A discussion of the advantages of single conductor, three-phase cables, type of insulation, location and size of manholes, ventilation of ducts, fireproofing cables and joints, etc.

THE POWER COMPANY'S PROBLEM IN THE ELECTRIC SUPPLY FOR LARGE SINGLE-PHASE LOAD

W. C. L. Eglin **Vol. xxxv—1916, pp. 1289-1292**

The power company must be able to supply energy of uniform pressure, single-phase, two-phase or three-phase, at whatever voltage best suits customer. These conditions best met by polyphase units. When demand for single-phase current is heavy enough to produce unbalance, some means of balancing must be provided. Three methods are discussed Correction for power factor on each individual large consumer's line is suggested.

Discussion incorporated with that of paper by Philip Torchio on "Supply of Single-Phase Loads from Central Stations."

SUPPLY OF SINGLE-PHASE LOADS FROM CENTRAL STATIONS

Philip Torchio **Vol. xxxv—1916, pp. 1293-1301**

American central stations have extensively adopted single-phase distribution from polyphase stations. Individual regulators employed. Generators with good single-phase characteristics or in certain cases generators with kilovolt ampere rating in excess of kilowatt capacity of steam unit are employed. Customers assist balancing by dividing load between phases. Question of power supply to N. Y., N. H. & H. R. R. discussed. Equipment described.

Discussion, (including that of paper by W.C.L. Eglin), pages 1302-1313, by Messrs. W. S. Murray, P. Junkersfeld, D. B. Rushmore, L. E. Imlay, H. R. Summerhayes, N. W. Storer, E. H. Martindale, E. F. W. Alexanderson, J. L. Harper, H. W. Buck, J. E. Kershner, C. F. Scott, W. C. L. Eglin, P. Torchio, F. Osgood and C. F. Harding.

General discussion.

SINGLE-PHASE POWER PRODUCTION

E. F. W. Alexanderson and G. H. Hill **Vol. xxxv—1916, pp. 1315-1327**

The general tendency of electric power supply is toward centralization of stations and to be consistent stations must be standardized. From this standpoint single-phase power can best be supplied from polyphase systems. Operation and theory of phase converters discussed.

Discussion incorporated with that of paper by Gilman and Fortescue on "Single-Phase Power Service from Central Stations."

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Unbalance in voltage when single-phase power is supplied direct from polyphase circuit explained. Law of distribution of load in polyphase system deduced. Outline of theory of single-phase generator given. Essential requirements for phase balancing, requirements for control apparatus, behavior of balancer under short circuit.

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A general discussion of the advantages of various methods of single-phase generation and operation with some facts relative to comparative costs.

16. CONTROL, REGULATION AND SWITCHING

THE LIQUID RHEOSTAT IN LOCOMOTIVE SERVICE

A. J. Hall — Vol. xxxv—1916, pp. 167-171

A description of the liquid rheostat in locomotive service giving in detail the arrangement of the mechanical parts and means of controlling it.

Discussion, pages 172-173, by Messrs. C. D. Knight and R. E. Hellmund.

A discussion mainly of the liquid rheostat used in mine-hoist service.

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RUPTURING CAPACITIES OF OIL CIRCUIT BREAKERS

Stephen Q. Hayes **Vol. xxxv—1916, pp. 1523-1530**

A series of notes on the rupturing capacity of oil breakers. Description of result obtained by root-mean-square of maximum peak of current wave that occurs while breaker is opening multiplied by root-mean-square of open-circuit voltage that occurs immediately after breaker opens. Attention called to different classes of ratings. Recommendations made as to most desirable method of rating and ability of breakers to be re-operative.

Discussion incorporated with that of paper by E. M. Hewlett on "Rating of Oil Circuit Breakers."

RATING OF OIL CIRCUIT BREAKERS

E. M. Hewlett **Vol. xxxv—1916, pp. 1531-1533**

Paper points out several difficulties which are encountered in rating by actual current breakers, but generally favors that these ratings be on the basis of the current to be opened in the arc at the operating voltage of the system.

Discussion, pages 1534-1549, by Messrs. C. Lichtenberg, N. L. Pollard, G. A. Burnham, J. L. Harper, H. W. Buck, J. B. Taylor, K. C. Randall, L. E. Imlay, C. A. Adams, E. M. Hewlett, S. Q. Hayes, H. R. Summerhayes, P. M. Lincoln, L. W. Chubb and P. Lindemann.

A general discussion.

17. TRACTION

OPERATION ON THE NORFOLK AND WESTERN RAILWAY

F. E. Wynne **Vol. xxxv—1916, pp. 147-153**

A description of the great advantages, from an operating standpoint, incident to the inauguration of electric service on the Elkhorn grade of the Norfolk and Western Railway Co. and why it is possible almost to double the capacity of the road by the use of 12 electric locomotives, instead of the 33 Mallet locomotives formerly in service.

Discussion, pages 154-166, by Messrs. A. H. Armstrong, R. E. Hellmund, F. H. Shepard, B. A. Behrend, W. I. Slichter, C. F. Scott, W. Arthur, H. M. Hobart and F. E. Wynne.

A general discussion with particular emphasis on regenerative braking and the operation of liquid rheostat.

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CHATTERING WHEEL SLIP IN ELECTRIC MOTIVE POWER

G. M. Eaton **Vol. xxxv—1916, pp. 175-179**

The paper shows that chattering wheel slip is characteristic of all types of electric motive power. The application of the motive power in the electric and steam drives is compared, and the reasons for the chattering wheel slip and the means of measuring and rectifying the same are given.

Discussion, pages 180-182, by Messrs. S. T. Dodd, W. I. Slichter, C. F. Scott, W. L. Merrill and G. M. Eaton.

A general discussion.

HIGH-VOLTAGE D-C. RAILWAY PRACTISE

Clarence Renshaw Vol. xxxv—1916, pp. 347-360

This paper deals with the fundamental differences in apparatus for 1200 or 1500 volts as compared with former 600-volt standards. It points out the tendency to use higher d-c. voltages with the multiplicity of voltages slightly differing such as 2400, 3000, 3600, 4200, etc. It recommends in order to avoid confusion, the establishment at once of a standard high voltage. It is shown that final voltage standards are usually fixed by economic standards rather than physical limitations and 5000 volts is suggested as very satisfactory. The 5000-volt line at Jackson, Michigan, is briefly described.

Discussion, pages 361 and 383, by Messrs. F. J. Sprague, W. J. Davis, Jr., W. B. Potter, Calvert Townley, S. I. Oesterreicher, B. F. Wood, E. V. Pannell, A. H. Armstrong, S. Haar, C. Schwartz, N. W. Storer and C. Renshaw.

A detailed presentation of the arguments for and against the adoption of higher d-c. voltages and standardization.

18. LIGHTING AND LAMPS

ILLUMINATION OF THE PANAMA-PACIFIC INTERNATIONAL EXPOSITION

W. D'A. Ryan Vol. xxxv—1916, pp. 757-782

This paper describes the system of lighting adopted for the P-P. I. E., which was generally conceded to have initiated a new era in the art of illumination. From a narrow engineering point of view the lighting would have been regarded as inefficient, but the object striven for was to suppress high intrinsic brilliancy, while bringing out the architectural beauties of the exposition structures in the most effective manner.

No discussion.

20. MISCELLANEOUS APPLICATIONS OF ELECTRICITY

THE TRUE NATURE OF SPEECH

J. B. Flowers Vol. xxxv—1916, pp. 213-231

A proof that speech is a rapid variation in the intensity of the voice and mouth tones according to definite sound patterns called letters of the alphabet. Photographs are taken with aid of string-galvanometer of each letter of the alphabet. From the curve the phonographic alphabet is obtained by measuring the variations in intensity of the main tone of the record.

A design for a voice-operated phonographic alphabet writing machine is described.

Discussion, pages 232-248, by Messrs. H. B. Williams, L. T. Robinson, A. C. Crehore, W. Maver, Jr., W. J. Hammer, L. W. Chubb, C. A. Adams, J. B. Taylor and J. B. Flowers.

A general discussion including the development of the theory of the string galvanometer.

ELECTRIC DRIVE FOR REVERSING ROLLING MILLS

Wilfred Sykes and David Hall **Vol. xxxv—1916, pp. 501-519**

This paper answers some of the questions which have arisen in the rapid displacement of steam drive by electric drive for reversing rolling mills, and describes the constructions which have been found desirable.

Discussion, pages 520-537, by Messrs. K. A. Pauly, E. S. Jeffries, D. M. Petty, R. Tschentscher, H. D. James, F. G. Liljenroth, B. Wiley, H. S. Page, P. Lindemann, A. Gray and W. Sykes.

A discussion of the relative merit of steam and electric drive for reversing mills. Statistics of installation at Steel Company of Canada. Comparison of European and American practise.

MOTOR EQUIPMENTS FOR THE RECOVERY OF PETROLEUM

W. G. Taylor **Vol. xxxv—1916, pp. 539-552**

This paper presents data covering the horse power requirements and kilowatt-hour consumption for the various operations in drilling and maintaining producing oil wells. The use of the slip-ring induction motor for drilling, pumping and cleaning wells. Special controllers and resistance. Pumping, cleaning and "pulling" rods by a Y-delta or two-speed machine.

Discussion, pages 553-554, by Messrs. F. Woodbury and A. M. Dudley. General discussion.

SOME FEATURES OF DOMESTIC ELECTRIC COOKING AND HEATING

H. B. Peirce **Vol. xxxv—1916, pp. 1001-1011**

From tests made on a number of domestic cooking and heating installations, it would appear that electric cooking has a better load factor than a lighting load and that this factor improves as the number of ranges increases. The errors incident to these tests are discussed. Suggestions are made for checking these results by others. In the heating field, the effect of water heaters superimposed on range loads is discussed in relation to their effect on the central station loads and income.

Discussion, pages 1012-1015, by Messrs. J. B. Fisken, C. E. Magnusson, W. D. Peaslee, L. F. Curtis, R. W. Pope, E. R. Perry, H. F. Holland and H. J. Gille.

A general discussion.

21. TELEPHONY AND TELEGRAPHY

INDUCTIVE INTERFERENCE AS A PRACTICAL PROBLEM

A. H. Griswold and R. W. Mastick **Vol. xxxv—1916, pp. 1051-1087**

A review of the factors which affect inductive interference in telephone circuits from high-voltage power transmission circuits, a presentation of practical considerations regarding the reduction of interference, and description of actual cases of the application of these means of reduction. Balanced and residual voltages and currents, wave shapes of voltages and currents, transposition schemes, three particular cases of parallels.

Di cussion, pages 1088-1094, by Messrs. F. Bedell, L. T. Merwin, J. B. Fisken W. D. Peaslee, R. F. Robinson, L. J. Corbett, C. A. Whipple and R. W. Mastick.

A discussion of effects of leaking insulators, charging electrolytic arresters, carelessness in making transpositions and an appeal for co-operation of telephone and power companies.

CHARACTERISTICS OF ADMITTANCE TYPE OF WAVE-FORM STANDARD
Frederick Bedell **Vol. xxxv-1916, pp. 1156-1170**

A description of the characteristics of a certain type of standard for determining how near an actual wave is to a true sine wave and for prescribing allowable limits of deviation. An investigation to determine whether a standard can be specified that will be more suitable in its characteristics and more practical in its application.

Discussion, pages 1171-1186, by Messrs. H. S. Osborne, L. F. Curtis, C. E. Magnusson, L. W. Chubb, L. T. Merwin, L. J. Corbett, J. B. Fisken, W. D. Peaslee, H. J. Ryan, R. W. Mastick, F. Bedell and Report by Joint Committee on Inductive Interference.

A discussion of the various factors involved in the selection of a wave-shape standard and the penalizing of upper harmonics. An appeal for cooperation between power companies, telephone companies and manufacturers.

22. MISCELLANEOUS TOPICS AND INSTITUTE AFFAIRS

THE MUNICIPALLY-OPERATED ELECTRICAL UTILITIES OF WESTERN CANADA
A. G. Christie **Vol. xxxv—1916, pp. 33-87**

The paper discusses a number of public utilities in various cities in Western Canada. The characteristics of these cities are reviewed and a brief outline of equipments of the various plants is given. The costs and methods of financing these utilities are discussed at considerable length and the charges for various services are summarized.

Discussion, pages 88-98, by Messrs. P. Betts, H. G. Stott, R. P. Bolton, E. J. Cheney, C. H. Sharp, A. Reid and A. G. Christie.

A general discussion of the advantages and disadvantages of municipal ownership of public utilities and methods of financing them.

CHATTERING WHEEL SLIP IN ELECTRIC MOTIVE POWER
G. M. Eaton **Vol. xxxv—1916, pp. 176-179**

The paper shows that chattering wheel slip is characteristic of all types of electric motive power. The application of the motive power in the electric and steam drives is compared, and the reasons for the chattering wheel slip and the means of measuring and rectifying the same are given.

Discussion, pages 180-182, by Messrs. S. T. Dodd, W. I. Slichter, C F. Scott, W. L. Merrill and G. M. Eaton.

A general discussion.

A METHOD OF DETERMINING THE CORRECTNESS OF POLYPHASE WATT-METER CONNECTIONS
W. B. Kouwenhoven **Vol. xxxv—1916, pp. 183-206**

A description of a method of checking the correctness of the connections of a polyphase watt-hour meter and proof that the methods most commonly used are unreliable. Rules are worked out that make the rectification of incorrect connections simple. Another method is described which may be used on balanced or unbalanced three-phase circuits at any power factor, providing the opening of one phase at a time is permissible.

Discussion, pages 207-211, by Messrs. W. H. Pratt, G. A. Sawin, L. W. Chubb, C. A. Adams and W. B. Kouwenhoven.

A general discussion.

THE TRUE NATURE OF SPEECH

J. B. Flowers **Vol. xxxv—1916, pp. 213-231**

A proof that speech is a rapid variation in the intensity of the voice and mouth tones according to definite sound patterns called letters of the alphabet. Photographs are taken with aid of string-galvanometer of each letter of the alphabet. From the curves the phonographic alphabet is obtained by measuring the variations in intensity of the main tone of the record.

A design for a voice-operated phonographic alphabet writing machine is described.

Discussion, pages 232-248, by Messrs. H. B. Williams, L. T. Robinson, A. C. Crehore, W. Maver, Jr., W. J. Hammer, L. W. Chubb, C. A. Adams, J. B. Taylor and J. B. Flowers.

A general discussion including the development of the theory of the string galvanometer.

THE FUTURE OF WATER POWER IN THE UNITED STATES

Charles W. Comstock **Vol. xxxv—1916, pp. 249-260**

A compilation of figures showing the total fixed installed primary power in the United States and similar figures for the total installed water power. With these figures, those compiled by the Commissioner of Corporations are summarized and compared. The geographic distribution of installed water power is studied together with the development of water power between 1889 and 1909. The author next takes up the possibilities of water power development and makes an appeal for a federal policy of encouraging business enterprise instead of obstructing it.

No discussion.

IRON LOSSES IN DIRECT-CURRENT MACHINES

B. G. Lamme **Vol. xxxv—1916, pp. 261-286**

It is shown that no great accuracy is practicable in the calculation of actual iron losses, except in special cases. A brief explanation of several causes of variation in losses is given.

The four principal sources of core loss are considered, namely—armature-ring loss, armature-tooth loss, eddy currents in buried conductors, and pole-face losses. Under eddy current losses an explanation is given of certain losses not usually taken into account with a crude method of calculation and some tabulated results.

Under pole-face losses an empirical formula is given, also tabulated results.

The effect of load on losses is discussed and some of the effects of flux distortion on losses are shown.

Discussion, pages 287-299, by Messrs. H. F. T. Erben, W. S. Moody, W. B. Potter, F. H. Kierstead, H. M. Hobart, W. J. Foster, J. L. Burnham, L. T. Robinson, A. S. Langsdorf and B. G. Lamme.

A general discussion of iron losses in d-c. machines and transformers.

THE INFLUENCE OF FREQUENCY OF ALTERNATING OR INFREQUENTLY REVERSED CURRENT ON ELECTROLYTIC CORROSION

Burton McCollum and G. H. Ahlborn **Vol. xxxv—1916, pp. 301-327**

This paper describes experimental work done to determine the coefficient of corrosion of iron and lead in soil with varying frequencies of alternating or reversed current with 60 cycles per second as the highest frequency and a two-week period as the lowest. Some d-c. tests being made as a check on the methods.

The importance of the conclusions reached grows out of the fact that there are large areas in practically every city in which the polarity of the underground pipes reverses with periods ranging from a few seconds to an hour or more due to the shifting of railway loads. Corrosion under such conditions is shown to be much less than has generally been supposed.

Discussion, pages 328-345, by Messrs. P. Torchio, A. Maxwell, A. F. Ganz, J. L. R. Hayden, S. M. Kintner, C. Hering, A. P. Way, C. B. Martin, T. M. Roberts, L. W. Chubb, T. Spooner, M. Toch and B. McCollum.

A general discussion of electrolytic corrosion and methods of mitigation.

ELECTROCHEMICAL INDUSTRIES AND THEIR INTEREST IN THE DEVELOPMENT OF WATER POWER

Lawrence Addicks **Vol. xxxv—1916, pp. 385-392**

A presentation of the great value of the electrochemical industries to this country and their fundamental interest in cheap power. They offer the almost ideal power load but must be located strategically as regards supplies and markets. Niagara power is not cheap enough or sufficient for their needs under present conditions. Great expansion should follow the development of cheaper power particularly in that vital field, the nitrate industry. An appeal is made for a more liberal water power policy on the part of the government.

Discussion incorporated with that of paper by L. B. Stillwell on "Relation of Water Power to Transportation."

WATER POWER DEVELOPMENT AND THE FOOD PROBLEM

Allerton S. Cushman **Vol. xxxv—1916, pp. 393-402**

The great increase of the population of the United States, has been chiefly in the urban districts, resulting in a continuously growing demand for food with a relatively small proportion of the population as food producers.

To increase production per acre requires the production of nitrogen, one of the three principal fertilizer ingredients. This is distinctly a water power proposition involving the fixation of atmospheric nitrogen. More than 80 per cent of mixed fertilizers produced in the United States is used east of the Allegheny Mountains, and for the fertilizer problem water power must be developed where the demand for the fertilizer exists. A proper plan of water power development will have a profound influence on the development and distribution of cheap fertilizer ingredients.

Discussion incorporated with that of paper by L. B. Stillwell on "Relation of Water Power to Transportation."

RELATION OF WATER POWER TO TRANSPORTATION

Lewis B. Stillwell **Vol. xxxv—1916, pp. 403-416**

The relative importance of water power in its relation to transportation, as depending upon its cost and the cost of competing steam power.

Ratio of cost of fuel for locomotives in country as a whole, in various sections, and in a number of different railroads, to total cost of operation.

Effect of recent progress in art of producing electric power by steam upon water power values.

Power and transportation development on navigable streams.

Illustrations of the limit of investment in developing a water power, as fixed by cost of competing steam power.

Comparative cost of canals and railroads.

Illustrations of comparative speed and power consumption in railroad and canal operation.

Discussion (including that of papers by L. Addicks and A. S. Cushman), pages 417-430, by Messrs. D. B. Rushmore, F. A. Lidbury, H. G. Stott, G. Dunn, J. B. Whitehead, L. H. Baekeland, J. J. Carty, L. S. Randolph, L. Addicks, A. S. Cushman and L. B. Stillwell.

A general discussion of the principal features of the three papers.

WATER POWER AND DEFENSE

W. R. Whitney **Vol. xxxv—1916, pp. 431-439**

As the United States has no adequate domestic source of fixed nitrogen, and as nitric acid is an absolute necessity in the manufacture of explosives and in the production of dye stuffs, the Army, Navy Agriculture and Interior Departments should immediately cooperate in determining course to be taken.

It is pointed out that failure to establish such an industry has been due to the proximity of Chile and the impossibility of competing with the cheap water powers of Scandinavia. National safety demands the development of such an industry whether it be supporting or not, but once established the products would be of the greatest value in times of peace, and many other industries would be stimulated.

Discussion incorporated with that of paper by Gano Dunn on "The Water Power Situation, Including Its Financial Aspect."

THE WATER POWER SITUATION, INCLUDING ITS FINANCIAL ASPECT

Gano Dunn **Vol. xxxv—1916, pp. 441-456**

The endeavor of this paper is to present, from the point of view of the engineer, certain aspects of the attitude of capital towards water powers. Actual and threatened laws, popular prejudices, unprofitable developments in the past, and also physical and natural difficulties which handicap hydroelectric as compared with steam-electric plants make a reasonable profit essential to induce investment. The rising cost of water power and the decreasing cost of steam power. Length of time a permit or franchise may run before recapture clauses take effect. Water power developed as a matter of conservation of coal supply.

Discussion (including that of paper by W. R. Whitney), pages 457-477, by Messrs. F. A. Lidbury, L. Addicks, G. Dunn, J. H. Finney, L. H. Baekeland, C. G. Atwater, C. Townley, G. R. Smith, D. B. Rushmore, O. T. Crosby.

A general discussion from the viewpoints of the engineer, financier, manufacturer and congressman.

THE RELATION OF PURE SCIENCE TO INDUSTRIAL RESEARCH

President's Address

J. J. Carty **Vol. xxxv—1916, pp. 479-488**

STANDARDIZATION

C. Le Maistre **Vol. xxxv—1916, pp. 489-496**

A general review of development of standardization committees and organizations here and abroad. A citation of the many advantages of proper standardization and an appeal for universal cooperation. Particular reference is given to standardization of electrical machinery with emphasis laid on the adoption of a standard temperature rise basis.

Discussion, pages 497-500, by Messrs. C. H. Sharp, F. Osgood, C. P. Steinmetz, C. Le Maistre and C. A. Adams.

A general discussion.

EFFECT OF BAROMETRIC PRESSURE ON TEMPERATURE RISE OF SELF-COOLED STATIONARY INDUCTION APPARATUS

V. M. Montsinger **Vol. xxxv—1916, pp. 599-626**

This paper is divided into three parts, as follows: (1) A general review of the principal laws of the dissipation of heat,—radiation, conduction and convection. (2) The development of a simple formula for the effect of altitude on the cooling of surfaces of different shapes. (3) A general discussion of the method of conducting experimental observations at different altitudes on three different shaped surfaces.

Discussion, pages 627-633, by Messrs. R. W. Sorensen, A. Gray and V. M. Montsinger.

A general discussion of methods and results obtained.

EXPERIENCES IN TESTING PORCELAIN

E. E. F. Creighton **Vol. xxxv—1916, pp. 739-744**

The results of numerous experiences in testing porcelain insulators particularly in regard to porosity, absorption of water, surface leakage and dielectric losses. Considerable energy is required to drive moisture out of a porous insulator and it has been found best to restrict the oscillator testing to dry porcelain, whereas the wetter the porcelain the more effective is the 60-cycle test.

Discussion incorporated with that of paper by R. H. Marvin on "A New Method of Grading Suspension Insulators."

A NEW METHOD OF GRADING SUSPENSION INSULATORS

R. H. Marvin Vol. xxxv—1916, pp. 745-752

Attention is drawn to the known disadvantages of the uneven distribution of voltage in long strings of disks. The general theory showing how the distribution is determined by the various capacities of the units is given. It is shown how the distribution can be improved by grading, or varying the internal capacity of the units.

The proposed method of grading consists in placing flat metal rings on the insulator, around the cap and stud respectively, the porcelain disk being enlarged for this purpose.

A simple method of measuring the voltage distribution is described using a single needle gap.

The results of tests with and without grading are given, the graded strings showing a decidedly better distribution of voltage.

Discussion, pages 753-755, by Messrs. F. W. Peek, Jr., and E. E. F. Creighton.

A general discussion.

ILLUMINATION OF THE PANAMA-PACIFIC INTERNATIONAL EXPOSITION

W. D'A. Ryan Vol. xxxv—1916, pp. 757-782

This paper describes the system of lighting adopted for the P-P. I. E., which was generally conceded to have initiated a new era in the art of illumination. From a narrow engineering point of view the lighting would have been regarded as inefficient, but the object striven for was to suppress high intrinsic brilliancy, while bringing out the architectural beauties of the exposition structures in the most effective manner.

No discussion.

SUGGESTIONS FOR ELECTRICAL RESEARCH IN ENGINEERING COLLEGES

V. Karapetoff Vol. xxxv—1916, pp. 895-910

This paper gives a list of topics in electrical engineering suitable for thesis, research and advanced study. A plea is made for systematic research, each college specializing year after year in only a few topics. Cooperation is urged with individual inventors and investigators. Various types of investigation are enumerated, such as invention, experimental study, theoretical study, library search, and compilation of data.

Discussion, pages 911-923, by Messrs. J. B. Whitehead, A. E. Flowers, C. E. Skinner, F. C. Caldwell, E. E. Creighton, D. D. Ewing, C. F. Harding, N. S. Diamant, J. J. Carty, D. H. Braymer, A. A. Nims and A. Gray.

A general discussion from the viewpoint of the college professor, inventor and manufacturer.

TRACTIVE RESISTANCES TO A MOTOR DELIVERY WAGON ON DIFFERENT ROADS AND AT DIFFERENT SPEEDS

A. E. Kennelly and O. R. Schurig Vol. xxxv-1916, pp. 925-953

A complete report on an investigation of tractive resistances of urban roads to a motor delivery wagon equipped with solid rubber tires. The "tractive resistance" as used in this paper, includes still-air resistance, but does not include wind resistance and the resistance internal to the truck. The test truck is fully described. The results included are (1) overall efficiency of truck mechanism and (2) tractive resistances of a number of typical urban roads. The components of tractive resistance for a typical road are also given.

Discussion, pages 954-955, by Messrs. A. A. Nims and O. R. Schurig.

A discussion of "vehicle efficiency," "road resistance," "air resistance," etc.

APPLICATION OF A POLAR FORM OF COMPLEX QUANTITIES TO THE CALCULATION OF ALTERNATING-CURRENT PHENOMENA

N. S. Diamant **Vol. xxxv—1916, pp. 957-978**

In the calculation of a-c. phenomena by means of complex quantities, as a rule, the rectangular components of the vector are used. A simple method for dealing directly with the vectors themselves is described and consists in introducing the operator j^n, where n, contrary to ordinary usage, may be any positive or negative fraction. For convenience of reference a summary of formulas is given and also a very short bibliography.

Discussion, pages 979-981, by Messrs. A. Gray, E. E. F. Creighton, J. B. Whitehead, E. H. Colpitts and N. S. Diamant.

A general discussion of the various mathematical determinations.

SOME FEATURES OF DOMESTIC ELECTRIC COOKING AND HEATING

H. B. Peirce **Vol. xxxv—1916, pp. 1001-1011**

From tests made on a number of domestic cooking and heating installations, it would appear that electric cooking has a better load factor than a lighting load and that this factor improves as the number of ranges increases. The errors incident to these tests are discussed. Suggestions are made for checking these results by others. In the heating field, the effect of water heaters superimposed on range loads is discussed in relation to their effect on the central station loads and income.

Discussion, pages 1012-1015, by Messrs. J. B. Fisken, C. E. Magnusson, W. D. Peaslee, L. F. Curtis, R. W. Pope, E. R. Perry, H. F. Holland and H. J. Gille.

A general discussion.

INSULATOR FAILURES UNDER TRANSIENT VOLTAGES

W. D. Peaslee **Vol. xxxv—1916, pp. 1187-1194**

This paper presents the results of recent investigations on the failure of insulators under impact and combined impact and normal frequency voltages. Microphotographs are included. The breakdown of a dielectric involves energy which is a time function, and the importance of the duration of the stress in determining the magnitude of the voltage necessary to puncture an insulator are discussed. The importance of the elimination of air holes and defects in porcelain is shown. Some essential features of a successful line insulator are stated.

Discussion, pages 1195-1205, by Messrs. J. B. Fisken, W. D. Peaslee, R. Howes, L. T. Merwin, H. J. Ryan, R. W. Mastick, R. M. Boykin, A. A. Miller and E. E. F. Creighton.

A general discussion including experiences of certain power transmission lines.

ELECTRICAL MACHINERY TESTS AND SPECIFICATIONS BASED ON MODERN STANDARDS

H. M. Hobart **Vol. xxxv—1916, pp. 1259-1287**

Comparisons are made of the standardization rules for electrical machinery now in force in various countries showing that machinery built in conformance with the American rules will usually also conform with rules employed in other countries. Suggestion is made that 55 degrees could be employed as the ambient temperature of reference for tropical ratings. Attention is called to a series of acceptance tests on some large waterwheel generators and to the temperature results obtained by making cyclic heat runs on these machines.

No discussion.

THE EFFECT OF RECENT DECISIONS ON THE WORK OF INVENTORY AND APPRAISAL

Philander Betts **Vol. xxxv—1916, pp. 1369-1374**

In order that inventories and appraisals shall be useful in determining all the appropriate elements of value, they must be classified as to age, condition, use, and extent of use in each class of service.

Discussion, incorporated with that of paper by Julian Loebenstein on "Growth and Depreciation."

CONTINUOUS INVENTORIES: THEIR PREPARATION AND VALUE

Harry E. Carver **Vol. xxxv—1916, pp. 1375-1387**

A discussion of the advisability of attempting a continuous inventory, giving possible uses and advantages to be derived therefrom. Also, the preparation of such an inventory. Suggestions for the division of property into four general groups for that purpose, outlines of general forms and methods for collecting and recording data required.

Discussion incorporated with that of paper by Julian Loebenstein on "Growth and Depreciation."

GROWTH AND DEPRECIATION

Julian Loebenstein **Vol. xxxv—1916, pp. 1389-1407**

It is generally assumed that a complex utility property will depreciate to an approximately fixed per cent condition. This is shown by theoretical and actual curves to be incorrect. It is shown that the manner of the company's growth affects its per cent condition.

The necessity of reserves, the manner in which they may be kept and the return which should be allowed on them, whether reinvested or not, is discussed. Several commission and court decisions are quoted to show the tendency to disallow a return on a reserve and arguments are presented in refutation of the decisions.

Discussion (including that of papers by Philander Betts and Harry E. Carver), pages 1408-1436, by Messrs. W. B. Jackson, G. W. Whittemore, D. B. Rushmore, E. J. Cheney, W. S. Franklin, P. Betts, H. E. Carver, W. R. McCann, F. Gill, L. R. Nash, F. C. Merriell and J. Loebenstein.

A general discussion of factors involved in the three papers.

RUPTURING CAPACITIES OF OIL CIRCUIT BREAKERS

Stephen Q. Hayes **Vol. xxxv—1916, pp. 1523-1530**

A series of notes on the rupturing capacity of oil breakers. Description of result obtained by root-mean-square of maximum peak of current wave that occurs while breaker is opening multiplied by root-mean-square of open-circuit voltage that occurs immediately after breaker opens. Attention called to different classes of ratings. Recommendations made as to most desirable method of rating and ability of breakers to be re-operative.

Discussion incorporated with that of paper by E. M. Hewlett on "Rating of Oil Circuit Breakers."

RATING OF OIL CIRCUIT BREAKERS

E. M. Hewlett **Vol. xxxv—1916, pp. 1531-1533**

Paper points out several difficulties which are encountered in rating by actual current breakers, but generally favors that these ratings be on the basis of the current to be opened in the arc at the operating voltage of the system.

Discussion, pages 1534-1549, by Messrs. C. Lichtenberg, N. L. Pollard, G. A. Burnham, J. L. Harper, H. W. Buck, J. B. Taylor, K. C. Randall, L. E. Imlay, C. A. Adams, E. M. Hewlett, S. Q. Hayes, H. R. Summerhayes, P. M. Lincoln, L. W. Chubb and P. Lindemann.

A general discussion.

TOPICAL INDEX.