Lightning Surges in Paired Telephone Cable Facilities

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The problem of protecting apparatus against lightning surges from connected transmission facilities has become more complex with the use of solid state devices in apparatus design. Consideration of the protection requirements for such apparatus has indicated that existing information concerning the incidence and characteristics of lightning surges is insufficient to develop optimum protection measures. A recently completed field investigation provides additional information in this specific area.

The results of this field investigation and supplemental laboratory surge tests indicate that, in well-shielded underground cable pairs, electrical surges do not exceed approximately 90 volts peak, and that transistorized apparatus capable of withstanding such surge amplitudes needs no further protection. In aerial and buried cable, however, transistorized apparatus requires protection up to the full sparkover potential of 3-mil protector gaps, i.e., to about 600 volts peak. A firm basis for testing and evaluating transistorized apparatus from the lightning surge voltage standpoint is presented.

I. INTRODUCTION

The 3-mil air gap carbon block protector, which has a maximum sparkover value of 600 peak volts, is the basic protection device employed by the Bell System for the protection of communication apparatus against extraneous potentials. Prior to the introduction of transistors and miniaturized circuitry, it was the general practice in apparatus design to provide a withstand level for both metallic* and longitudinal† potentials greater than 600 peak volts so as to coordinate directly with 3-mil protector gaps. This customary design objective of providing an inherent withstand capability exceeding the operating value of standard protector gaps is not always feasible in the case of apparatus employing

* Voltage appearing between the conductors of a pair.
† Voltage appearing between a conductor and ground.

solid state devices. Furthermore, lower voltage protection cannot be attained satisfactorily by simply reducing protector-gap spacing below 3 mils, since excessive protector maintenance would be introduced. To meet the lower voltage requirements of apparatus employing transistors, therefore, it is necessary at present either to modify the circuitry so that surge currents appearing in the more susceptible components are limited in magnitude, or to introduce an additional stage of protection employing semiconductor diodes supplementing the gaps. These protection measures may introduce significant additional expense and, in some cases, produce adverse effects on transmission characteristics.

It became apparent that selection of optimum protection measures to meet the exacting requirements of transistorized apparatus necessitated a more complete knowledge of the incidence and characteristics of lightning surges in the range below the operating level of standard protector gaps. Recognizing this, a field investigation was undertaken to supplement existing information in this area. The results of this recently completed field study and conclusions drawn from analysis of the data are presented in this article.

Since it appeared, at the time the investigation was undertaken, that the present practice of employing 3-mil protector gaps as basic apparatus protection would continue into the foreseeable future, all circuits used for purposes of observation were equipped with such protectors. The area of study therefore was intentionally restricted to surges up to about 600 peak volts as limited by protector operation.

Observations of lightning surges appearing in trunk pairs in aerial and buried cable were recorded by means of automatic cathode ray oscillographs. The plant locations selected were in areas known to experience heavy thunderstorm activity. Surges were also monitored by means of peak amplitude recording devices in urban underground cables. Because of the shielding provided by buildings and buried piping facilities, the exposure of cables to lightning in this situation was relatively low.

Information of engineering value secured includes the probability distribution of voltage magnitudes and the rise and decay time characteristics of surges in the lower voltage range specifically under study. Such data have been used as a basis for selecting waveshapes suitable for laboratory testing of the energy and power handling capabilities of transistorized apparatus.

II. FACILITIES OBSERVED AND MEASURING PROCEDURES

Field data on lightning surge characteristics were obtained from types of telephone plant having two degrees of lightning exposure:

1. Low exposure, typified by underground plant in well-shielded urban areas.
2. High exposure, typified by aerial and buried cables in suburban and rural areas.

2.1 *Low-Exposure Facilities*

The study of surge activity in underground cable was conducted on spare trunk pairs in Baltimore, Maryland; Pontiac, Michigan; and South Orange, New Jersey. Table I gives a brief description of the route and make-up of these facilities.

As indicated in Table I, field observations were made on two types of trunks: those in all-underground cable and those in underground cable with aerial subscriber complements. A total of five trunks for the three locations was monitored for both longitudinal and metallic voltages with gas-tube-type, peak voltage counters. The counters were designed to record surge voltages in three voltage ranges from 90 volts up to the sparkover value of protector blocks.

2.2 *High-Exposure Facilities*

The waveshapes of lightning surges in aerial and buried cable were studied with cathode-ray oscillographs arranged to monitor continuously the pair selected for observation and to record automatically on 16-mm film all surges exceeding 60 volts peak. On each test pair, simultaneous measurements were made of open-circuit longitudinal surge voltages and any resultant metallic voltages appearing across a representative resistive termination. Spare H88-loaded trunk pairs in aerial cable were

TABLE I — DESCRIPTION OF UNDERGROUND TRUNKS MONITORED WITH SURGE COUNTERS

Cable Location	Type of Cable	Circuit Length (miles)
South Orange to West Orange, N. J.	400-pair underground cable with aerial complements	4
South Orange to Summit, N. J.	455-pair 100% underground cable with H88 loading	6
Pontiac to Birmingham, Mich.	Underground cable with aerial complements and H88 loading	8
Baltimore to Pikesville, Md.	900-pair 100% underground cable with H88 loading	8½
Baltimore to Towson, Md.	900-pair underground cable with aerial complements and H88 loading	8

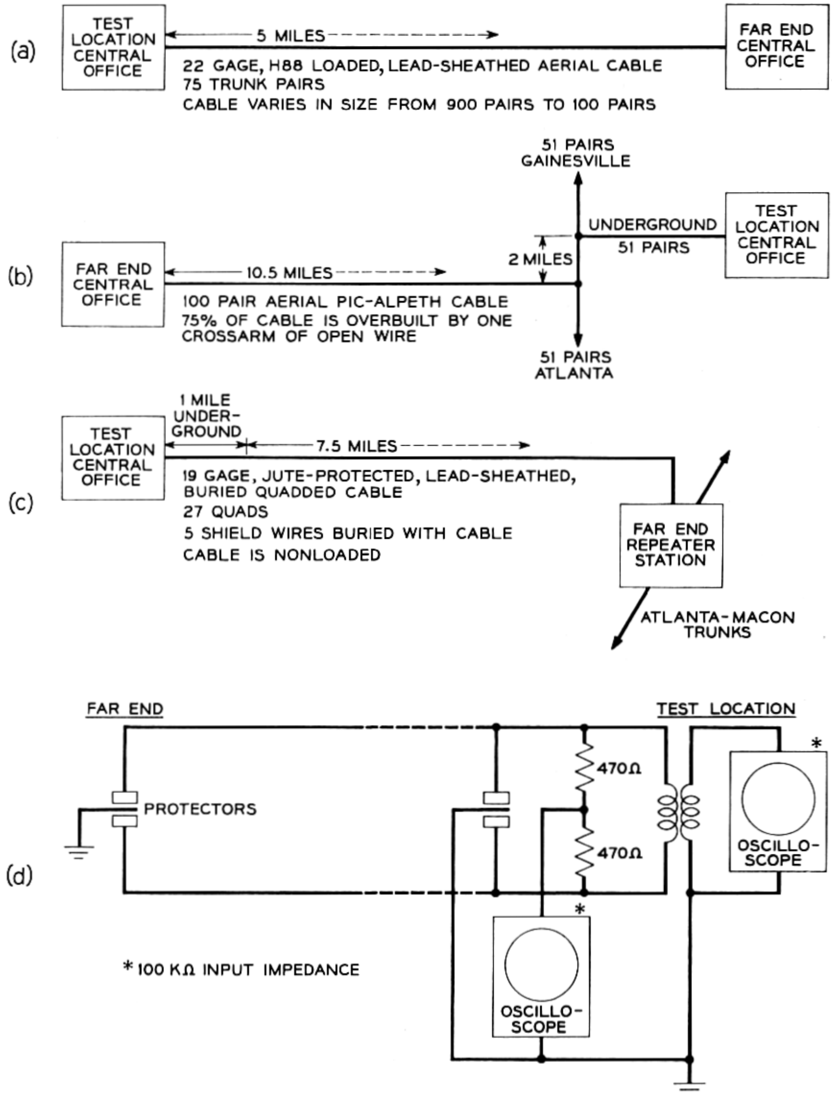

Fig. 1 — Characteristics of test cable at (a) Mt. Freedom, N. J., (b) Buford, Ga., (c) Griffin, Ga.; (d) arrangement of measuring equipment at test locations.

studied in Buford, Georgia, and Mt. Freedom, New Jersey. The buried cable studies were conducted in Griffin, Georgia, on a spare nonloaded trunk. Descriptions of the cable involved and the measuring equipment used at each of these test locations are presented in Fig. 1.

Supplemental laboratory surge tests were also conducted on a one-mile test cable to augment the information on the behavior of underground cables with aerial complements and extensions.

III. RESULTS

The incidence and characteristics of the lightning surges recorded and the resulting protection considerations will be discussed in the order of the degree of plant exposure.

3.1 *Facilities Having Low Lightning Exposure*

Surge characteristics in underground plant were studied in: (a) trunks in all-underground cable, (b) trunks in cable with aerial subscriber complements and (c) trunks extended aerially. The first two situations were studied in the field. The third was investigated subsequently in the laboratory.

The field study of surge activity in well-shielded urban underground plant, covering the first two categories, revealed that in no case did voltages attain the 90-volt triggering value of the lowest stage of the counters. During the five-month observation period, a total of 44 thunderstorm days was reported by the U. S. Weather Bureau for these areas. Several of these storms were known to be quite severe, with their centers located over the test cables. The counters were tested periodically during the study period to ensure proper operation. The lack of surge activity recorded during this study reveals the shielding benefits enjoyed by urban underground plant. In such areas, buildings and buried metallic piping systems divert and dissipate lightning strokes that otherwise might directly involve the telephone cables. Furthermore, duct runs usually contain two or more cables, the sheaths of which are bonded at each manhole. Surge current will, therefore, divide between the cables, and the voltage induced in any one cable will be proportionately reduced.

On the basis of these field studies, it appears that apparatus capable of withstanding surges in the order of 90 to 100 volts peak will not require lightning protection when associated with all-underground cable pairs (trunk or loops), whether such pairs are in an all-underground cable or one with well shielded aerial complements. The significant point is that this conclusion holds only for well-shielded plant, the shielding being provided by closely spaced buildings, extensive power distribution and buried metallic piping systems, and other telephone cables in the same conduit run.

The question now arises as to the magnitude of surges that may appear in a 100 per cent underground trunk complement through coupling with underground pairs extended aerially in cable having greater exposure to lightning than those employed in the field study.

Information on the following specific points relative to such surge coupling is useful in estimating the secondary exposure likely to be experienced by apparatus connected to the 100 per cent underground trunk pairs:

1. The ratio between an open-circuit longitudinal voltage surge on a disturbing circuit (underground pair associated with an aerial extension) and the resultant voltage appearing in a disturbed circuit (100 per cent underground trunk pair).

2. The resultant magnitude and waveshape of longitudinal current appearing in the disturbed circuit.

To secure this information, supplemental laboratory surge tests were conducted on a 50-pair, one-mile test cable. Longitudinal impulses (approximately 50 by 250 microseconds*) were applied to one or more cable pairs acting as the disturbing circuit. Several cases were investigated: energizing a single pair, then 5 pairs in parallel and finally 25 pairs in parallel. Measurements were made of longitudinal open-circuit voltage and short-circuit current in the disturbing circuit. Measurements were then made of longitudinal open-circuit voltage and short-circuit current in a disturbed pair. Pairs both adjacent and remote from the disturbing circuit were investigated.

The ratio of longitudinal open-circuit voltage appearing in a disturbed pair to the longitudinal open-circuit voltage in the disturbing circuit varied, depending on test conditions, from about 0.47 to 0.85. The lower value was obtained when only a single pair was energized and the larger value when the surge was applied to 25 pairs paralleled at the generator end. Although the magnitude of the open-circuit surge voltage appearing in the disturbed circuit was significantly lower than that in the disturbing circuit, the waveshapes of the two were essentially the same. In the cases investigated it was found that the longitudinal short-circuit current in the disturbed pair was approximately 3 milliamperes per volt appearing in the disturbing circuit. The short-circuit current in the

* That is, 50 microseconds rise time to crest and 250 microseconds from origin to point where wave has decayed to half of crest value.

disturbed pair assumed the shape of a square pulse about 20 microseconds in duration. From a protection standpoint, this radical reduction in the duration of the induced current wave in the disturbed circuit is probably the most significant bit of information secured in these laboratory tests. Semiconductor components, when exposed to lightning surges, usually fail as a result of overheating of their junction or junctions — the heating effect being related to the magnitude and duration of the junction current. Therefore, the possibility of failure from longitudinal current of semiconductor components in apparatus associated with a disturbed pair is much reduced because of the relatively short duration of the coupled surge.

It is of further interest to note the effect of grounding the disturbing circuit at the far end, such as would occur with protector operation. This condition was investigated by grounding one of the conductors constituting the disturbing circuit, and it was found that the open-circuit longitudinal voltage on the disturbed pair was reduced approximately 50 per cent and the short circuit longitudinal current 30 per cent below the values that would obtain if the conductor of the disturbing circuit had not been grounded. This indicates the order of beneficial shielding enjoyed by the disturbed circuit when protector blocks operate on the disturbing circuit.

Additional laboratory surge studies were made employing a one-mile test cable to determine the protection requirements for apparatus connected to underground pairs extended aerially. These tests revealed that surges having typical waveshapes will propagate longitudinally on a cable pair for one mile with little attenuation. Therefore, underground cable pairs extended aerially or in buried plant should be considered as exposed to lightning, unless protection is applied at the underground junction to limit surges from the exposed extensions.

3.2 *Facilities Having High Lightning Exposure*

The lightning exposure of buried and aerial cable is sufficiently severe to require supplementary protection for transistorized apparatus associated with this type of plant. The most useful way of defining protection requirements in this situation is in terms of a simulated lightning surge which such apparatus must withstand in laboratory tests. Simulated surges, of course, must be based on surge conditions in the field. Consequently, derivation of suitable test surges requires knowledge of the distribution of waveshapes and peak voltages of lightning surges appearing in the plant.

3.3 *Longitudinal Surges*

The data on longitudinal surges in aerial cable at Buford covered a period of six months, during which time six thunderstorm days occurred and 103 oscillograms were obtained. Additional data on aerial cable were secured at Mt. Freedom, with 105 oscillograms being recorded during three thunderstorm days. The buried cable studies conducted at Griffin covered a period of six months, during which 36 thunderstorm days occurred and 1120 oscillograms of longitudinal surges were obtained. Since these cables involved very little unexposed plant, the surge magnitudes and waveshapes recorded at the central offices should also be reasonably representative of surge conditions along the cable route.

Comparison of the recorded waveshapes of longitudinal surges induced in aerial and buried cables indicates that the two types of plant do not differ significantly in their response to lightning surges. The data also confirm that load coils have little or no effect on the waveshape of longitudinal surges. This observation is based on the similarity of the surges recorded on H88-loaded aerial cable and those recorded on non-loaded buried cable. These surges were found to be essentially impulses, as exemplified in Fig. 2. Longitudinal impulses can conveniently be characterized on the conventional basis of crest magnitude, time to crest and time from origin to the point at which the wave has decayed to one-half of crest value.

Both the rise time to crest and decay time to half-crest value of lightning surges observed in cable exhibited log-normal distributions.

The peak voltages of surges induced in cable pairs were found to follow an exponential distribution similar to the lightning stroke currents that produce these voltages.

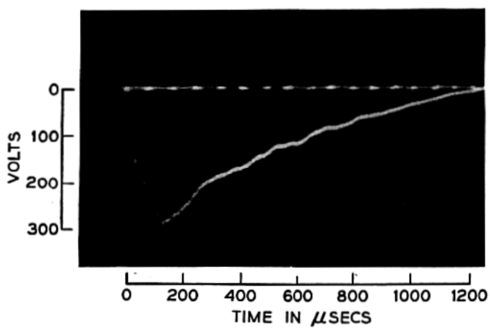

Fig. 2 — Representative longitudinal lightning surge in cable plant.

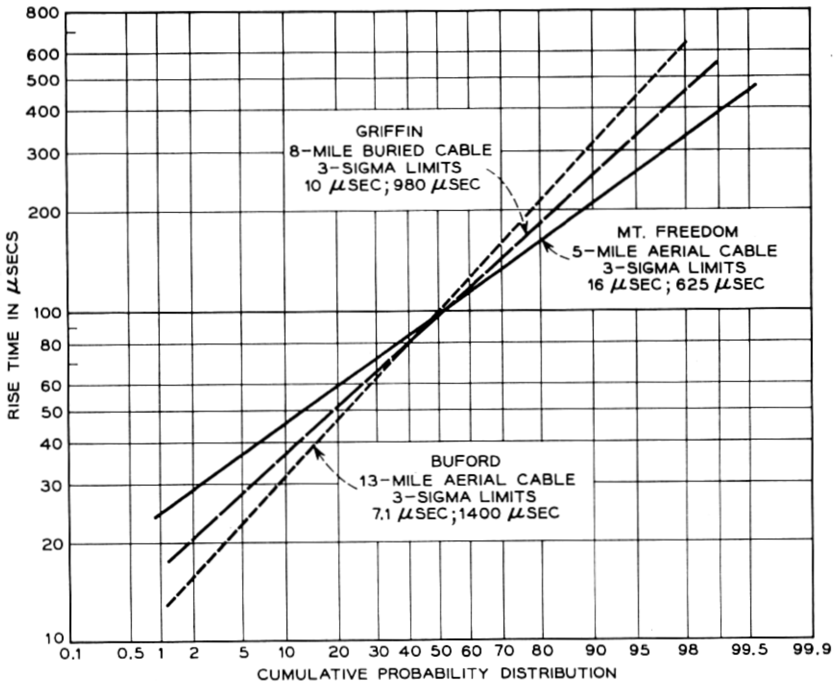

Fig. 3 — Distribution of rise times.

3.3.1 *Rise Time Characteristics*

Distribution of surge rise times for the three test locations are presented in Fig. 3. The median rise time measured at each location was approximately 100 microseconds, but the dispersion about the median value varied widely among locations, probably due to the difference in cable lengths involved. As a surge propagates along a cable pair, there is some modification in waveshape. Consequently, slightly greater dispersion should be expected in longer cables. This is borne out by the measurements plotted in Fig. 3.

3.3.2 *Peak Voltage Characteristics*

The peak voltages recorded in aerial and buried cable in the range below protector block operation (voltages less than 400 volts) were found to be exponentially distributed. This distribution provides a basis for determining the probability of any given surge exceeding a particular value. The derivations of these probability functions for aerial and buried cable are given in the Appendix. These probability functions, used in conjunction with the average number of surges induced in the test cables per thunderstorm day, provide an order-of-magnitude estimate of the number of surges per thunderstorm day exceeding any given amplitude. The similarity between the peak voltage distributions for aerial and buried cable makes it feasible to develop a single plot of the estimated number of surges per thunderstorm day as a function of voltage.

Fig. 4 presents both the distribution that would be expected if no protector blocks were associated with the test pair and the modified distribution reflecting the operating characteristics of standard 3-mil air gap carbon protectors. This information is useful in the design of reliability tests for apparatus vulnerable to repeated low-amplitude voltage surges, and is used in the selection of suitable test surges, as discussed later.

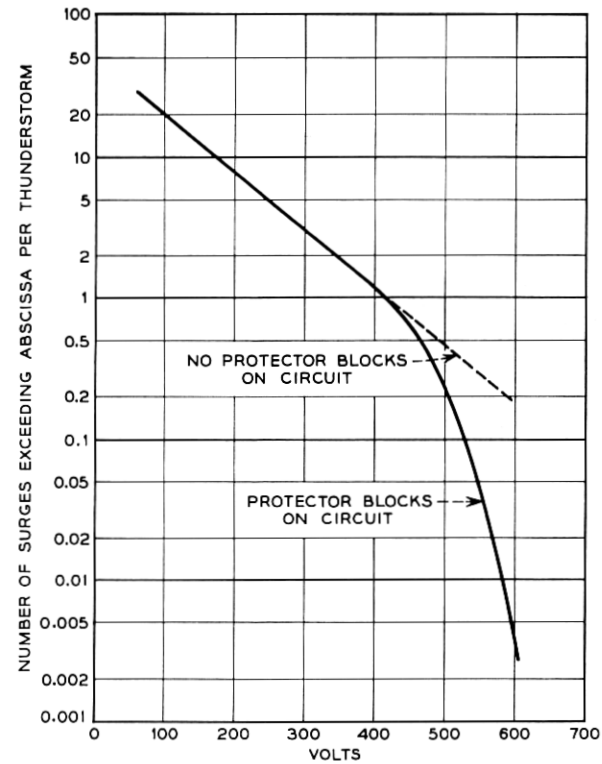

Fig. 4 — Surge voltage distribution on buried and aerial cable.

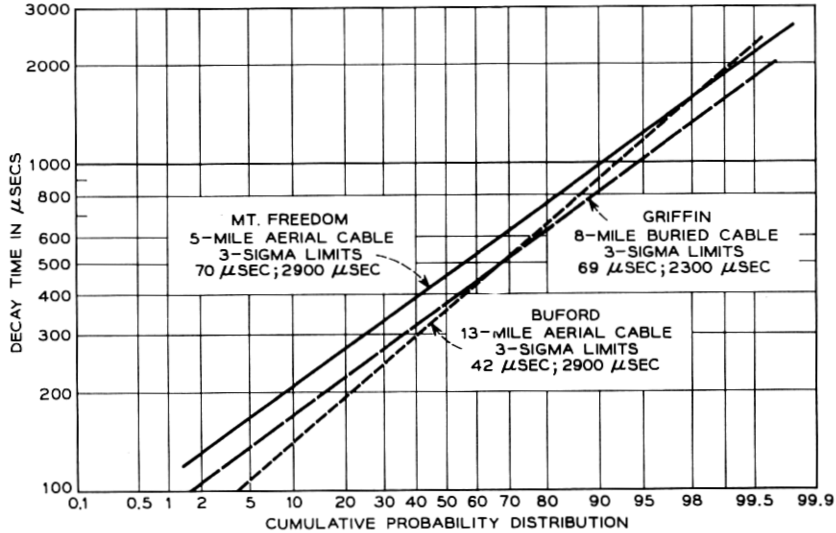

Fig. 5 — Distribution of decay times.

3.3.3 *Decay Time Characteristics*

The distributions of decay times of lightning surges appearing in cable plant are presented in Fig. 5. The median values and dispersions differed slightly among the three test locations. Median values ranged from 350 to 450 microseconds. Three-sigma limits ranged between 40 to 70 microseconds on the low side and between 2300 and 2900 microseconds on the high side. The variation of median values is possibly due to differences in the relative exposure of the test cables.

In Buford and Griffin, the cables traverse relatively level terrain and, therefore, should have fairly uniform exposure along their lengths. Close correlation is noted between the median decay time values for these cables. In Mt. Freedom, however, the cable is placed on hilly terrain, which results in a higher exposure for some sections of the cable. With the majority of the surges being induced into one section of the cable, a shift in the median value results.

3.4 *Metallic Surges*

Metallic surges were recorded on the same trunk cable pairs used at Buford and Griffin to record longitudinal surges. Measurements were made across a 940-ohm resistive termination. Simultaneous operation of the automatic recording oscillographs observing longitudinal and metallic voltages was arranged in order to permit correlation between each longitudinal surge and any resultant metallic surge.

In the absence of conductor insulation breakdown or protector operation, the circuit balance of cable pairs is sufficiently good that metallic surge voltages should be much lower than longitudinal surge levels, which is confirmed by the measurements secured in this study. Of all longitudinal surges exceeding 60 volts* only about 10 per cent produced metallic voltages exceeding 10 volts peak. However, when protector operation occurred, metallic surge potentials of significant magnitudes were produced. An approximate breakdown of those metallic surges which exceeded 10 volts peak is presented below on the basis of waveshape and magnitude:

1. Twenty per cent were low-amplitude, high-frequency oscillations having maximum peaks of about 35 volts and frequency components ranging from 10 kc to approximately 50 kc.

2. Twenty-five per cent were impulses ranging in amplitude up to about 60 volts peak, which were probably caused by protector operation on adjacent pairs.

3. Fifteen per cent ranged in amplitude from 120 to 200 volts peak. The oscillograms of the associated longitudinal surges definitely indicated protector operation on the test pair although the surge amplitudes were considerably lower than the level normally required for protector block operation. The protector blocks on the test pair were changed periodically during the study period, but these low-voltage operations (16 in all) occurred with the same set of blocks. However, visual inspection of these protector blocks by local personnel did not reveal anything unusual in their appearance.

4. Forty per cent of the metallic surges exceeded 350 volts peak. These surges were all associated with protector operation on the test pair.

Examination of the oscillograms of these high-amplitude metallic surges and the corresponding longitudinal surges illustrates some interesting aspects of protector block operation. Fig. 6(a) shows one type of single-block operation where the discharge is continuous for the duration of the surge. Fig. 6(b) illustrates another type of single-block operation in which clearing and restriking of the arc discharge occurs. This situation is the result of circuit regulation when the longitudinal surge potential is just sufficient to initiate gap sparkover.

* Threshold value of automatic recording oscillographs measuring longitudinal surges.

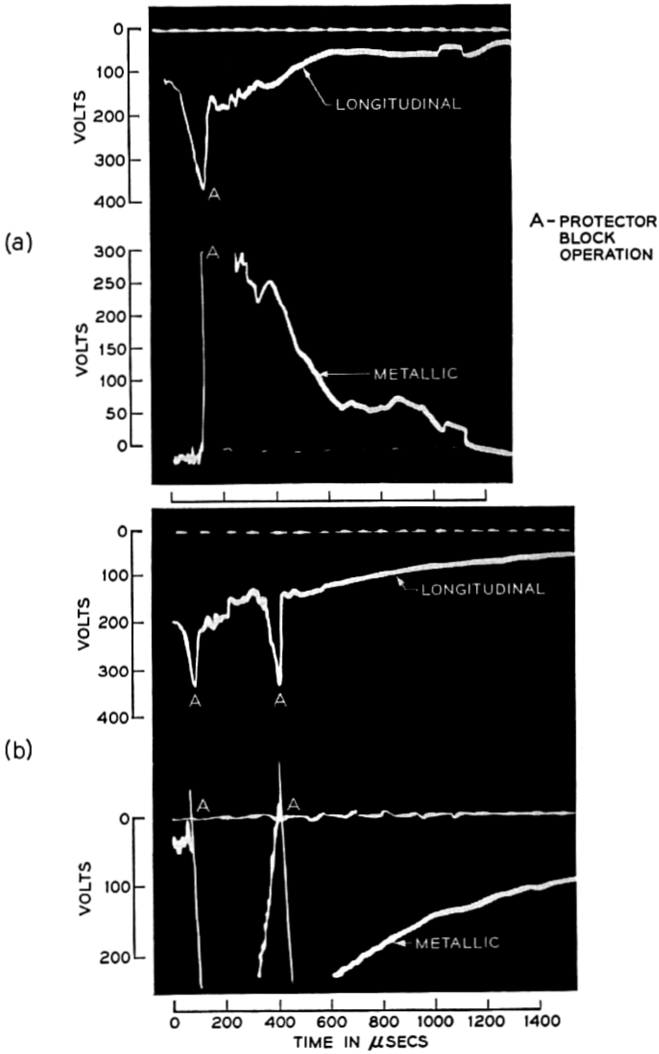

Fig. 6 — Lightning impulse voltages on a nonloaded buried cable pair: (a) with protector operation on one conductor; (b) with multiple protector block operation on one conductor.

A brief explanation of surge voltage relationships during single-block operation as indicated by the oscillograms follows:

At point A [Fig. 6(a)], the gap associated with one conductor operated and remained operated for the duration of the surge. The longitudinal voltage dropped to about one-half of peak value as the oscilloscope is connected to the midpoint of a 940-ohm termination (see Fig. 1).* The metallic surge shows the true voltage unbalance, which is the difference between the arc discharge voltage on one conductor (approximately 50 volts) and the longitudinal surge voltage on the other conductor.

At the first point A [Fig. 6(b)], the gap associated with one conductor operated and remained operated for approximately 350 microseconds. The metallic surge began at point A and continued for the same duration. At the second point A the protector gap "cleared" and then operated again. When it cleared, the longitudinal scope recorded the true longitudinal voltage* and the metallic voltage dropped to zero. When the block restruck, the longitudinal scope again read one-half true longitudinal voltage and once more there was a metallic voltage.

Metallic surges resulting from operation of both blocks on a pair are shown in Figs. 7(a) and 7(b). In the first case, one block operated initially, then cleared, and then the other block operated. This sequence of operation produced a metallic surge having impulses of both polarities. In the second case; both blocks operated, but unbalances were produced by nonsimultaneous clearing and restriking of the two gaps.

Further explanation of surge voltage relationships resulting from a longitudinal surge of sufficient magnitude to operate both blocks is as follows:

At the first point A [Fig. 7(a)], the protector on one conductor operated, in this case, the one on the "tip" conductor. The recorded longitudinal voltage then dropped to one-half of the actual value and the metallic surge began. At the second point A, the protector on the "ring" conductor operated and the longitudinal surge voltage dropped to essentially zero. At the third point A, the protector on the "tip" conductor cleared. This is evidenced by the reappearance of metallic voltage of reversed polarity.

Fig. 7(b) illustrates a phenomenon that commonly occurs during the operation of protector gaps on telephone circuits. The discharge is not a continuous process but is punctuated by a random restriking of the arc discharge. In this case there was sufficient longitudinal potential to operate both blocks, but apparently some differences in electrode conditions caused nonsimultaneous clearing and restriking of the arc discharge which produced metallic potentials. It is only during the brief

* In effect, the longitudinal scope always reads the true open circuit voltage until one block operates; then it reads one-half the true longitudinal voltage. The metallic oscilloscope always reads the total voltage difference between the two conductors of the pairs.

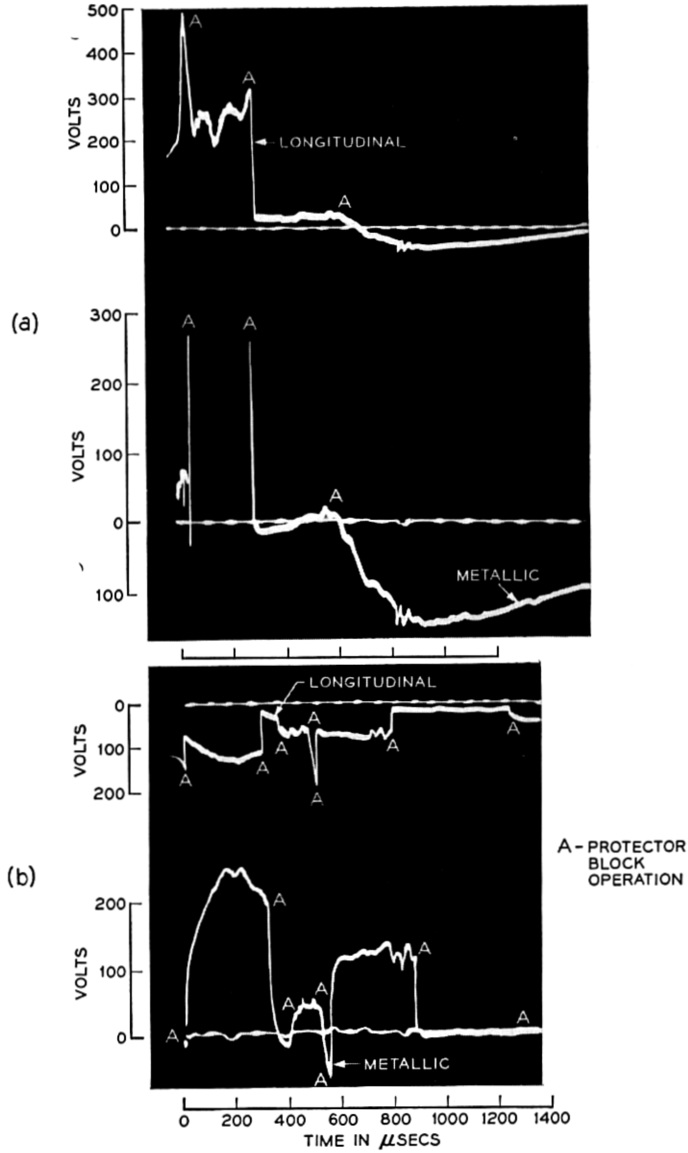

Fig. 7 — Lightning impulse voltages on a nonloaded buried cable pair: (a) with protector block operation first on one conductor, then on the other; (b) with multiple striking and restriking of protector blocks.

periods when the two gaps are either both discharging or not discharging that metallic potentials are reduced to negligible values.

IV. SELECTION OF SUITABLE WAVEFORMS FOR LABORATORY TESTING

The similarity of longitudinal waveforms observed in buried and aerial plant under loaded and nonloaded conditions makes it practicable to employ common waveforms for laboratory testing of apparatus intended for use with all of these types of plant. In the past, a 10 by 600-microsecond surge was selected on the basis of limited field data. The supplemental surge data obtained in this study makes it possible to select waveshapes for laboratory testing which more closely simulate surges produced in the telephone plant by natural lightning.

Analysis of the recorded data obtained during this study provided the distributions of rise times, peak voltages and decay times presented in Figs. 3, 4 and 5. Using these distributions as a basis, it is possible to select suitable laboratory test surges.

Since the severity of a surge is dependent on its peak voltage and its decay time, it is necessary to establish whether decay time is independent of peak voltage before computing the joint probability of occurrence of a surge with a given amplitude and decay time. Accordingly, new decay time distributions were developed from the recorded data for two voltage ranges; voltages below 225 volts and voltages above 225 volts. Fig. 8 presents the results of this analysis. It will be observed that there is a slight correlation between the decay time and voltage. This is the result of the manner in which the surge current in the sheath induces voltage onto the cable pairs. The capacitive coupling between the sheath and the core results in an integration of the sheath current. Thus, surges of longer duration will tend to produce higher voltages on the cable pairs. In determining the joint probability of exceeding a given amplitude and a given decay time, this correlation, as indicated by the field data, should be included by using the probability distribution of decay times associated with higher voltages (upper curve in Fig. 8).

The parameters of laboratory test surges should be so selected as to evaluate apparatus properly for its dielectric strength and its energy and power handling capabilities. The effect of these factors on the parameters of test surges is discussed below.

Surges suitable for test purposes should have a peak amplitude of at least 600 volts to provide a minimum test of apparatus dielectric strength, since 3-mil protector gaps associated with apparatus assure protection only against surges in excess of this value. Furthermore, when the thermal time constants of vulnerable components are small, power is

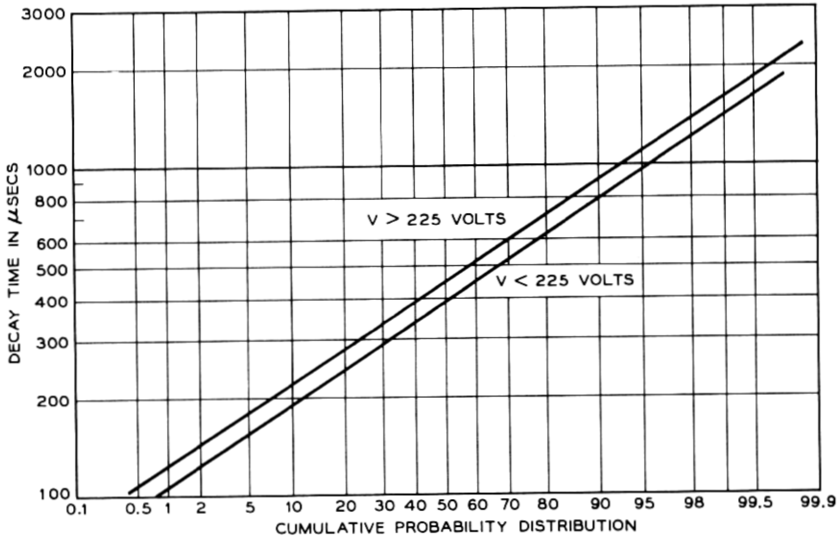

Fig. 8 — Distribution of decay times.

more detrimental than energy content and, given two surges of equal content, more power will be delivered by the surge with the higher amplitude.

The energy content of a surge is dependent on its peak voltage and waveshape (i.e., rise time and decay time). Test surges should have short rise times for two reasons. A short rise time will provide a more severe test of inductive circuit elements and, for a given decay time, the shorter the rise the higher will be the total energy of the surge. Accordingly, a 10-microsecond rise time has been selected as it is approximately the lower 3-sigma limit of the rise times recorded in the field.

In those instances where the energy-handling capability of apparatus is the controlling factor, the reliability of a surge testing program will depend on the degree of assurance that the energy content of the test surge will not be exceeded in the field. The total energy of an impulse with a short rise time is proportional to the decay time and the square of the voltage. The energy content of any arbitrarily assumed test surge can be exceeded in the field in two ways: surges of lower amplitudes but appreciably longer decay times, or surges of higher amplitude and only somewhat shorter decay times. This second classification can be eliminated, however, by selecting test surges having peak amplitudes of 600 volts or greater, as the standard 3-mil air gap protectors associated with equipment will not permit surges in excess of 600 peak volts. To determine the probability of exceeding the energy of a particular test surge, the joint probability of two factors must be calculated: (a) the probability of obtaining a particular voltage and (b) the probability that a surge of this voltage has a sufficiently long decay time such that its total energy exceeds the energy content of the test surge. These joint probabilities must be summed for all surges with realizable combinations of voltages and decay times which exceed the energy of the test surge.

Mathematically the procedure is as follows: The energy content of a lightning impulse* is:

$$\text{Energy } (E) = \int [f(t)]^2 \, dt,$$

where

$$\begin{aligned} f(t) &= 0 && \text{for} \quad t < 0 \\ &= \frac{vt}{t_0} && \text{for} \quad 0 < t < t_c \\ &= ve^{-b(t-t_0)} && \text{for} \quad t > t_0 , \end{aligned}$$

$$v = \text{peak amplitude of impulses,}$$

$$b = \frac{0.69}{\text{decay time to half value}} = \frac{0.69}{d},$$

$$t_0 = \text{time to crest amplitude.}$$

Therefore,

$$E = \int_0^{t_0} \left(\frac{v}{t_0}\right)^2 t^2 \, dt + \int_{t_0}^{\infty} v^2 e^{-2b(t-t_0)} .$$

However, due to the small percentage of the total energy produced during the rise time, the surge energy can be approximated by:

$$E = \int_0^{\infty} v^2 e^{-2bt} \, dt = \left. \frac{v^2 e^{-2bt}}{-2b} \right|_0^{\infty} = \frac{v^2}{2b} = \frac{v^2 d}{1.38} .$$

Assuming a test surge of amplitude V_0 and decay time d_0, the probability $[P]$ that a surge of somewhat lower amplitude V_1 will have greater energy content is determined as follows:

$$[P] = [P(V_1)][P(d > d_1)].$$

* Impulse = rapid rise to crest amplitude followed by a slow exponential fall.

But, to insure that surge V_1 has an energy content equal to test surge V_0,

$$\frac{V_1^2 d_1}{1.38} = \frac{V_0^2 d_0}{1.38}.$$

Therefore,

$$d_1 = \left(\frac{V_0}{V_1}\right)^2 d_0.$$

To determine the total probability of surges encountered in the field having greater energy content than the test surge requires the summation of [P] for all possible values of V. These probabilities need be summed for voltages only above 400 volts, since lower voltages would require associated decay times far longer than observed or expected in cable plant. This follows for two reasons: In order for a small amplitude surge to have an energy content equal to that of the test surge, its decay time must increase as the square of the voltage ratio of these surges. This would require existence of decay times much longer than 2,000 microseconds, a condition generally contrary to all test observations, and contrary to the observed correlation between peak voltages and decay times which indicated that lower voltage surges have smaller decay times.

Therefore, the total probability (P_T) of exceeding the energy of a particular test surge is:

$$(P_T) = \sum_{v=400\text{v}}^{v=600\text{v}} [P(\Delta v_1)][P(d \geqq d_1)],$$

where Δv = specified voltage increments

$$d_1 = \frac{V_0^2 d_0}{V_1^2}.$$

Thus we have:

$$[P(400 - 410)][P(d \geqq d_1)] = A_1$$
$$\vdots$$
$$[P(590 - 600)][P(d \geqq d_x)] = A_x$$
$$(P_T) = \sum.$$

The probability of obtaining a voltage in the range Δv may be determined from Fig. 4. For example:

$$P(520 < v < 530) = P(v > 520) - P(v > 530) = 0.12 - 0.09 = 0.03.$$

The probability of obtaining a decay time greater than d_1 may be read directly from the upper curve of Fig. 8.

This type of calculation must be repeated for each test surge desired. In this study, test surges with peak amplitudes of 600, 700, 800 volts and a number of different decay times were examined. By providing several waveshapes with equivalent energy content: (a) a better indication may be obtained as to the adequacy of the thermal time constants of vulnerable apparatus components, (b) more latitude is provided for determining the dielectric strength margin of apparatus, and (c) flexibility is provided in the selection of laboratory surge forming circuit constants. The above calculation indicates the probability, per thunderstorm, of exceeding the energy content of a particular test surge. For engineering purposes, however, it is more practical to develop curves of apparatus energy-handling capabilities versus trouble expectancy in years rather than in thunderstorm days. Reference to isoceraunic charts indicates thunderstorm incidences varying from 5 to 90 thunderstorms per year for various sections of the country, with the higher incidences in the Southeast. However, even when a thunderstorm is reported in the general area of a particular cable it is not necessarily close enough to induce surges having magnitudes of the order under discussion. It is felt that an average of only 25 thunderstorm days per year in the higher storm incidence areas are likely to produce significant surges in the cable plant. This factor, together with the calculated probability per thunderstorm of exceeding various energy levels, provides the basis for the curves presented in Fig. 9. These curves indicate the probable surge trouble rate of apparatus tested with surges having parameters that will just cause failure.

The curves in Fig. 9 provide a means of determining the probable lightning surge-handling capabilities of apparatus in two ways. First, where the acceptable lightning trouble rate has been established by system requirements, the parameters of the appropriate test surge may be read from the curves. A second approach may be employed in the case where it is desired to determine the probable trouble rate with regard to a specific piece of apparatus. The procedure would be to establish, by tests, the withstand level of the apparatus in question by employing surge waveshapes selected from the curves. After determining the withstand point, the corresponding estimated trouble rate may be read from the curves.

The waveshapes presented in Fig. 9 will concurrently test apparatus for its dielectric strength, its energy-handling capabilities and its ability to dissipate power. Although these test surges were developed on the

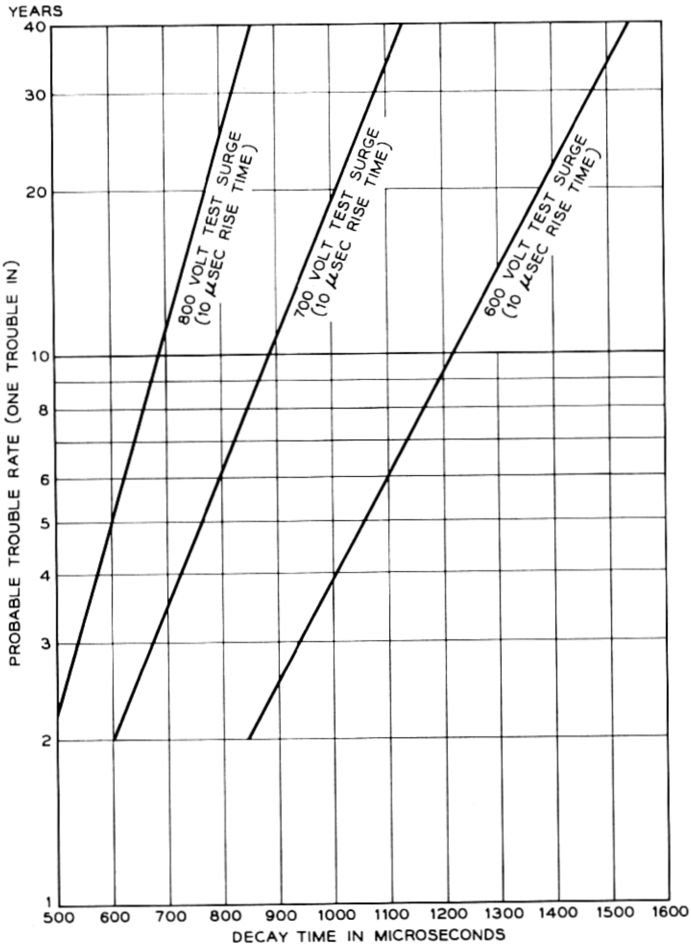

Fig. 9 — Relationship of probable trouble rates to test surges having parameters that will just cause equipment failure.

basis of longitudinal surge data, it is felt that they will provide a reasonable test of the surge-handling capabilities of apparatus, both longitudinally and metallically. Since the total energy contained in a metallic surge must be somewhat less than the total energy of the associated longitudinal surge, the recommended test surges, when applied metallically, will provide an added safety factor. However, this additional safety factor cannot be specifically evaluated from the limited metallic surge data obtained in the study.

V. ENERGY SPECTRUM OF LIGHTNING SURGES IN CABLE PLANT

The main detrimental effect of lightning surges on semiconductor devices is excessive heating of their junction or junctions, the heating effect being related to the energy content of the surge. Since semiconductor devices are used in circuits having different frequency response ranges, it is desirable to determine the energy versus frequency distribution of lightning surges.

Analysis of the energy versus frequency distribution was performed on a 25 by 160-microsecond surge, as it represented one of the shortest duration surges observed on cable plant in this study, and therefore contained higher frequency components. The analysis indicates that 85 per cent of the total energy of this wave is contained in the frequency band up to 3,500 cycles per second. For comparison with a longer duration surge, a similar analysis was performed on a 10 by 1000-microsecond surge, which indicated that 90 per cent of the energy of this surge is contained in the frequency band up to 660 cycles per second. Plots of the cumulative per cent energy as a function of frequency for both of these surges are given in Fig. 10.

In view of the limited frequency spectrum of the energy content of longitudinal surges, it is desirable to determine the energy versus frequency distribution of those metallic surges which are oscillatory. The oscillograms of metallic surges showed the shortest time interval be-

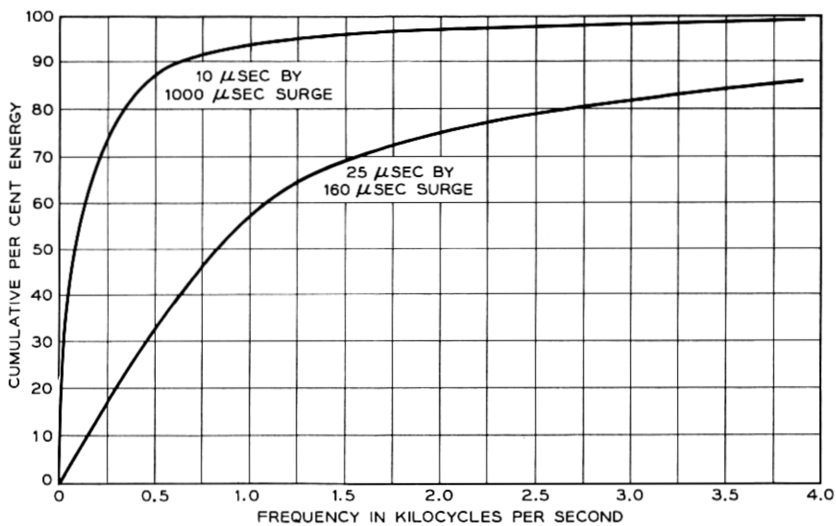

Fig. 10 — Cumulative distribution of energy vs. frequency for two sample surges.

tween polarity reversals to be 80 microseconds. An energy-frequency spectrum analysis for such a wave indicates that 90 per cent of the energy is contained in frequencies below 7 kc. It therefore appears that most of the energy of metallic surges appearing across a resistive termination is likely to be in the frequency band below 7 kc. This does not, however, preclude the need for lightning protection of apparatus operating at carrier frequencies. If reactive components are present in the metallic termination, the resulting metallic surges may have considerable energy in the higher-frequency bands because of spurious oscillations.

VI. SUMMARY AND CONCLUSIONS

Lightning surges were recorded in trunk pairs in aerial and buried cable at several locations known to experience heavy thunderstorm activity. Surges were also monitored in trunks in well-shielded underground cables in urban areas. Observations included measurement of longitudinal surge voltages (from conductor to sheath or ground) and metallic surge voltages (between conductors of a pair). Supplemental laboratory measurements of surge characteristics in simulated underground plant were made using test cable.

In the underground cables monitored, no surges appeared in excess of 90 volts (the minimum sensitivity of measuring equipment) although a total of 44 thunderstorm days occurred during the observation period at the three test locations. Based on this field experience and supplemental measurements made on test cable, it was concluded that apparatus capable of withstanding surges up to 90 volts peak should not require lightning protection if connected to well-shielded all-underground cable pairs. This category includes underground trunks in cables with well-shielded, aerial subscriber complements such as block cable. However, underground pairs extended aerially, or in buried plant, should be considered as exposed to lightning, unless protection is applied at the underground junction to suppress surges from the exposed extensions.

In the aerial and buried cable plant studied, about 1400 surges were recorded, ranging in peak amplitude from 60 volts (minimum sensitivity of equipment) up to 450 volts, the value at which carbon block protectors operated. About 90 per cent of the recorded surges were longitudinal; the remainder were metallic. Analysis of this data helped establish the relationship between the parameters of specific test surges and the probable lightning trouble rate of exposed transistorized apparatus. This information will facilitate appropriate laboratory testing of apparatus for specific levels of reliability.

APPENDIX

With the recording technique used in this study, only those surges in the range above 60 volts and less than the operating value of carbon block protectors were registered. The 3-mil gap, carbon protector blocks associated with "exposed" cable plant limit maximum voltages to a nominal value of 500 volts. Due to manufacturing and field duty variations, the operating value of these carbon blocks may vary from approximately 400 to 600 volts. Protector block operation, therefore, affected the distribution of peak voltages above 400 volts. The recorded data established the distribution of surge voltages between the limits of 60 volts and approximately 400 volts. This distribution was extended to 600 volts by considering the effects of block operation in the 400 to 600 volt range as discussed later.

In the aerial cable plant at Buford, Georgia, a total of 103 surges was recorded during the six-month study period. In the buried cable plant at Griffin, Georgia, a total of 1120 surges was recorded for the same period of time. Histograms of the distribution of these surges as a function of voltage are presented in Figs. 11 and 12 for the two types of

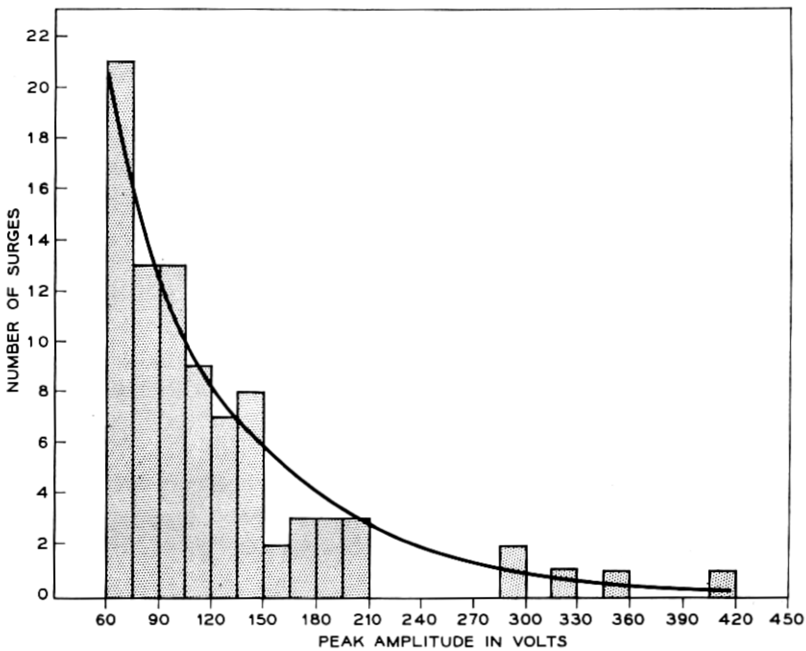

Fig. 11 — Amplitude distribution on aerial cable.

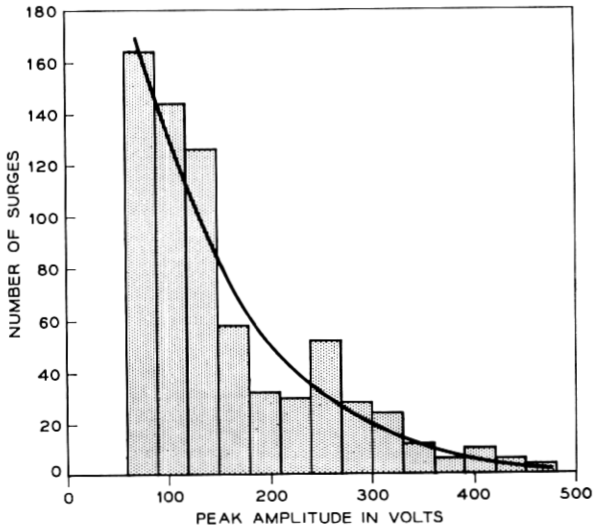

Fig. 12 — Amplitude distribution on buried cable.

plant. These distributions are of an exponential form and can be closely approximated by

$$y = ce^{-aV},$$

where

y = number of surges,
V = peak voltage of the surge.

Smoothing of the raw data (fitting of an exponential by the method of least squares) resulted in the plots on Fig. 13. The constants for the exponential distribution on aerial cable are $a = 0.012$ and $c = 40$. The constants for the buried cable are $a = 0.0094$ and $c = 330$.

The large difference in the calculated values of c for the two types of plant merely reflect the difference in the sample sizes and will not affect their probability distributions. It will be noted that the values calculated for the constant term a for the two types of plant varies over 20 per cent, but it is recommended that the smaller value, calculated for buried cable, be used for both types of cable installation for two reasons. First of all, much more data were obtained in the buried cable study, which permitted a more accurate determination of the shape of the exponential distribution. Also, since our objective is to provide suitable surge voltages for laboratory testing of apparatus, it is safer to use the

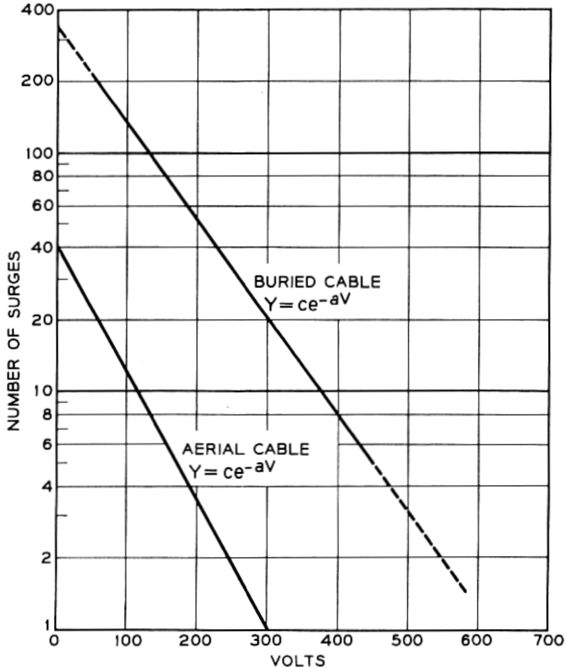

Fig. 13 — Amplitude distribution of surges on aerial and buried cable.

distribution with the smaller value of a which predicts a greater percentage of higher voltage surges.

Having determined the distribution of surge voltages, it is possible to estimate the probability that V is less than or equal to some value T:

$$P(V \leqq T) = \int_0^T f(x)\,dx = \int_0^T Ce^{-aV}\,dV$$

$$= -\frac{C}{a}e^{-aV}\Big|_0^T = \frac{C}{a}(1 - e^{-aT}).$$

This equation must be normalized, since

$$P(V > 0) = 1.$$

Therefore,

$$P(V \leqq T) = 1 - e^{-aT}.$$

Using the previously established value of a, the probability distribution of surge voltages was then plotted (Fig. 14). This, however, gives

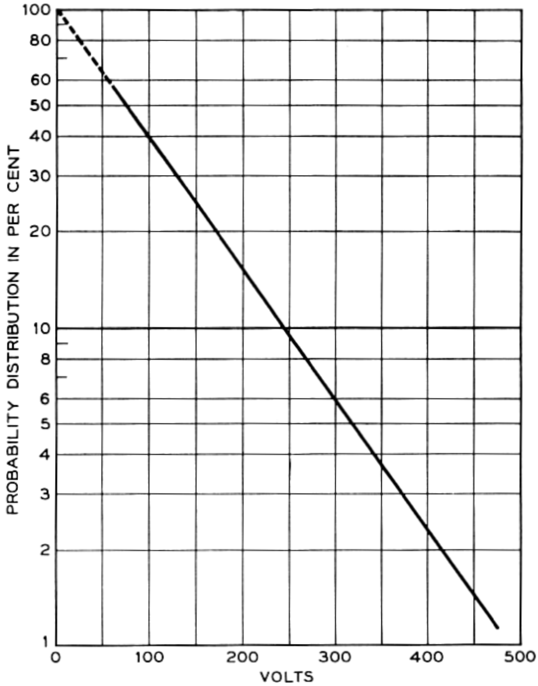

Fig. 14 — Probability distribution of all surges in buried and aerial cable.

the distribution of *all* surges to the cable plant, while the voltages recorded in the field were truncated, with only values above 60 volts being recorded. The desired distribution is, therefore, the conditional probability that a voltage peak exceeds T volts given that it is greater than 60 volts. This may be accomplished by shifting the distribution function to the left until the probability of exceeding 60 volts is equal to one.

Thus,

$$P(V > T) = e^{-aT}e^{60a},$$

where $T \geqq 60$ volts. Therefore,

$$P(V > T) = e^{0.565}e^{-0.0094T} = 1.76e^{-0.0094T}.$$

This expression provides the probability distribution presented in Fig. 15.

To estimate the number of surges per thunderstorm day which exceed any given amplitude, it is necessary also to determine the average num-

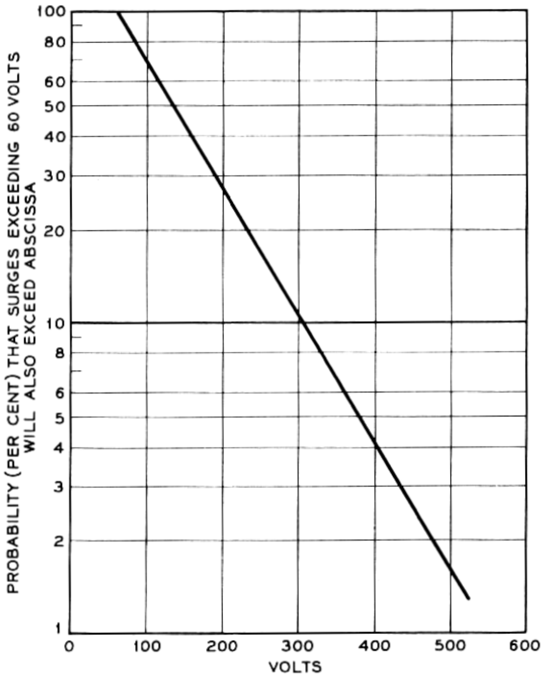

Fig. 15 — Probability distribution of all surges exceeding 60 volts in buried and aerial cable.

ber of surges induced in a cable per thunderstorm day. An estimated value was computed by counting the total number of recorded surges over the entire study period and dividing by the number of thunderstorm days occurring in the area. Very good correlation was established between observed thunderstorm days (on film) and those reported by local weather stations.

A total of 36 thunderstorm days was recorded in the vicinity of the buried cable at Griffin and six thunderstorm days were recorded in the vicinity of the aerial cable at Buford. These 42 thunderstorm days recorded for the two test locations accounted for a total of 1220 surges, for an average of 29 surges per thunderstorm day.

The actual number of surges induced in a cable, however, is approximately 2.5 times this value or 73 surges per storm. This results from the fact that multiple surges occur in approximately half of all lightning strokes, and that the average number of surges in a multiple discharge stroke is about four. The interval between surges is approximately $\frac{1}{10}$ second.[1,2] The sweep speed of the test oscillographs (full scale deflection

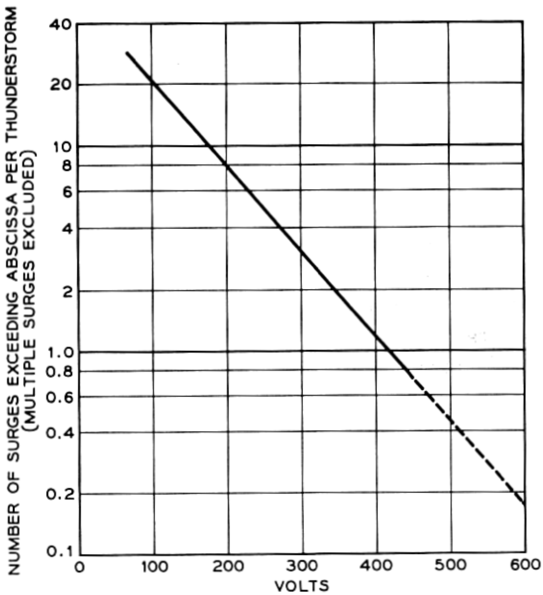

Fig. 16 — Surge distribution on buried and aerial cable, no protector blocks.

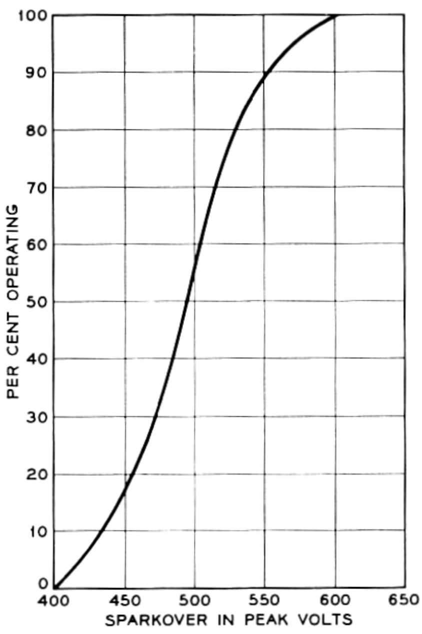

Fig. 17 — Sparkover distribution characteristics of 3-mil carbon block protectors.

of 1500 microseconds) was such that only the first surge was actually recorded in the field test. When evaluating apparatus that is vulnerable to repeated low-amplitude voltage surges, the occurrence of these multiple-stroke discharges must be considered. Lightning surge failure of most apparatus, however, is caused by the inability of the apparatus to handle the surge energy. Since subsequent surges in a multiple-stroke discharge generally have a lower energy content, apparatus vulnerable to surge energy will be most susceptible to failure on the initial surge, eliminating the need to test for the effects of multiple discharges.

Fig. 16 presents a plot of the expected distribution of surges (excluding multiple surges) on buried or aerial cable plant as a function of peak voltage in the absence of associated 3-mil protector blocks. The effect of protector blocks is to reduce the probability of observing voltages in the range of 400 to 600 volts. The distribution of protector block operation as a function of peak voltage had been determined, and is presented in Fig. 17. When this probability distribution is applied to the probable incidence of various surge voltages in cable plant the curve shown in Fig. 4 results. Fig. 4 gives the expected number of surges (excluding multiple surges) per thunderstorm exceeding any given voltage, up to the maximum sparkover voltage of 3-mil protector gaps.

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