Lightning Current Observations in Buried Cable

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Results are given of observations of lightning currents, voltages, and charges in a buried cable over most of three lightning seasons. These are compared with theoretical expectations. Data regarding the incidence of lightning strokes to ground, as observed with automatic recording equipment, are also reported, together with comparisons with similar data published previously.

Introduction

LIGHTNING currents in buried telephone cable are of considerable importance in that they may cause excessive voltages between the cable sheath and the conductors with resultant insulation failure, and may also cause severe damage by crushing the cable or fusing holes in the sheath. The incidence of lightning strokes to buried cable, the resulting voltages, and lightning trouble expectancy, have therefore been subjects of theoretical, experimental, and field studies, which, together with operating experience, have pointed the way to improvements in the design of communication cable to minimize its liability to lightning damage, and in the application of remedial measures where excessive lightning trouble has been experienced.[1]

The territory around Atlanta, Georgia, has appeared to be particularly severe with respect to these lightning hazards, because of high earth resistivity and high thunderstorm rate. Buried cables initially installed in this territory were accordingly provided with protective measures in the form of increased core-sheath insulation and shield wires buried with the cable. In spite of these measures, however, a substantially higher rate of lightning damage than anticipated was experienced, as a result of which a new design was adopted for the transcontinental coaxial cable westward from Atlanta. In this cable, the lead sheath was insulated from an outside corrugated 10-mil copper shield by a 100-mil layer of thermoplastic insulation intended to prevent the entrance of lightning currents into the sheath and thereby to minimize voltages between the sheath and the cable conductors.

Simulative tests with surge currents, believed to have a wave shape representative of lightning stroke current, had indicated satisfactory agreement between measured and calculated voltages between sheath and cable conductors. It appeared, therefore, that the departure from predicted

[1] References are listed at end of paper.

lightning trouble expectancy in the earlier cables was due to one or more of the following conditions: a higher rate of occurrence of lightning strokes during thunderstorms, higher stroke currents than in other parts of the country, a longer duration of the lightning currents than assumed, or a higher incidence of strokes to buried cable than predicted theoretically. The observations described here, the larger part of which have extended over a period of three lightning seasons, were intended to secure information on these points. The data forming the principal subject of this paper were obtained from a section of the coaxial cable mentioned above, which for a number of reasons was particularly suitable for the purpose.

I. Theoretical Expectations

1.0 *General*

As mentioned above, the observations were made on a cable route through territory of high thunderstorm rate and high earth resistivity, both of which facilitate measurements of currents along the cable. As a result of the high thunderstorm rate, the incidence of strokes to ground is high, and because of the high earth resistivity, the number of strokes to ground near the cable which flash to latter is also high. Another result of the high earth resistivity is that the attenuation of current along the cable is relatively low, so that currents and voltages may be observed at appreciable distances along the cable from the points of the lightning strokes. The rate of attenuation is, furthermore, smaller the longer the duration of the lightning current, that is, the longer the time to half-value. Since lightning trouble experience in this territory indicated the possibility of currents of rather long durations, this was an additional factor favorable to the purposes of the tests, although, like the others, it increases the liability of cables to lightning damage.

Though the relationships of the various factors mentioned above to earth resistivity and to lightning current wave shape have been dealt with in detail in the study[1] referred to above, they are briefly reviewed here to facilitate comparisons with and discussions of the observations.

1.1 *Incidence of Strokes to Buried Cable*

The current in a lightning stroke to ground spreads in all directions from the point where it enters the earth. If a cable is in the vicinity, it will provide a low resistance path, so that much of the current will flow to the cable and in both directions along the sheath to remote points. The current in the ground between the lightning channel and the cable may give rise to a voltage drop along the surface of the earth sufficient to exceed the breakdown gradient of the soil, particularly when the earth resistivity is high. The lightning stroke will then arc directly to the cable from the point where it enters the ground, often at the base of a tree. Furrows exceeding 100 feet in length have been found along the ground path of such an arc.

For a crest current J in the lightning stroke, the arcing distance in meters is given by[1]

$$r = k(J\rho)^{1/2} \tag{1}$$

where J is in kiloamperes, ρ is the earth resistivity in meter-ohms and k is a constant depending on the surface breakdown gradient of the soil. Low resistivity soil, up to $\rho = 100$ meter-ohms, has an average breakdown gradient of about 2500 volts/cm, and the corresponding value of k is about .08. For high resistivity soil, $\rho = 1000$ meter-ohms and up, the average breakdown gradient is about 5000 volts/cm and $k \cong .047$. Thus, for an earth resistivity of 2000 meter-ohms, and $J = 100$ ka, $r \cong 21$ meters or 70 feet.

The number of strokes arcing to a cable of length s may conveniently be expressed as

$$N = 2\bar{r}sn \tag{2}$$

where n is the number of strokes to ground per unit area, $\bar{r}$ is an equivalent arcing distance, and $2\bar{r}s$ an equivalent area near the cable within which the cable is assumed to attract all lightning strokes. In obtaining $\bar{r}$, the number of strokes arcing to the cable from various distances r as given by (1), depending on the current in the strokes, must be evaluated. This number and the equivalent arcing distance will thus depend on the crest current distribution of lightning strokes. For the distribution curve shown by Curve 1 in Fig. 1, the effective distance in meters is[1]

$$\begin{aligned} \bar{r} &\cong .36\rho^{1/2} \text{ when } \rho \leq 100 \text{ meter-ohms} \\ &\cong .22\rho^{1/2} \text{ when } \rho \geq 1000 \text{ meter-ohms} \end{aligned} \tag{3}$$

Thus, for soil having an average resistivity near the surface (to a depth of at least 10 meters) of 2000 meter-ohms, $\bar{r} \cong 10$ meters $= 33$ feet.

A cable will thus collect direct lightning strokes for an effective distance $\bar{r}$ to either side of it, and when the incidence of strokes to ground per unit area is known, the number of strokes to a cable of a given length may readily be calculated. The incidence of strokes to ground has been estimated, on the average, as about 2.4 per square mile for each 10 thunderstorm days, and the corresponding expectancy of strokes to a buried cable, per 100 miles of length, is about 2.1 for 10 thunderstorm days when the earth resistivity is 1000 meter-ohms and 3.0 when it is 2000 meter-ohms.

The distribution of the crest currents in direct strokes to a cable may be obtained by use of Curve 2 in Fig. 1, which is a theoretical curve derived from Curve 1. Thus for a total of 2.1 for 10 thunderstorm days, the incidence of strokes exceeding 60 ka is $2.1 \cdot 0.2 = 0.42$. In Fig. 2 are shown crest current distribution curves for cable currents due to direct strokes obtained in this manner, together with distribution curves for currents due to both direct strokes and strokes to ground not arcing to the cable. The latter curves may be obtained by methods similar to those used in evaluating curves for the lightning trouble expectancy of buried cable, which are

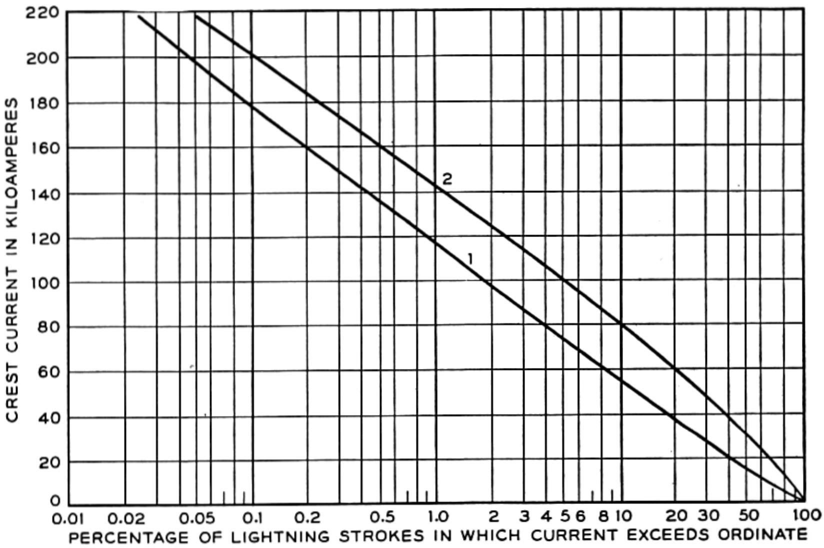

Fig. 1—Distribution of crest currents in lightning strokes.

Curve 1. Currents in strokes to transmission line ground structures, based on 4410 measurements, 2721 in U. S. and 1689 in Europe.

Curve 2. Currents in strokes to buried structures derived from Curve 1.

shown in Fig. 3 for cable having a dielectric strength of 2 kv between the sheath and the cable conductors.[1] The latter curves may, in fact, be used to find the incidence of cable currents of various crest values due to direct strokes and strokes to ground, by calculating the cable currents required to produce 2 kv between the sheath and the core corresponding to various sheath resistances shown in Fig. 3. Thus for a sheath resistance of 2 ohms per mile and an earth resistivity of 1000 meter-ohms, this current is 14.2 ka (see Section 1.3) and for a sheath resistance of 1 ohm, it is 28.4 ka, etc., as plotted in Fig. 2 for an earth resistivity of 1000 meter-ohms.

From the above it follows that a verification of the distribution curves in Fig. 2 by observations of lightning currents in buried cable would apply equally well to the curves in Fig. 3, which have been used to evaluate the liability of such cable to lightning damage.

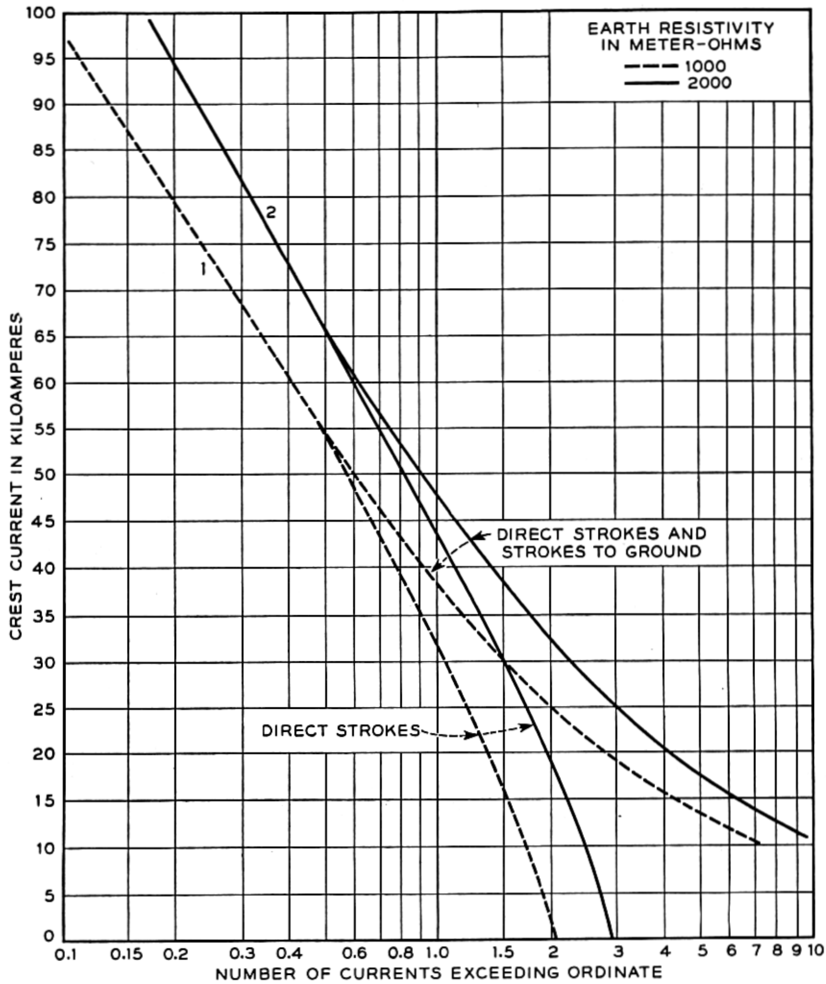

Fig. 2—Incidence of currents exceeding ordinate per 100 miles and 10 thunderstorm days.

1.2 *Propagation of Currents Along Cable*

The current entering the cable at or near the stroke point, depending on whether a direct stroke or a nearby stroke to ground is involved, is attenuated as it travels along the sheath towards remote points. The current leaving the sheath must flow through the adjacent soil, and the leakage current is therefore smaller the higher the soil resistivity. Thus the current will travel farther the higher the earth resistivity. It has been shown elsewhere[1, 2] that a sinusoidal current would be propagated as

$$I(x) = I(0)\, e^{-\Gamma x} \tag{4}$$

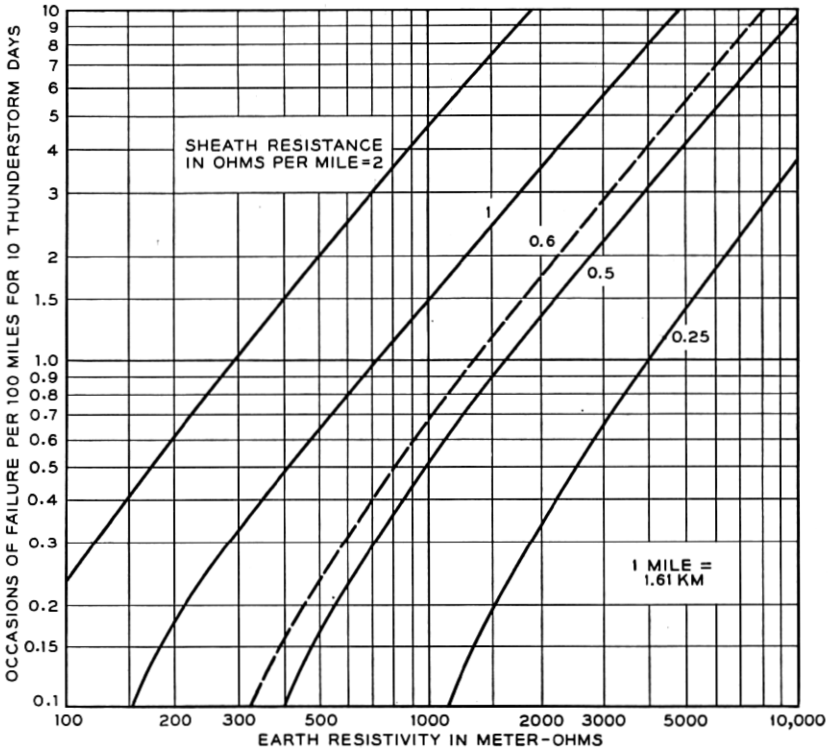

Fig. 3—Theoretical lightning trouble expectancy curves showing number of times insulation failures due to excessive voltages would be expected per 100 miles for 10 thunderstorm days, for cables having sheath resistances as indicated on curves and 2000 volts insulation between core and sheath. Dashed line represents full size cable.

where $I(0)$ is the current in the sheath in one direction from the stroke point, $I(x)$ the current at the distance x, and the propagation constant Γ per meter is given by:

$$\Gamma = \sqrt{i\omega\nu/2\rho} \tag{5}$$

where $\omega = 2\pi f$, ν = inductivity of the earth = $1.257 \cdot 10^{-6}$ henry/meter, and ρ is the earth resistivity in meter-ohms.

Let it be assumed that the current at the distance x has been evaluated for a given earth resistivity ρ and radian frequency ω. If the earth resistivity is increased by a factor k, or if ω is decreased by the same factor, it is evident from (4) and (5) that the same current will be obtained at the distance $x_1 = k^{1/2}x$. Thus, if the earth resistivity is increased by $k = 4$, $x_1 = 2x$ and the current attenuation will be half as great as before. This rule applies to surge-currents of a given wave-shape as well, since they may be regarded as composed of sinusoidal components, each of which would

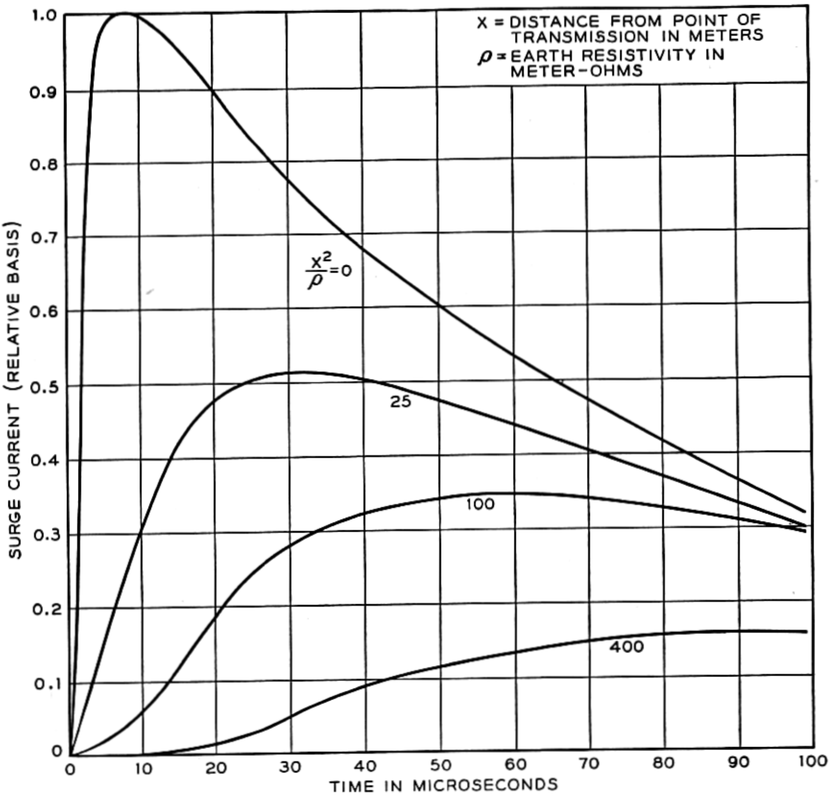

Fig. 4—Attenuation and distortion of surge current transmitted along a buried conductor.

travel farther by the factor $k^{1/2}$. Furthermore, it follows by the same reasoning that for surge-currents of congruent wave-shapes, but different durations, the rate of attenuation is inversely proportional to the square root of the duration. That is to say, let in one case the current reach its crest value at the stroke point in 5 microseconds and its half-value in 65 microseconds, and let the crest current at a given distance x have a certain value. Then, if in another case the current reaches the same stroke-point crest value in 20 microseconds, with half-value in 260 microseconds, the same crest current as that found before at x is obtained at twice the distance x. This follows because all component frequencies of the first surge are related to corresponding components of the second surge by the same factor, viz. 4.

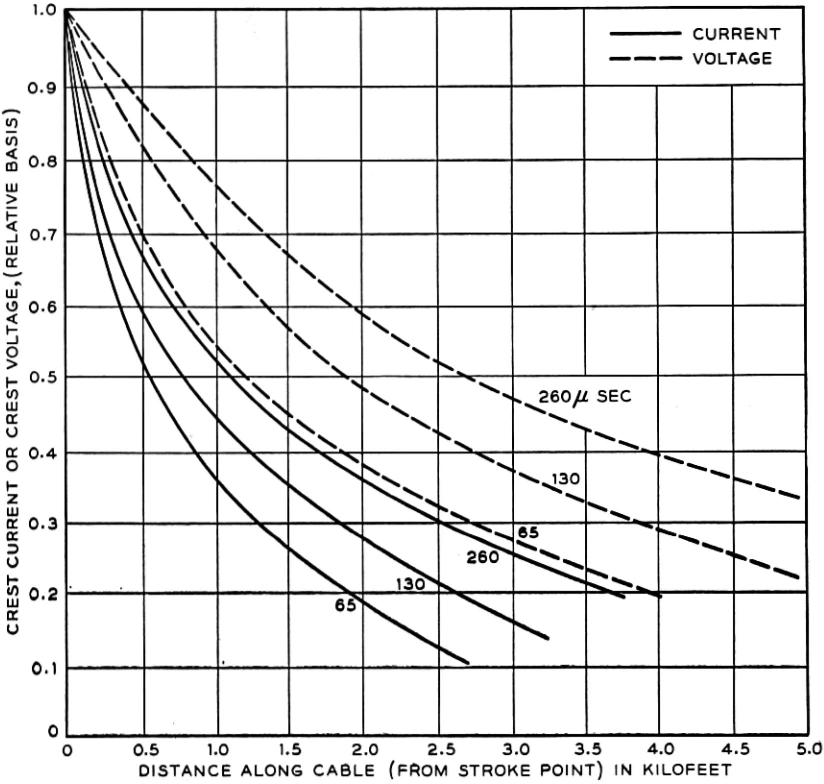

Fig. 5—Variation in crest current in cable and in voltage between sheath and copper shield for stroke currents having various times to half-value as indicated on curves, for an earth resistivity of 1000 meter-ohms.

In Fig. 4 are shown curves[2] from which the attenuation may be obtained for a surge-current reaching its crest value in 5 microseconds and its half-value in 65 microseconds, as shown by the curve for $x^2/\rho = 0$. The crest current has attenuated by 50 per cent when $x^2/\rho = 25$ or $x = 5\rho^{1/2}$. Thus, for an earth resistivity of 1000 meter-ohms, $x = 160$ meters $= 525$ feet when the time to half-value of the current at the stroke point is 65 microseconds, while $x = 1050$ feet when the current at the stroke point reaches its half-value in 260 microseconds. In Fig. 5 are shown crest current attenuation curves obtained in this manner, together with similar curves for the voltage, between the sheath and the core conductor of an ordinary cable, or between the copper shield and the lead sheath of the cable on which these observations were made.

1.3 *Crest Values and Attenuation of Voltages*

The current along the copper shield produces a voltage between this shield and the lead sheath, due to the resistance drop along the shield from the stroke point to a point sufficiently remote for the current in the shield to have become negligible. This voltage is proportional to the unit-length resistance of the copper shield. From the considerations of the preceding section, it follows that the voltage will be proportional to the square root of the earth resistivity and, if the wave-shape remains congruent but the duration of the current is changed, that it will be proportional to the square root of the duration or of the time to half-value. These two propositions follow from the fact that the voltage is proportional to the distance traveled by the current before it is attenuated to a given value.

The crest voltage between the sheath and the cable conductors of an ordinary cable, or between the copper shield and the insulated lead sheath of a cable of the type on which these observations were made, is given by the following expression for a current reaching its half-value in 65 microseconds:

$$V = 2.25\, JR\rho^{1/2} \tag{6}$$

where V is in volts and J is the crest current in kiloamperes, R the resistance per mile of the outer envelope (in this case the copper shield), and ρ the earth resistivity in meter-ohms. This formula follows from expressions given in the paper referred to previously, which also contains curves from which the voltage attenuation along the cable shown in Fig. 5 may be obtained. For a resistance of .7 ohm/mile, which is that of the copper shield, and ρ = 1000 meter-ohms, the crest voltage for a current of 1 ka would thus be 50 volts; and, for a crest current of 200 ka, 10,000 volts. If the dielectric strength of the thermoplastic insulation exceeds 10 kv, the liability of such cable to lightning damage would thus be small, unless the time to half-value of the current substantially exceeds 65 microseconds.

II. Experimental Installation

2.0 *General*

From the preceding discussion it is seen that a lightning current dropping to half-value in some 50 to 75 microseconds, which is of the wave-shape ordinarily assumed, would attenuate to half its crest value in 500 to 1000 feet when the earth resistivity is from 1000 to 2000 meter-ohms. With

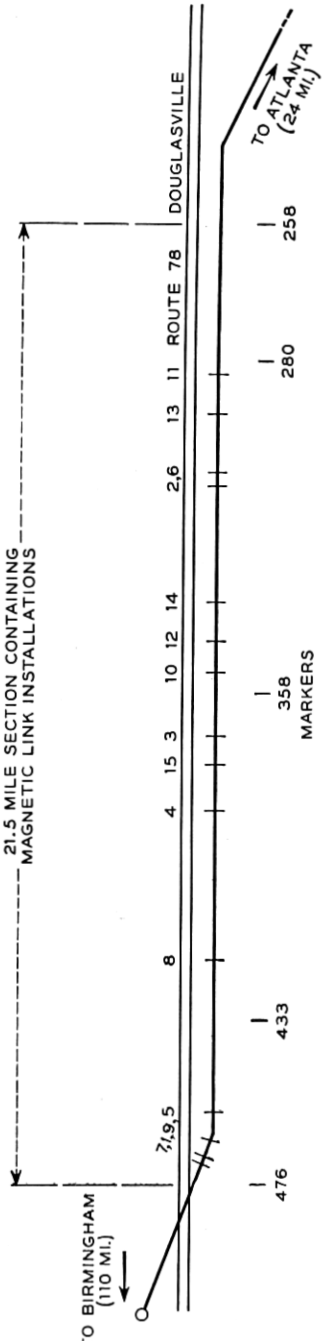

Fig. 6—Location of test section with points of 15 numbered maximum observed cable currents indicated (Table I).

test points along the cable at intervals of about 2300 feet, as employed in the observations, it should thus be possible to secure substantial indications at a number of points along the test section, although closer spacings would of course be desirable.

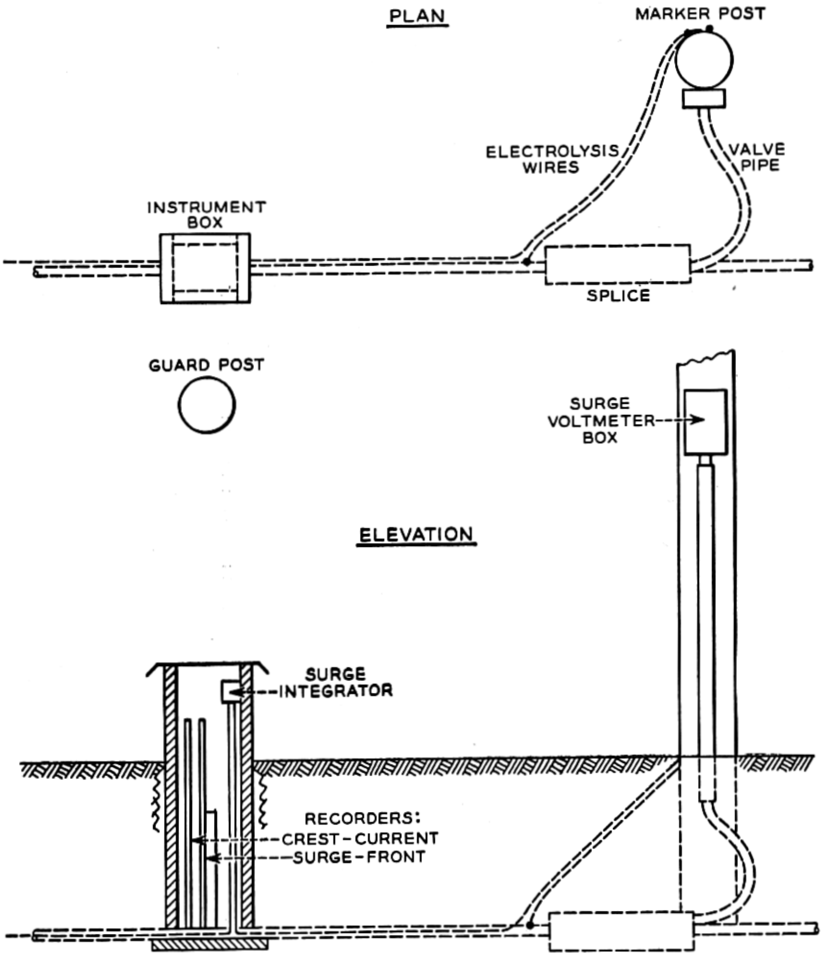

Fig. 7—Typical instrument arrangement at splice points about 2300 feet apart.

In Fig. 6 is shown the 21.5-mile test section and in Fig. 7 a typical installation at every second splice in the cable. At these points the lead sheath is accessible through a lead gas-pressure pipe extending to a marker post, an arrangement which was utilized in making measurements of voltage between the sheath and the outside copper shield. At the same points an insulated wire is installed along the outside of the copper shield for measurement of voltage drop in the copper jacket, in connection with routine corrosion surveys. This facilitated measurements of the charge transferred along the shield by lightning currents, as described in the following. Magnetic link instruments intended to measure the steepness of the wave front were also employed, but lacked the sensitivity required for accurate measurements and are not discussed further here.

In addition to these measurements of current, charge, and voltage, involving the cable structure, observations were also made of the incidence of strokes to ground as described later in this paper.

2.1 *Crest Current Measurements*

To measure crest currents in the cable, magnetic links[3] were mounted at distances of 1.6, 5.7, 12.7, and 36.4 inches from the center of the cable, to cover a current range from 1 to 220 ka. The readings on these magnetic links indicated the total current in the cable, that is, the sum of the currents in the copper shield, the lead sheath, and inside cable conductors.

2.2 *Measurements of Charge*

These measurements were made by means of *surge integrators*.[4] In principle this instrument consists of a shunt R_0 across which is connected a coil of inductance L. When a surge current $I_0(t)$ passes through the shunt, the current $I(t)$ in the coil is given by:

$$L \frac{dI(t)}{dt} = R_0 I_0(t)$$

$$I(t) = \frac{R_0}{L} \int_0^t I_0(t)\, dt$$

$$= \frac{R_0}{L} Q_0(t)$$

where $Q_0(t)$ is the charge which has passed through the shunt up to the time t. By measuring the crest value $\hat{I}$ of the current $I(t)$, the total charge may be obtained from the relation:

$$\hat{Q}_0 = \frac{L}{R_0} \hat{I}$$

This relation is always valid if the surge current rises to a peak value and then decays uniformly. The relation should provide a good approximation to the total charge conveyed by natural lightning strokes, even if there are small oscillations.

The shunt R_0 consisted of about 26 feet of the copper shield over the cable, which had a resistance of about 3.5 milliohms. The inductance L consisted of two coils connected in series, each containing a magnetic link. The larger of these coils had 187 turns of copper wire, the smaller 50 turns. The larger coil provided the greater sensitivity, on account of the more intense magnetization of the link. The relation between the current $\hat{I}$ in the coil and the deflection on the magnetic link meter[3] used to measure the intensity of magnetization was obtained by calibration with direct current.

The inductance of the two coils in series was about 700 microhenries and the d-c resistance about .39 ohms. The time constant of the coils L/R was thus about 1800 microseconds, which is large compared to the duration of the main surge of a lightning stroke, which may last for 100 to 500 microseconds. The instrument will thus effectively integrate the main surge, but will not record the charge which may be caused by a small tail current of much longer duration.

The measurements of charge were made mainly to determine the time to half-value of the currents. The theoretical curves in Part I and elsewhere in this paper are based on a current of the form:

$$J(t) = 1.15\hat{J}\ (e^{-at} - e^{-bt})$$

where $a = .013 \cdot 10^6$, $b = .5 \cdot 10^6$ for a current reaching its crest value $\hat{J}$ in about 5 microseconds and decaying to its half-value in 65 microseconds. If $\alpha = R/L = .00056 \cdot 10^6$ for the surge integrator, the total charge recorded for a current of the above wave shape is

$$\hat{Q} = \hat{J}1.15\left[\frac{1}{a+\alpha} - \frac{1}{b+\alpha}\right] = \hat{J} \cdot 83 \cdot 10^{-6}$$

for a current decaying to its half-value in 65 microseconds. The relationship between $\hat{Q}/\hat{J}$ and the time to half-value, $t_{1/2}$, is as follows for currents reaching their half-values in 65, 130, 260, and 520 microseconds:

$\hat{Q}/\hat{J}$:	83	160	295	540 microseconds
$t_{1/2}$:	65	130	260	520 microseconds

From a curve of $\hat{Q}/\hat{J}$ versus $t_{1/2}$, the time to half-value may be obtained from the observed ratio of charge to crest current. The values given later on, in Table I, were obtained in this manner. If a triangular wave shape had been assumed, the times to half-value would have been $\hat{Q}/\hat{J}$ and therefore somewhat longer.

2.3 *Measurements of Voltage Between Sheath and Copper Shield*

These measurements were made by means of a magnetic link voltmeter consisting of a solenoid of inductance L containing the magnetic link and a series resistance, R. When a constant voltage E is suddenly applied the current through the coil is

$$I = \frac{E}{R}(1 - e^{-(R/L)t})$$

If the time constant L/R is small in comparison with the time to crest value of a variable voltage to be measured, there will be no material delay between the crest value of the voltage and that of the current in the coil. The applied voltages may therefore be obtained by multiplying the coil current as obtained from the magnetic link reading by the series resistance, provided the latter is much greater than the impedance of the circuit to which the instrument is connected. Since the voltmeter in the present case was designed to measure the voltage between the sheath and the copper shield, and the surge impedance of this test circuit is less than 3 ohms, comparatively low values of series resistance could be used. Three separate solenoids and series resistances were used, to provide three voltage ranges, from 0 to 1.5 kv, 0 to 4 and 0 to 9 kv.

2.4 *Magnetic Link Calibrations*

When several magnetic links, which have been exposed to the same field, are inserted in the magnetic link meter, considerable differences in the deflections may be observed due to variations in the material of the links. For this reason, all links used in this installation were placed in a magnetic field of 257 gauss and were then classified according to their response in the magnetic link meter. This field was such as to produce deflections in the most useful part of the meter range, centering around mid-scale.

By this method the magnetic links used in the installation were divided into four classes, in accordance with the ratio of the deflection observed on the magnetic link meter for the link in question to the average deflection for all links. The maximum deviation from the average in each class was about $\pm$ 3 per cent. Instruments of the same type at all installations were provided with links of the same class, to minimize inaccuracies.

2.5 *Observations of Incidence of Strokes to Ground*

To obtain data on the incidence of strokes to ground, observations were made at one location within the test section, by means of an automatically operated magnetic wire recorder arranged to record thunder picked up by a microphone. The recorder was provided with a triggering arrangement which put it in operation on the approach of a thunderstorm, by action of the voltage induced in an antenna by lightning current. The induced voltage from a given lightning stroke was also made to record itself upon the magnetic wire; and, from the delay between this indication and the recorded thunder, the distance to the lightning stroke could be determined upon play-back of the wire record. In this manner the number of strokes to ground within areas of various radii around the observation point could be ascertained, and thus the incidence of strokes to ground. These observations were made during the 1947 and 1948 lightning seasons.

III. Results of Observations

3.0 *General*

From the preceding discussion of theoretical expectations and of the experimental arrangement, it is evident that considerable attenuation would take place between the stroke point and the nearest test points on either side, for a stroke midway between the latter. Accurate evaluation of the maximum current, voltage, and charge, and of the current wave-shape, would thus be rather difficult for strokes nearly midway between test points, since these quantities would have to be evaluated by extrapolation from the observations at the points along the cable. Such extrapolation is rendered more accurate by employing the theoretical attenuation curves given in Fig. 5. This has been done for the currents, by trial and error, until the current wave-shape derived at the stroke point approximately coincided with that assumed for the attenuation curve used in the extrapolation.

These observations involving the cable structure extended over the greater part of three lightning seasons, and included a total of 108 thunderstorm days, 35 in 1946, 38 in 1947 and 35 in 1948. The average number of thunderstorm days per year as recorded by the Atlanta Weather Bureau is 49, which compares with about 60 given on the U. S. Weather Bureau map.[5] The more significant data are tabulated in Table I.

In the following, the observations made of currents, voltages and charges along the cable are discussed for a number of the more important strokes and compared with theoretical expectations. This is followed by a discussion of the observed incidence of cable currents of substantial magnitude and of the incidence of strokes to ground observed at one location along the route and at a second point in the northern part of the country.

3.1 *Wave-Shapes and Attenuation of Currents*

In Fig. 8 is shown the distribution along the cable of the crest currents, the crest voltages, and the charges, for the most severe direct stroke measured, which had a crest value of 70 ka and a total charge of 11 coulombs. This stroke occurred to a 35-foot antenna connected to the cable and used in oscillographic observations of induced voltages due to strokes to ground, as another means of securing data on stroke currents. At this same point

TABLE I
SUMMARY OF CURRENTS EXCEEDING 10 KA

Stroke No. *	Year	Date	Extrapolated Crest Current (Kiloamperes)	Extrapolated Max. Charge (Coulombs)	Derived Time to Half-value (Microseconds)	Shown In
1	1946	April 7	30	7	430	
2	35	June 21	20	4	170	
3	Thunder-	June 21	15	14	950	
4	storm	Aug. 3	16	3.6	190	Fig. 11
5	Days	Aug. 3	16	4	240	
6		Aug. 25	50	11.2	190	Fig. 9
7	1947	May —	20	12	580	
8	38	July 28	14	4	240	
9	Thunder-	Aug. 5	14	3.8	180	
10	storm	Aug. 18	10	6.4	620	
	Days					
11	1948	April 19 to 23	20	8	370	
12	35	July 14	15	7.6	530	
13	Thunder-	July 28	70**	11.2	130	Fig. 8
14	storm	July 28	50	8.8	140	Fig. 10
15	Days	Aug. 4	12	12	1000	

* For location of strokes, see Fig. 6.
** Measured at stroke point.

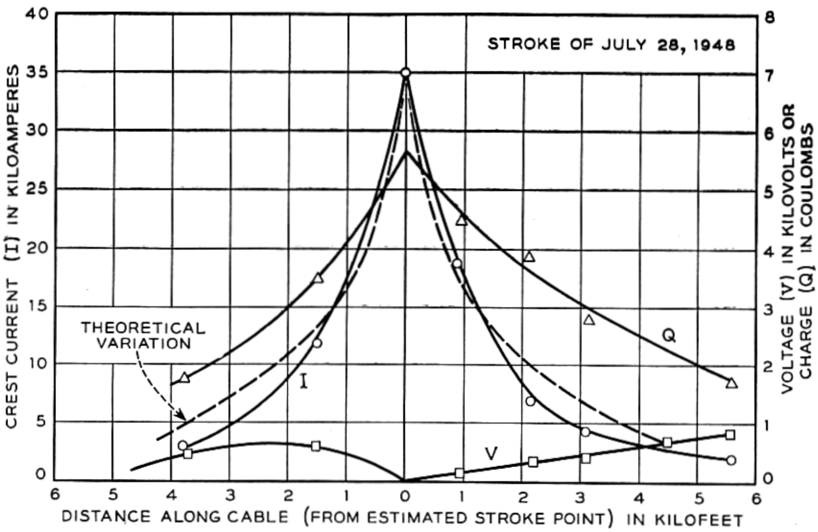

Fig. 8—Variation in crest current, voltage, and charge along cable for max. observed stroke current of 70 ka, having a time to half-value of 130 microseconds. Dashed curve shows theoretical variation of current for this time to half-value and an earth resistivity of 1200 meter-ohms. Variation in voltage between sheath and copper shield indicates breakdown between sheath and copper shield near stroke point.

simulative surge tests had been made three years before to obtain data on voltages in the cable due to surge currents, and tests had also been made of the dielectric strength of the thermoplastic insulation between the sheath and the copper shield. These latter tests disclosed low dielectric strength in the thermoplastic insulation at the location of the antenna referred to above, a defect which was repaired at the time. The voltage curve in Fig.

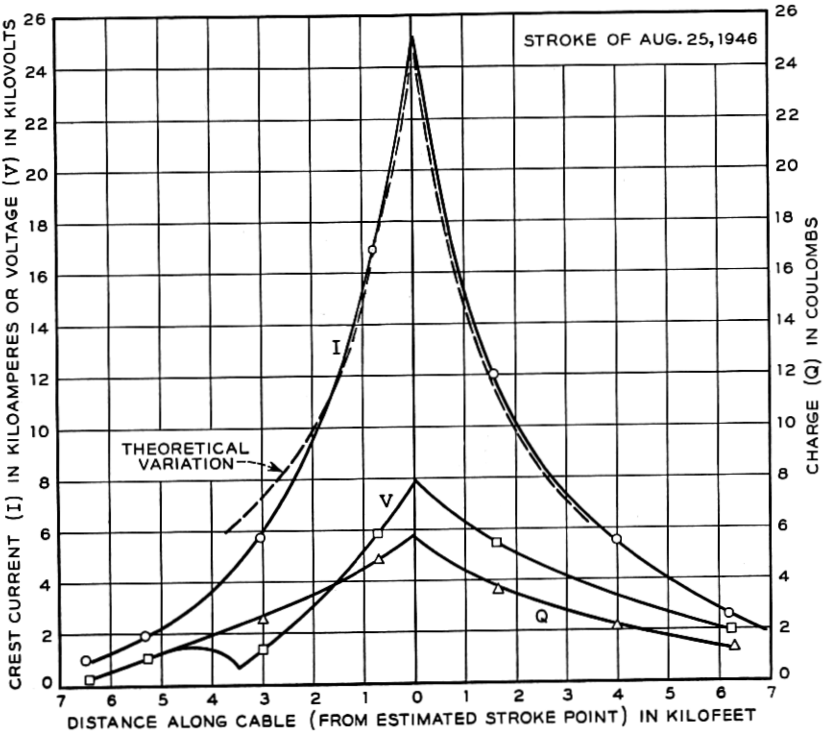

Fig. 9—Variation in crest current, voltage, and charge along cable for an extrapolated stroke current of 50 ka, having an estimated time to half-value of 190 microseconds. Dashed curve shows theoretical variation of current for this time to half-value and an earth resistivity of 1700 meter-ohms.

8 indicates that breakdown of the thermoplastic insulation occurred as a result of excessive voltage between the sheath and the copper jacket, but no other damage to the cable resulted. In Fig. 8 is also shown the theoretical variation in crest current along the cable, for a uniform earth of 1200 meter-ohms resistivity, for a stroke current reaching its half-value in 130 microseconds, as obtained from the crest current and charge at the stroke point.

In Fig. 9 are shown similar curves for an extrapolated stroke current of 50 ka and 190 microseconds to half-value, together with the theoretical attenuation curve for the current for 1700 meter-ohms, which appears to provide a fairly satisfactory check on the extrapolation. The maximum observed voltage obtained by extrapolation is about 8 kv, which compares with 5.6 calculated as outlined in Section 1.3. The higher observed voltage may be due to a long duration tail current of small value, which may increase the voltage appreciably because of its slow rate of attenuation along the cable.

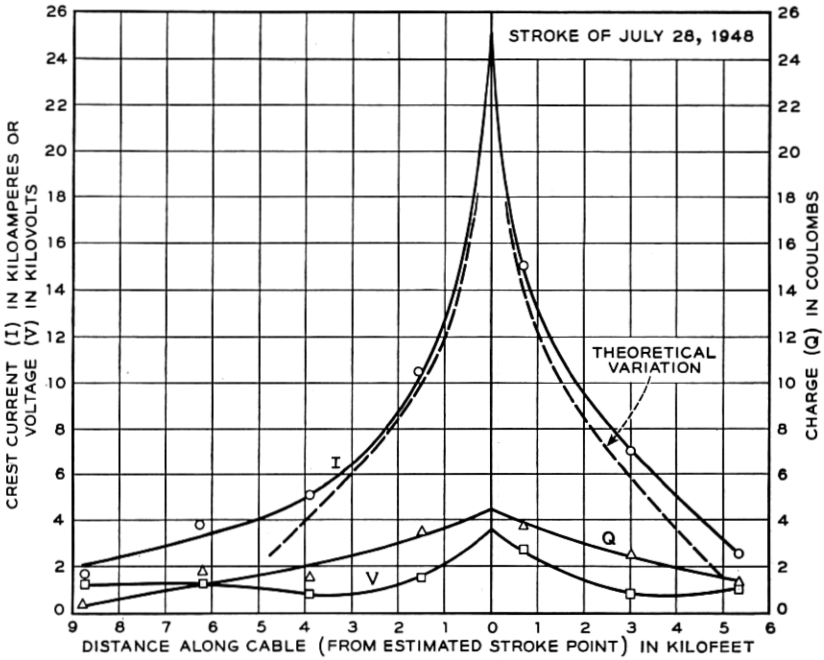

Fig. 10—Variation in crest current, voltage, and charge along cable for an extrapolated stroke current of 50 ka, having a time to half-value of 140 microseconds. Dashed curve shows theoretical variation of current for an earth resistivity of 1200 meter-ohms.

In Fig. 10 are shown similar curves for an extrapolated stroke current of 50 ka, reaching its half-value in 140 microseconds, together with theoretical attenuation curve for the current, for an earth resistivity of 1200 meter-ohms. The maximum extrapolated voltage is in this case about 3.5 kv, as compared with 4.1 calculated for 1200 meter-ohms.

The curves in Fig. 11 are for a fairly low extrapolated current, 16 ka, reaching its half-value in 190 microseconds. Again satisfactory agreement between observed and calculated attenuation is obtained. The maximum observed voltage of 1.5 kv in this case agrees with that calculated for an earth resistivity of 1200 meter-ohms.

Some of the other observations, not reproduced here, were less consistent than those shown, probably due to the combined effects of more than one stroke; but they permitted fairly satisfactory determinations of crest currents and times to half-value.

From Table I it appears that the minimum duration to half-value is about 130 microseconds, the maximum about 1000 and that the average for the three most severe strokes is about 150 microseconds. In general the duration appears to be longer the lower the crest currents, the average for currents of 20 ka and less being about 500 microseconds to half-value.

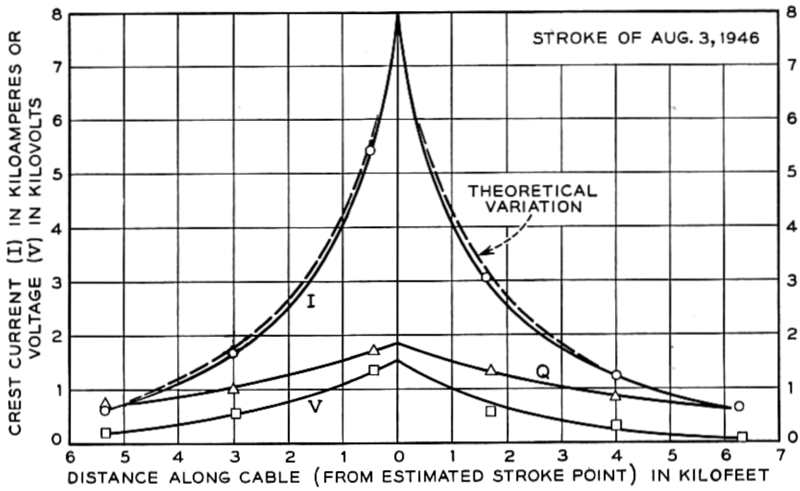

Fig. 11—Variation in crest current, voltage, and charge along cable for an extrapolated stroke current of 16 ka, having a time to half-value of 190 microseconds. Dashed curve shows theoretical variation of current for this time to half-value and an earth resistivity of 1200 meter-ohms.

In the above derivations a simple wave-shape was assumed, although actually it is likely to be rather complex with many fluctuations. The use of an equivalent simple wave-shape is, however, permissible in evaluating the liability to lightning damage, since statistical results rather than the wave-shapes of individual currents are of main importance.

Regarding the cause for the long duration of the currents, it appears to be inherent in meteorological rather than geological conditions, as for the wave-shapes of lightning currents in general. The significance of meteorological conditions is also indicated by the observations discussed in Section 3.3. In the case of strokes to the cable, the latter provides a path of very low impedance compared to that of the lightning channel, so that the wave-shape is determined by the impedance of the lightning channel and the distribution of charge along the leader and in the cloud. This is also true for strokes to ground not arcing to the cable, at least during the time required for the tip of the channel to propagate from the earth towards the cloud, which may be of the order of 50 to 100 microseconds, depending on the height of the cloud. During this inverval ionization of the soil around the base of the channel provides a path in the earth of low impedance compared to that of the channel, as shown in the paper referred to previously. It is possible of course that, during later stages of the discharge, the resistivity of the earth to some extent may limit the current, as the impedance of the completely ionized channel will then be lower and that in the earth higher because of the lower current in the earth with resultant decrease in ionization. This, however, would tend to reduce the current and thereby decrease rather than increase the time to half-value, and at the same time it would tend to cause a long duration tail current of low magnitude.

3.2 *Incidence of Cable Currents of Various Crest Values*

In Fig. 12 is shown the number of observed currents exceeding various crest values, together with curves of the crest current distribution expected on the basis of the theoretical curves given in Fig. 2. The latter curves, together with those in Fig. 3, are based on an incidence of strokes to ground of 2.4 per square mile for 10 thunderstorm days, a value derived from the rate of strokes to transmission line ground structures, as outlined in the paper referred to previously. Although the observations appear to be in fairly satisfactory agreement with theoretical expectations, a total of 15 currents is hardly sufficient as a check of the theoretical curves, particularly since the latter presume a uniform earth structure.

The intersections of the theoretical curves (Fig. 12) with the axis of abscissae indicate that from five to seven of the currents were due to direct strokes. Actually, visual evidence of direct strokes was found in but two cases, in which the strokes occurred to and damaged test equipment. This does not preclude the possibility of additional direct strokes, as evidence thereof in the absence of cable damage may easily escape detection.

3.3 *Incidence of Strokes to Ground*

In Fig. 13 is shown the incidence of strokes to ground observed during 1947 and 1948 from one point within the test section, by the method described in Section 2.5. In the same figure are shown the results of similar observations by the same method, made at one location in New Jersey during 1948 for purposes of comparison. Published data obtained from direct visual and aural observations at one locality in Massachusetts[6] are also shown in the same figure.

As shown by the curves in Fig. 13, the observed or apparent incidence of strokes to ground diminishes as the radius of the observation area increases, for the reason that more of the remote than of the near strokes of low intensity escape observation. To find the actual incidence, a curve of the apparent incidence versus the radius of the observation area may be extrapolated to an area of zero radius. On account of the comparatively few observations for small radii, however, such extrapolation is rather inaccu-

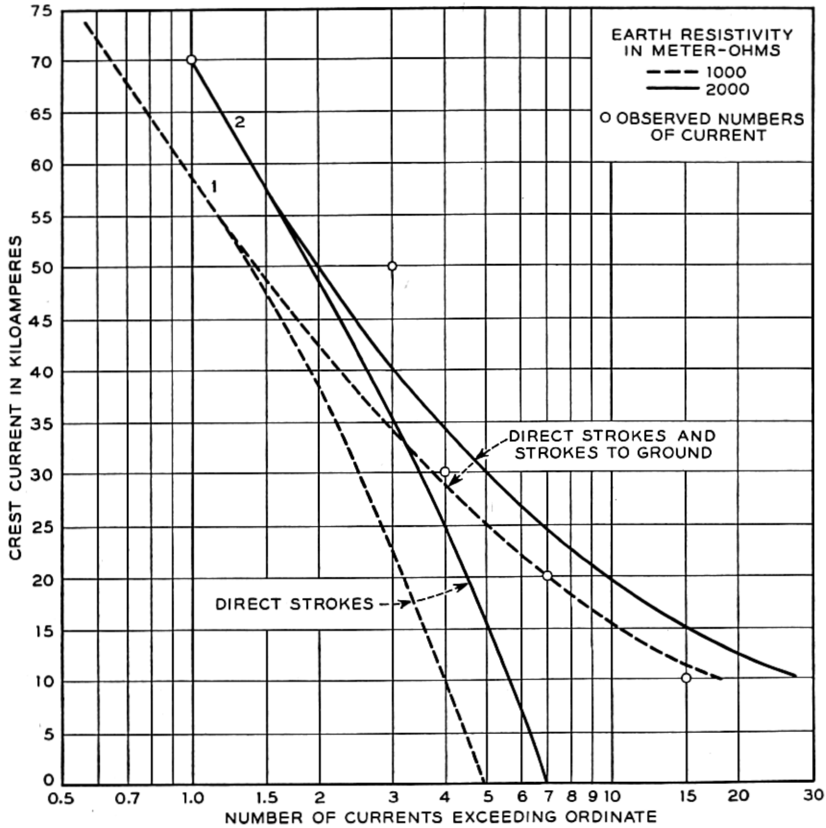

Fig. 12—Comparison between observed and theoretically expected number of currents exceeding given crest values during 108 thunderstorm days in a 21.5-mile section.

rate. Improved accuracy is obtained by using theoretical expectancy curves in the extrapolation as indicated by the curves in the figure. These curves are derived on the assumption that the proportion of currents exceeding a given crest value I is given by $P(I) = e^{-kI}$ where k is a constant —a relation in substantial agreement with observations[1]—and that the energy in the electromagnetic wave from the stroke current, as well as that in the sound wave due to the thunder, is proportional to I^2/r^2, where r

is the distance to the stroke. If the trigger arrangement in the apparatus mentioned in Section 2.5 is sufficiently sensitive to be operated by strokes so remote that the thunder cannot be distinguished above noise on the wire record, then the energy in the sound wave would be controlling, in the sense that it would determine the making of a usable record. On the other hand if the triggering should occur only for strokes of such substantial intensity

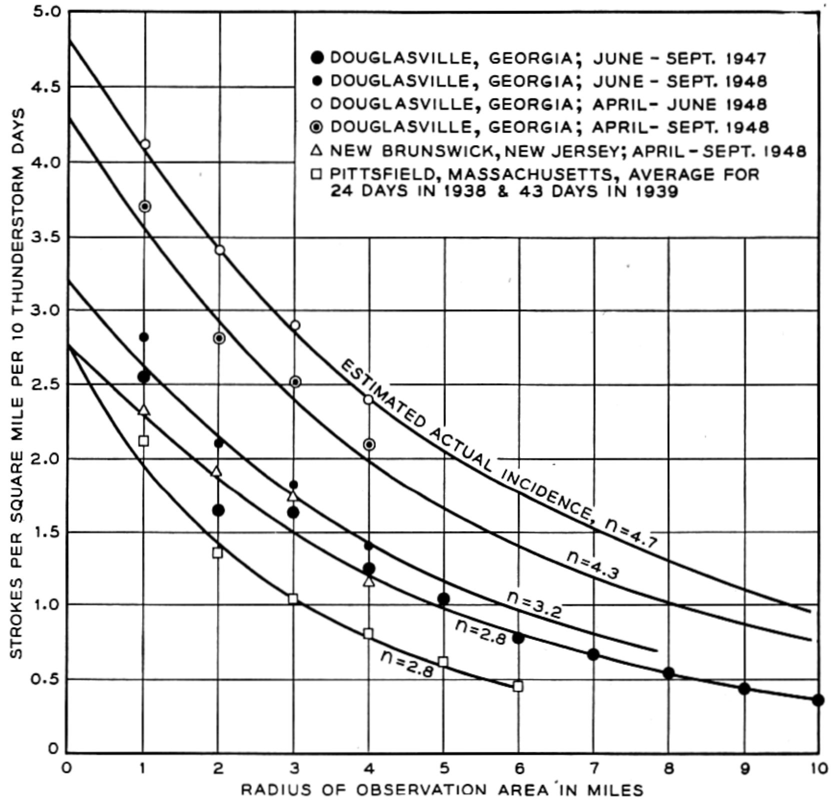

Fig. 13.—Apparent incidence of strokes to ground, per square mile per ten thunder storm days, as a function of radius of observation area.

that some of the more remote strokes of low intensity would not be recorded, then the energy in the electromagnetic wave would be controlling. Similarly, in the case of direct visual-aural observation, the light radiation from the stroke may be assumed proportional to I^2/r^2. If, for any of these methods the energy density is taken as $u = cI^2/r^2$ where c is a constant and the minimum energy required for observation is u_0, then only stroke currents in excess of $I = (u_0/c)^{1/2}r$ would be observed. The observed or apparent number of strokes to ground within an area of radius r would then be, for an actual incidence n of strokes to ground and with $P(I) = e^{-kI}$:

$$N_a = 2\pi n \int_0^r re^{-\alpha r} dr$$

$$= \frac{2\pi n}{\alpha^2} [1 - e^{-\alpha r} (1 + \alpha r)]$$

where $\alpha = k(u_0/c)^{1/2}$.

The apparent incidence of strokes to ground $n_a = N_a/\pi r^2$ is accordingly

$$n_a = \frac{2n}{(\alpha r)^2} [1 - e^{-\alpha r} (1 + \alpha r)]$$

By choice of a proper value of α in the latter expression a theoretical curve, varying in substantially the same manner with r as a given observed curve, may be obtained. The actual incidence is next obtained by taking a value of n such that the two curves substantially coincide. This value of n also corresponds to the incidence given by the theoretical curve for $r = 0$, i.e. the value that would be expected if a sufficient number of observations were available for small values of r to permit extrapolation of the observed curves to $r = 0$. The value of n obtained in the above manner is about 2.8 for the New Jersey and Massachusetts and 1947 Georgia observations. The latter extended over the last half of the lightning season, while the 1948 Georgia observations, which indicate a higher incidence, extended over the entire season. The comparison, shown in the figure, between the observations in Georgia during the first and second halves of the 1948 season, indicates that the incidence during the first half is about 50 per cent greater than during the second half. A similar comparison of the New Jersey observations, not shown in the figure, indicates the opposite trend, i.e. a somewhat smaller incidence during the first half. The difference, however, is less marked than in the Georgia case.

There is reason to believe that this change in Georgia with the advance of the season is due to a change in the character of the lightning storms. During several years the more severe lightning damage on cable routes in this territory has occurred during early-season thunderstorms, which ordinarily are of the "frontal" type extending over fairly wide areas where hot and cold masses of air come together. These storms appear to be of greater extent, duration, and severity than the "convection" type of storm, ordinarily experienced later in the season, which occur more frequently as the result of local air convection currents but are of more limited extent and duration than storms of the frontal type.[7]

As mentioned before, the theoretical expectancy of lightning damage and of strokes to the cable discussed in this paper has been based on an incidence of 2.4 strokes per square mile for 10 thunderstorm days, a value derived from magnetic link observations of the rate of stroke occurrence to the aerial supporting structures of transmission lines, on the assumptions that they attract lightning strokes in accordance with laws established from laboratory observations on small-scale models, and that the average height of the ground wires is 70 feet above the earth or adjacent trees.[1] If this height had been taken as 60 feet instead the incidence would have been 2.8, in substantial agreement with that obtained from our observations for northern territory—in the main the territory traversed by the transmission lines from which the data were obtained.

The curves shown in Fig. 13 include substantial areas and a rather large amount of data and should, therefore, be fairly representative. Thus a radius of four miles corresponds to an observation area of 50 square miles. Within this area a total of 342 strokes was recorded during 1948 at the observation point in the test section near Atlanta. One of the storms during this period, in which the antenna was struck, passed directly over the observation point and provided a considerable amount of the data. However, even if the observations during this storm were omitted, the total for the season would have been reduced by less than 10 per cent, while the observations during July, August, and September would have been reduced about 20 per cent and would have been slightly lower than in the same 1947 period. The data thus indicate that the yearly incidence per square mile of strokes to ground is about 2.8 per 10 thunderstorm days in northern parts of the country, but may be as high as 4.3 in those southern parts where more severe types of thunderstorms occur. Considering, however, both the 1947 and 1948 observations in Georgia, it appears that an incidence of 3.7 would be a reasonable expectation for an entire season. With this incidence, rather than 2.4 as assumed in Fig. 12, Curves 1 and 2 in that figure would approximately correspond to earth resistivities of 500 and 1000 meter-ohms, respectively.

Conclusions

The observations indicate that the duration of lightning currents in the southern territory under observation is substantially longer than the average ordinarily assumed. The time to half-value of intense currents, which are of main importance as regards liability to lightning damage, is of the order of 150 microseconds, and for lower currents even larger. This, together with the higher incidence of strokes to ground and the high earth resistivity, would appear to account for the high rate of lightning damage experienced in this territory in cables of earlier design than the copperjacketed cable upon which measurements were made. The incidence of cable currents of various intensities, their rate of attenuation, and the resultant voltages appear to be in satisfactory agreement with theoretical expectations.

Acknowledgements

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