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LIGHTNING AND OTHER HIGH-VOLTAGE PHENOMENA[1]

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[With 11 plates]

I. Introduction

For a number of years the author has been actively engaged in research in various high-voltage phenomena. This work has been done from the standpoint of pure research to determine fundamental principles and from the standpoint of practice to better the insulation of apparatus, to extend transmission voltages, and to determine means of protecting transmission lines and buildings from lightning. By combining pure and applied research a much broader view is obtained, and there is no better test of theory than to attempt to apply it to practice in a simple way. It will often be found that essential factors have been overlooked.

In the following discussion the practical as well as the theoretical viewpoint will be kept in mind.

II. High-Voltage Phenomena

High electric pressure or voltages are necessary for economical long distance transmission, but when such voltages are used without proper precautions in design the energy may leak away from the lines with a hissing noise in the corona. The corona is a beautiful crown of light surrounding the conductors and is a manifestation of the ions and electrons moving in the electric field.

The sparking distance is also of theoretical and practical importance.

Laws of corona, sparking curves, etc., were established at the comparatively low voltages of the order of 250,000. These were successfully applied to 220,000-volt transmission lines.

III. Research at High 60-Cycle Voltages

Within the last few years the work has been extended to voltages of 1,000,000 volts above ground, 1,500,000 single-phase and over

[1] This report is a nontechnical summary of two papers, High Voltage Phenomena, Journal of Franklin Institute, January, 1924, and Lightning, an address delivered at the centenary of the Franklin Institute, September, 1924, and in the Journal in February, 1925. Complete technical information and data will be found in these papers.

1,000,000 3-phase 60-cycle root mean square values.[2] It was of interest to find if the laws and curves established at the lower voltages still applied at the very high voltages. The results of some of the very high 60-cycle tests will now be described.

CORONA

When voltage is applied between certain types of conductors, as, for instance, parallel wires a considerable distance apart compared to their diameters, and is gradually increased, a crown of light suddenly bursts out around the conductors at a very definite critical voltage. The light is accompanied by a hissing noise. This is called corona. As the voltage is increased, the corona extends farther and farther out until finally a spark extends from metal to metal. The air is said to be ionized in the corona brush. The sudden outburst occurs when the voltage gradient at the conductor surface, where it is greatest, is sufficient to bring the ions and electrons up to sufficient velocity in their mean free path to produce others by collision with atoms. Certain chemical changes take place in the air in the formation of ozone and nitrous oxides. Corona and brush discharges are the same phenomena. In fact, corona and spark-over are also the same. The brush or corona are sparks to space. On relatively large electrodes placed close together, the intermediate corona can not form and the first evidence of over stress is a spark between conductors. The reason for this is known. With certain conductor configurations any increase in the conductor diameter tends to reduce the stress. The corona extends out and stops when the diameter is such that the stress is below the breakdown stress. With other types of electrodes, an increase in diameter tends to increase the stress. A brush once started must, therefore, extend directly between electrodes. The first type is changed into the second type with increasing voltage and the resulting extension of corona.

Corona starts at a very definite voltage. Several years ago a law was established for calculating this critical starting voltage for parallel wires based upon tests up to 250,000 volts. The factors determining the critical voltage are diameter, spacing, roughness of surface, and temperature and barometric pressure. The diameter of the conductor is the most important factor. A law was also established to predetermine the loss caused by corona. There is no appreciable loss until the critical voltage is reached. The loss then increases as the square of the excess voltage above the critical voltage.

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[2] The single-phase tests have just recently (Oct. 8, 1925) been carried to approximately 2,200,000 root mean square or over 3,000,000 crest.

The mechanism of the corona is of extreme theoretical interest. There is also a practical interest because the laws of corona are very important in the design of high-voltage transmission lines. It is important to select the conductors so that a large percentage of the energy is not lost in the corona. A physical idea of what this means may be of interest. A 220,000-volt transmission line requires a conductor about 1 inch in diameter to prevent corona loss, while a million-volt line would require a conductor about 6.5 inches in diameter.

High voltages are economical when there is considerable power to transmit a considerable distance; 220,000 volts is economical when power of the order of 50,000 to 100,000 kilowatts is available to transmit distances of the order of 200 miles. With a million volts it would be possible to transmit 3,000,000 kilowatts 1,000 miles with about 12 per cent loss, using copper section equivalent to the 1 inch, 220-Kv. cable. The copper would of necessity be put in the form of a hollow tube to obtain the 6.5 inches diameter required by corona loss. There is, at present, no apparent economic need for 1,000,000-volt transmission.

The laws of corona established at the lower voltages were found to hold at the higher voltages.

Figure 1 shows the corona discharge from one of two parallel wires, while Table 1 shows good agreement between measured and calculated corona starting voltages for different electrodes.

TABLE 1.—*Corona on parallel brass tubes (60 cycles).*

Spacing		Visual corona voltages Kv. effective. $\delta=1.00$	
Inches	Cm.	Calculated	Observed
DIAMETER 3.5 INCHES=8.9 CM.			
75.5	192	790	730
111.5	283	876	895
147.5	375	915	915
183.5	466	990	990
DIAMETER 1.75 INCHES=4.45 CM.			
73.7	188	490	490
109.7	275	538	560
145.7	370	568	600
183.5	463	604	675
DIAMETER 1.0 INCH=2.54 CM.			
73	185	340	370
109	277	364	380
181	460	402	415

SPARK-OVER

The sparking distance between electrodes has been used for measuring high voltages.

A study of sparking distance is also of considerable theoretical interest and of practical interest in electrical design. It is necessary to know the sparking distances in order to supply sufficient clearances. The actual length of the spark for a given voltage depends upon the electrodes used and the temperature and barometric pressures.

A given voltage will spark the greatest distance between needle points and the minimum distance between planes and large spheres.

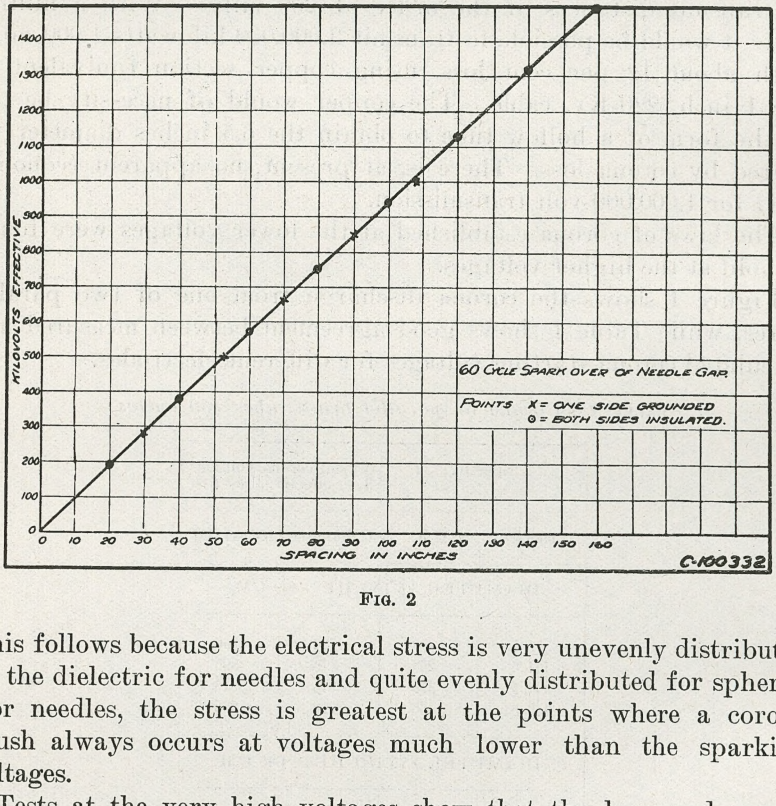

FIG. 2

This follows because the electrical stress is very unevenly distributed on the dielectric for needles and quite evenly distributed for spheres. For needles, the stress is greatest at the points where a corona brush always occurs at voltages much lower than the sparking voltages.

Tests at the very high voltages show that the laws and curves established at the lower voltages still hold. This is best illustrated in the curves that follow.

NEEDLE GAP

The needle gap spark-over curve is given in Figure 2 up to 1,500,000 volts effective. It will be noted that the curve is continuous from the low to high voltages. There is considerable variation in this curve with atmospheric conditions. Figure 3 shows a single-phase spark-over at 1,500,000 volts.

SPHERES

The spark-over voltage curve for spheres is given in Figure 4. The values follow the equation established at the lower voltage.

INSULATOR SPARK-OVER

Figure 5 gives the spark-over values for standard 10-inch disk-suspension insulators. The curves are continuous from the lowest voltage to the highest voltage.

THREE-PHASE ARCS

Power is usually transmitted three-phase. Investigations were made of three-phase arcs. The standard arrangement was to place the three electrodes in the corners of an equilateral triangle.

The pecularities of the three-phase arc and corona are that the voltages are usually lower than for single-phase; the spark forms in a Y if there is no dissymetry; the spark does not take place at the instant of maximum voltage between conductors but at the maximum voltage to neutral. A three-phase arc is shown in Figure 6.

The 60-cycle alternating-current arc passes through zero and maximum current 120 times a second. When the arc forms it rises due to the heat. This motion, together with the alternating current, causes the beautiful lace-like appearance of the arcs. The bright lines occur at maximum current.

PRACTICAL VALUE OF HIGH VOLTAGES

In addition to its purely theoretical and scientific value just discussed the production of a million volts also has a practical value. The immediate practical value is its use in testing 220-kv. apparatus with the required factors of safety. With the future in mind it is important to learn how to build transformers best suited for operating at voltages higher than those used at present. Even the so-called theoretical investigations of the present become the practical applications of the future.

PREDATORY VOLTAGES

The discussion so far has been limited to the useful type of voltage used in transmitting energy. The practical value of the research was to learn how to use these voltages without loss of energy

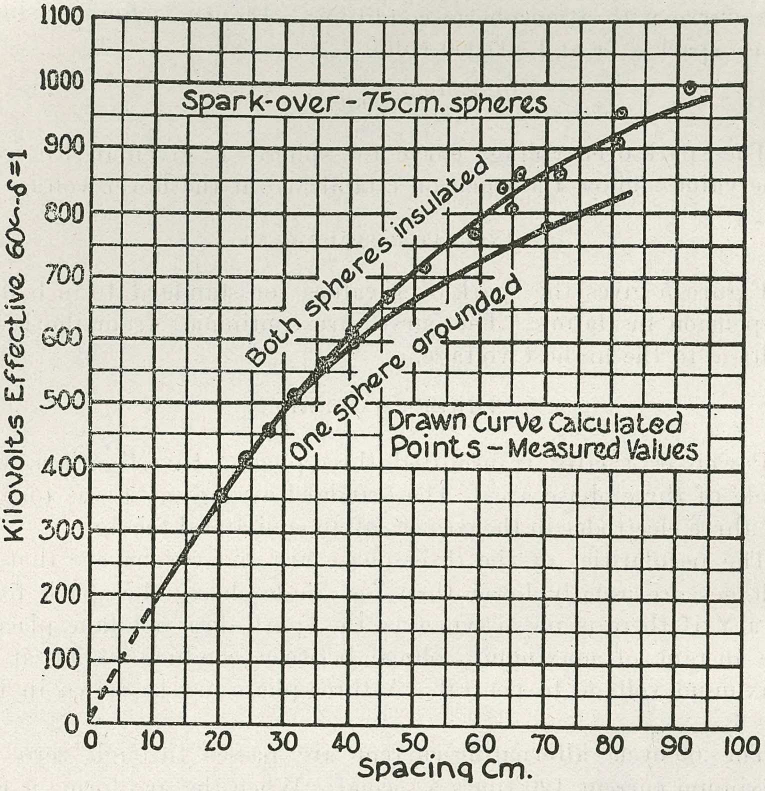
Spark-over - 75cm. spheres
Both spheres insulated
One sphere grounded
Drawn Curve Calculated
Points - Measured Values
Kilovolts Effective 60~ δ=1
Spacing Cm.
0
100
200
300
400
500
600
700
800
900
1000
1100
0
10
20
30
40
50
60
70
80
90
100

FIG. 4

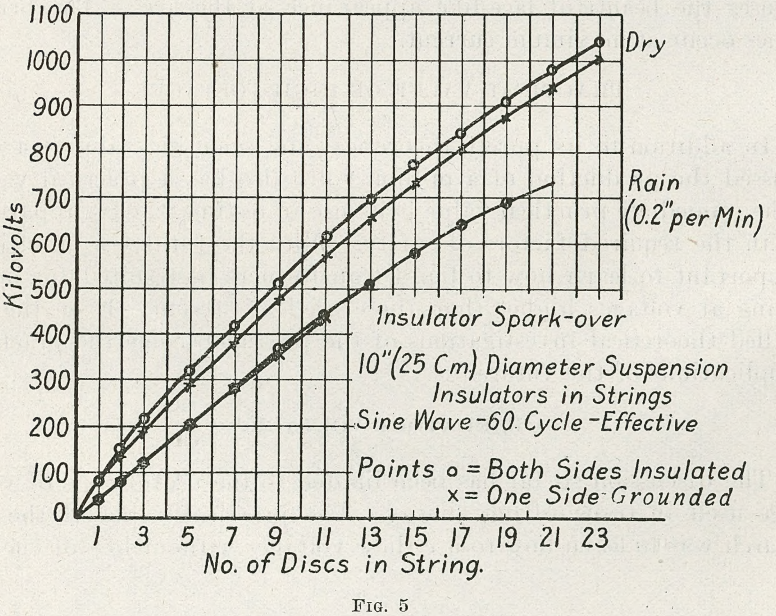
Dry
Rain
(0.2" per Min)
Insulator Spark-over
10" (25 Cm.) Diameter Suspension
Insulators in Strings
Sine Wave - 60 Cycle - Effective
Points o = Both Sides Insulated
x = One Side Grounded
Kilovolts
No. of Discs in String.
0
100
200
300
400
500
600
700
800
900
1000
1100
1
3
5
7
9
11
13
15
17
19
21
23

FIG. 5

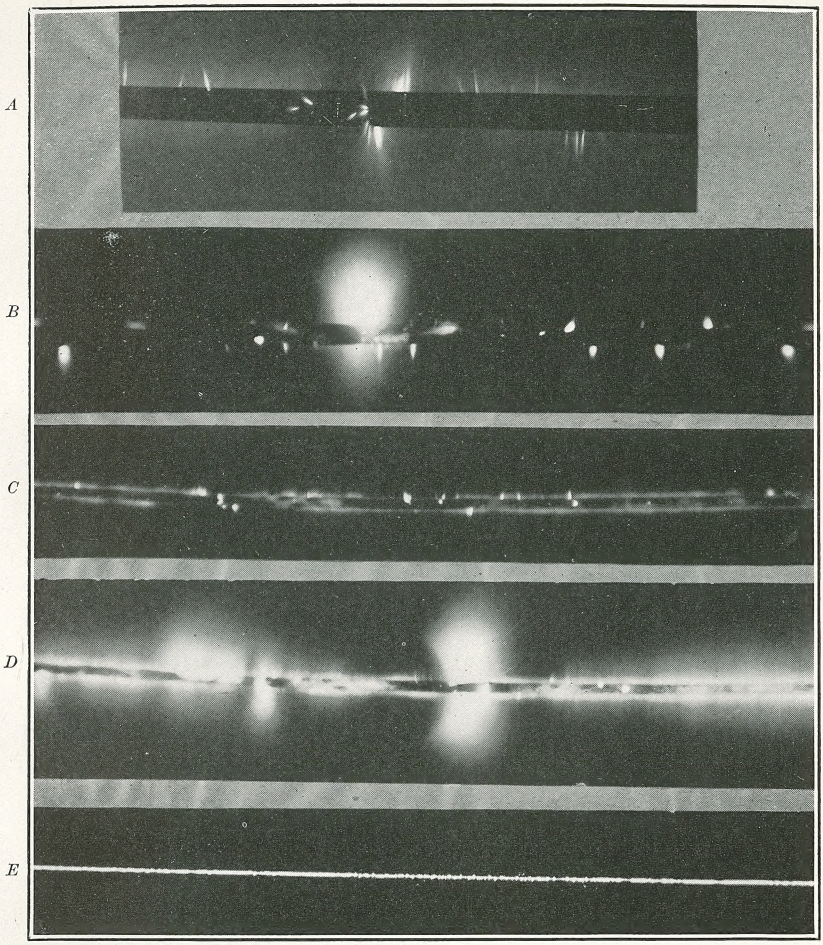

FIG. 1.—APPEARANCE OF CORONA ON CONDUCTORS AT SUPERVOLTAGES UNDER DIFFERENT CONDITIONS

A, 900 kv.; 3.5-inch tube; 144-inch spacing. *B*, 800 kv.; 1.75-inch tube; 144-inch spacing. *C*, 500 kv.; 1-inch tube; 72-inch spacing. *D*, 780 kv.; 1-inch tube; 108-inch spacing. *E*, 800 kv.; 0.040-inch tube; 144-inch spacing.

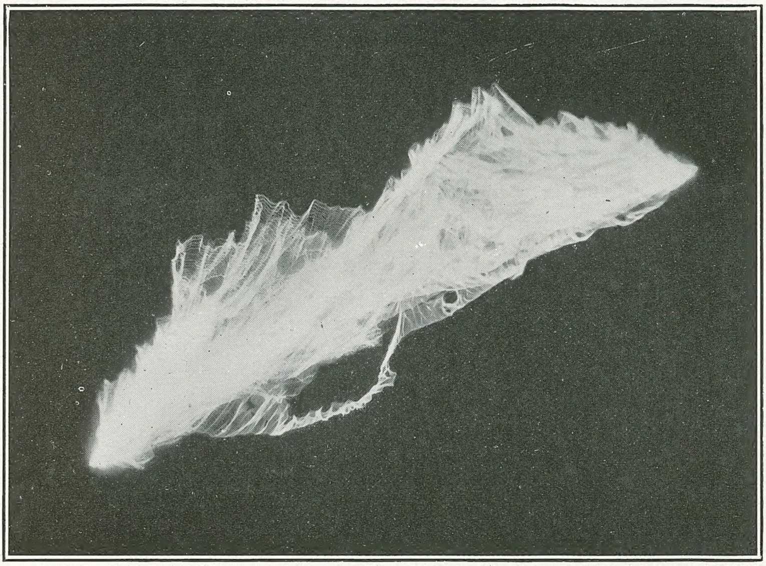

FIG. 3.—PHOTOGRAPH OF 1,500,000 VOLTS EFFECTIVE, OR 2,100,000 VOLTS MAXIMUM, SINGLE-PHASE ARC BETWEEN POINTS. DISTANCE=14 FEET. 60 CYCLES

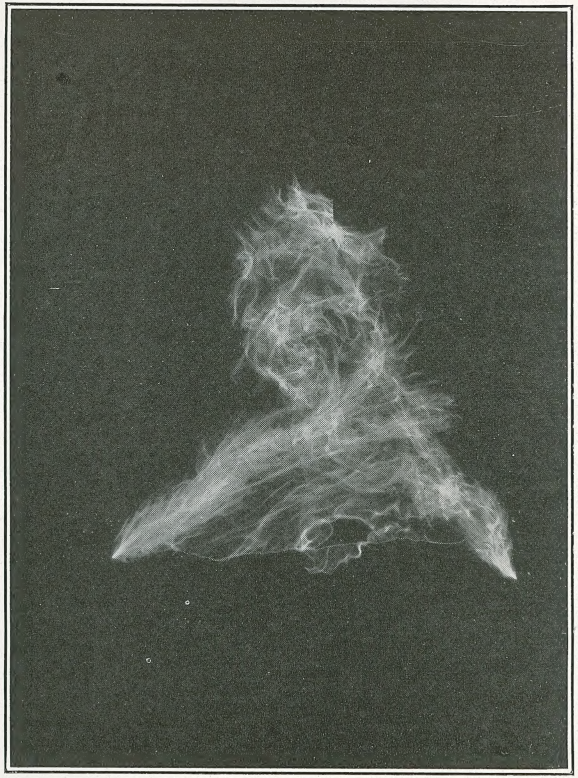

FIG. 6.—THREE-PHASE SPARK-OVER NEEDLES AT ONE MILLION VOLTS, 60 CYCLES, SINE WAVE, EFFECTIVE. NEEDLES ARRANGED IN AN EQUILATERAL TRIANGLE APPROXIMATELY 9½ FEET ON SIDE

Photo taken at right angles to plane of needles

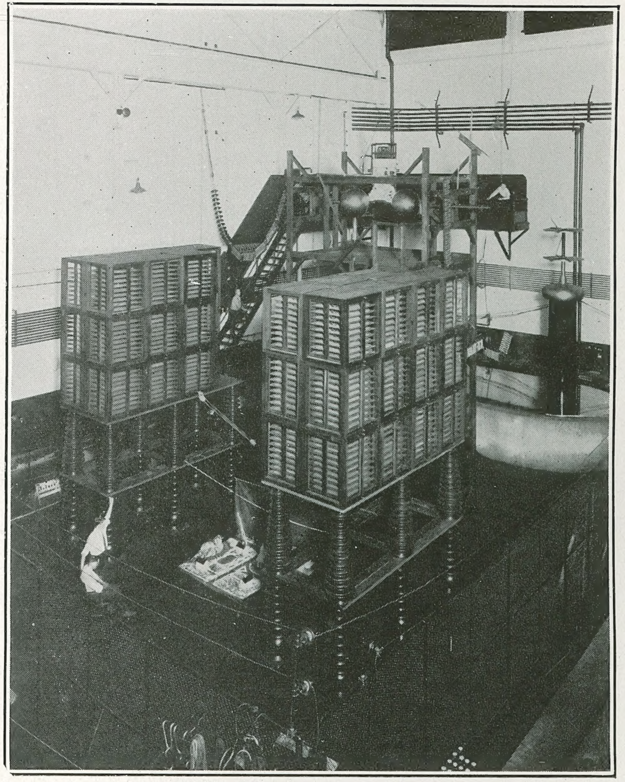

FIG. 7.—LIGHTNING GENERATOR USED TO PRODUCE ARTIFICAL LIGHTNING

FIG. 8.—WOOD SPLIT BY ARTIFICIAL LIGHTNING

FIG. 9.—METAL "PUNCTURED" BY LIGHTNING

FIG. 10.—SINGLE 1,500,000-VOLT LIGHTNING STROKE BETWEEN POINTS

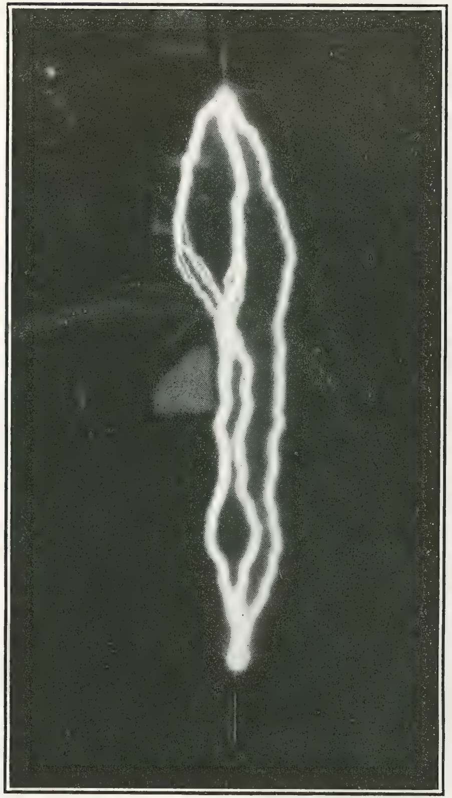

FIG. 11.—THREE 1,500,000-VOLT LIGHTNING STROKES BETWEEN POINTS. NOTE THAT SUCCESSIVE STROKES DO NOT FOLLOW THE SAME PATH

FIG. 12.—LIGHTNING DISCHARGE BETWEEN SPHERES. NOTE THICKNESS OF DISCHARGE

into the air and to prevent breakdown by spark-over. In addition it is necessary to learn how to prevent destruction by certain predatory voltages such as lightning.

IV. Lightning

A lightning stroke is generally thought of as a local but severe high-voltage discharge from some cloud. As a matter of fact, the electric energy that manifests itself in the flash is, in the moment previous to the flash, stored in the surrounding air for a considerable distance. The thunder cloud acts as one plate of a huge condenser, the earth as the other, while the intervening air is the insulation. When the voltage between earth and cloud becomes high enough, this insulation breaks down and the energy is dissipated in the short-circuit or lightning flash.

The electrical energy is changed into heat, light, sound, and chemical energy. The light is seen in the flash, while the sound is heard as thunder. Thunder is caused by air waves set up by the explosive nature of the discharge.

The chemical effects of the lightning stroke are often detected by our senses in the odor of ozone that is frequently noticeable after a storm. The chemical changes occur in the path of the discharge. The two main gases in the air are nitrogen and oxygen. Each molecule of oxygen is normally made up of two atoms. The electric field tears these apart. Some of these single atoms recombine in groups of three. Oxygen with a molcule made up in this way is called ozone. It is very active chemically because the extra atom is easily detached. The nitrogen of the air is also made to combine with the oxygen, producing nitrous oxide and, in the presence of vapor, nitric acid. Along the discharge path are untold numbers of electrons and ions—chunks of electricity moving at enormous velocities.

The voltage between cloud and ground previous to the discharge causes voltage between different parts of the atmosphere. Right under the cloud the voltage gradient or the voltage difference per foot of air measured in a vertical direction may be very high. In fact, a certain percentage of the lightning voltage exists between earth and any point above.

Lightning, the disorderly, predatory form of electricity, is dangerous, not because of its enormous energy but because of its enormous power and "flighty" habits. The distinction between energy and power is that energy is measured in kilowatt-seconds or kilowatt-hours, while power is measured in kilowatts. Kilowatts measure the rate at which work is being done. If energy is dissipated in a very short time the power is large and the result an explosion.

When lightning strikes an object great damage is generally done. However, it is not necessary for lightning to actually strike an object to cause damage. A discharge to earth may cause sparks in distant oil tanks or powder mazagines or destructive voltages on transmission lines. Voltages that occur by this "wireless" action are said to be induced.

LIGHTNING RESEARCH

A study of lightning is of scientific importance because there is manifest in the flash the dynamic effect of the electrons and ions, the elemental bricks of which it is believed that all matter is made; it is of engineering importance because an exact knowledge of the characteristics of lightning will make it possible to protect life, buildings, powder magazines, oil tanks, and transmission lines against it. The ideal method of making such a study is by observations of natural lightning in the field and researches with artificial lightning in the laboratory. Such a combined study was made in the laboratory and in the mountains of Colorado.

TWO MILLION-VOLT LIGHTNING GENERATOR

The artificial lightning was produced by a lightning generator which supplies 2,000,000 volts above ground, higher than most voltages induced on transmission lines. (See fig. 7.) The discharge from the lightning generator produces a loud, sharp explosive report, and the power is of the order of millions of kilowatts for a few millionths of a second. Currents as high as 10,000 amperes have been obtained. The voltages increase at the rate of millions of volts per second. In common with natural lightning, artificial lightning has interesting characteristics.

The large, wooden posts shown in Figure 8 were split by a 1,500,000-volt discharge. Longitudinally through the center of the stick is a hole of less than one thirty-secondth inch (0.8 mm.) in diameter. The wood around this hole has a "fuzzy" appearance, but does not appear burned. Immediately after being blown apart the wood has an odor of the gases of destructive distillation. Apparently these gases are formed suddenly by the discharge, and produce such high pressures that the wood is blown apart with great violence.

Even metal may be "punctured," as shown in Figure 9. In this case the metal formed a coating on a glass plate. The lightning discharge punctured the plate to the metal. The holes were apparently caused by the sudden formation of gases between the metal and the glass. A discharge striking through water disrupts it in much the same manner as oil is disrupted at 60-cycle voltages.

When lightning strikes the earth at some sandy spot its path is often defined by a glasslike tube. This tube, which may have branches like a tree, is, in fact, sand fused into "glass" by the lightning current. Such tubes are called "fulgurites," and can be produced by artificial lightning.

Because of the transient and explosive nature of lightning some quite unexpected phenomena frequently happen. Data will now be given on typical types of gaps, the needle gap representing the non-uniform field type, the sphere gap the uniform field, and the insulator representing the surface discharge.

Figures 10, 11, and 12 give characteristic sparks.

The lightning generator consists of high-capacity condensers just as in the case of the clouds, only the insulation is glass instead of air and it is relatively more compact.[3] As in the case of the cloud lightning, the electricity is stored at a relatively slow rate and discharged at an enormously rapid rate in a few millionths of a second.

The lightning generator has been of considerable help in gaining a knowledge of natural lightning. In fact, it has afforded a means of estimating the voltage of a real lightning stroke. The means was very simple and will be cited as an example of the general method of the research, which was to observe natural lightning and then observe artificial lightning on models built to scale in the laboratory. Actually, the function of the model is to solve electrostatic problems that are difficult to calculate.

THE VOLTAGE AND ENERGY OF NATURAL LIGHTNING

It was shown in the experiments at the very high voltages that approximately 150,000 volts maximum are required for every foot of spark. While this rule was found to apply up to the very highest laboratory voltage of about 3,000,000 maximum, it in itself gave no assurance that it would apply indefinitely, so that the voltage of lightning could be found by multiplying the length of the flash by the factor. However, an experiment which seems to offer an almost direct means of measuring lightning voltages will be described. When a lightning flash occurs within a certain distance of a transmission line, a certain percentage of the voltage of the bolt is induced on the line. The voltage of the bolt can not be measured, but its distance from the line and height of cloud can be estimated. The actual voltage induced on the line can be measured by gaps or estimated from insulator flash-overs. The author has measured lightning voltages on transmission lines in Colorado as high as

[3] A full technical description of the lightning generator will be found in the papers referred to in Note 1.

500,000; insulator flash-overs by lightning have occasionally indicated voltages as high as 1,500,000 or more.

A model was made to scale representing cloud and transmission line for a certain observed condition. By means of the lightning generator it was found that when a flash occurred from this model cloud 1 per cent of its voltage was induced on the model line. But it is known by observation that the voltage induced on an actual line under similar conditions is sometimes of the order of 1,000,000. If this is 1 per cent of the voltage of an actual lightning flash, the voltage of the flash must be 100,000,000 volts (fig. 13). This gives

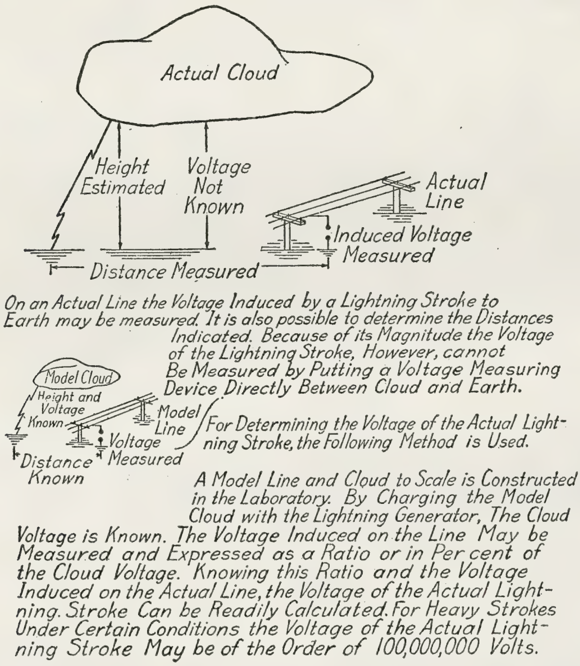

FIG. 13.—Method of measuring the voltage of an actual lightning stroke

a voltage of 100,000 per foot of spark (330 kv./m.), which, considering the possible error, indicates that the needle gap-spark curve may hold even at these extreme voltages. In fact, a value somewhat lower than the 150,000 volts per foot (495 kv./m.) of the laboratory would be expected, since the flash starts at the low-air density of the high altitudes. Time required to discharge would also indicate a reduced gradient. It has been the opinion of many observers that the voltage of lightning is relatively low or that the flash, once started, would extend great distances at low voltages by some progressive action. Progressive action is readily understood where the spark takes place over a series of clouds by a multigap action and can, in fact, be shown in the laboratory. When the flash is from cloud to ground or from one cloud to another through clear air, as is usual with lightning, it is not clear how progressive action can occur. While the field produced by the charge is fairly uniform, it is probable that at the instant before spark-over a needlelike streamer forms and breakdown then corresponds to the needle-gap distance. Needle-gap spark-over requires less than 20 per cent of the 30 kv./cm. required for uniform field. The sparking distance should usually correspond to a continuous voltage, because there is generally no large transient until after the spark starts.

It thus appears, by approximately direct measurement, that the order of voltage of a severe lightning stroke to ground may be

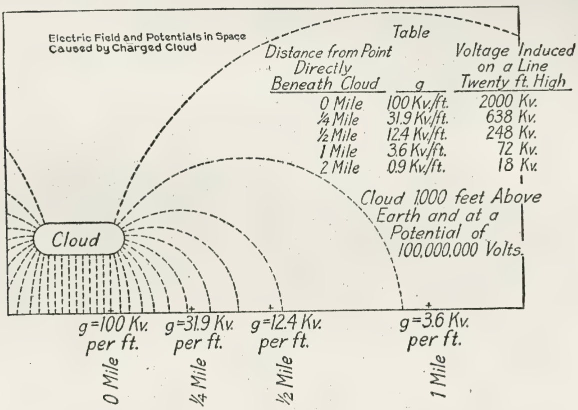

Fig. 14

about 100,000,000. This is about one million times the voltage of the ordinary lighting circuit or one thousand times the voltage of a very high voltage transmission line. The lightning voltage during a storm will, of course, vary over a very wide range, sometimes much higher but generally lower than the value above. It has been observed that during a severe thunderstorm there may be many induced strokes at very low voltages, a less number of moderate voltages, and so on to very few at the extreme voltages.

It will be noted that the above conditions require a gradient of 100 kv./ft. (330 kv./m.) in the most dense part of the electric field where the flash occurs and a gradient of less than a third of this a short distance away. See Figure 14, where the gradients are given for points near the surface of the earth.

It is estimated from the voltage and the size and height of the clouds that the current is of the order of 80,000 amperes and the energy 13,500 kilowatt-seconds or 3.8 kilowatt-hours. This energy is sufficient to operate an automobile about 5 miles or an electric toaster for a day. Since this energy is dissipated in a very short time, the power may be several thousand million kilowatts or horsepower. The effect is thus explosive and destructive.

The discharge of the cloud is probably generally nonoscillatory and takes place in the manner shown in Figure 15. A convenient measure of time is the microsecond or millionth of a second. The

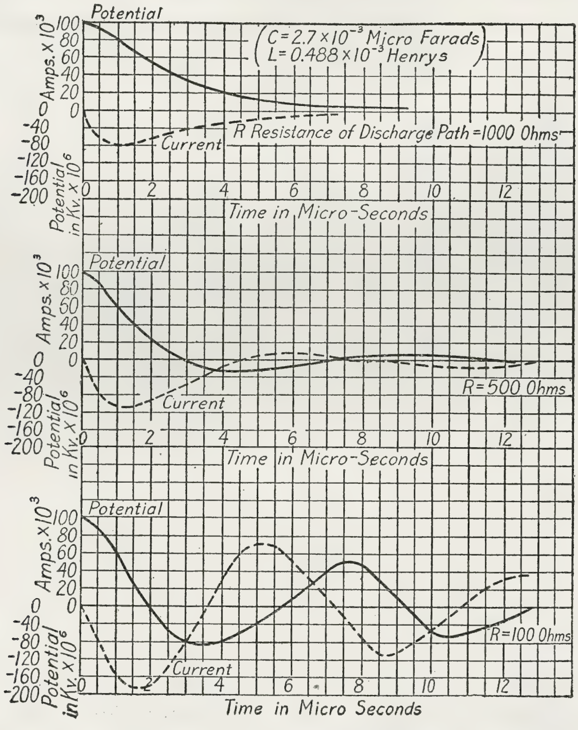

FIG. 15.—Transients for "cloud" discharge to earth

time of discharge may be very much longer if the resistance of the path is higher.

It may be of interest to point out that the voltage of the lightning generator is about 2 per cent and the power about 0.02 per cent of natural lightning. This practically corresponds to the lightning energy that appears on transmission lines.

LIGHTNING ON TRANSMISSION LINES

Most lightning disturbances on transmission lines occur by electrostatic induction and not by direct stroke. A charged cloud causes an electrostatic field to earth. Part of the field will terminate on a transmission line within its area. The line is said to have a "bound charge." If the voltage between earth and cloud becomes high enough, a lightning flash will occur. Although this flash may be a mile away from the line, the charge on the line is released and the insulated line increases from earth potential to some value above with polarity opposite to that of the cloud. An insulated line can be at earth potential just previous to the discharge because of the effect of the long part of the line not under the cloud, leakage over insulators, or through grounded neutral. A charge of the same sign as the cloud leaks away leaving a bound charge on the line with sign opposite to that of the cloud. The line remains at

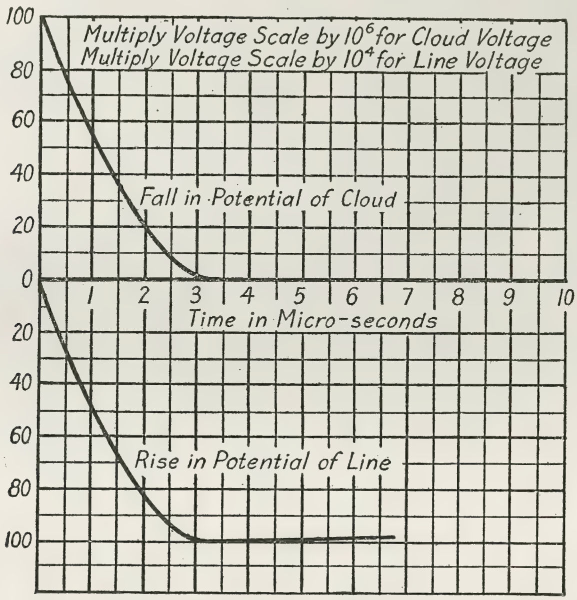

FIG. 16.—Transients for cloud discharge to earth

earth potential until the cloud discharges. The effect is then of a voltage suddenly applied between line and ground. The voltage of the line becomes maximum when the cloud voltage becomes zero. The manner in which the voltage increases on the line with decrease in voltage on the cloud is shown in Figure 16. The field that extended between line and cloud now extends between line and ground. The voltage wave travels over the line at the velocity of light. If the line insulators are strong enough or have a high enough impulse ratio, the impulse may travel to the power house to break down apparatus or to be harmlessly discharged to ground over the arrester, if it has low reactance and low impulse ratio. As this lightning wave travels over the line it becomes gradually dissipated

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by losses. The voltage that the line assumes at the instant of a sudden discharge is that of the equipotential surface at the point in which the line is located. This is approximately the gradient in kilovolts per foot times the height in feet. This is a certain percentage of the voltage of the lightning bolt. In studies in Colorado, as already stated, the author has actually measured induced lightning voltages on transmission lines as high as 500,000 volts. Insulator flash-overs have occurred that indicate induced voltages as high as 1,500,000 volts, although the greater percentage of voltages induced on transmission lines are very much lower than this. These figures, as already shown, afford a means of estimating the voltage of a lightning flash.

THE MAXIMUM VOLTAGE ON TRANSMISSION LINES

From the above it is apparent that the maximum lightning voltage that can appear on a transmission line under given conditions depends directly upon the height of the line. The maximum voltage that can appear on any line is equal to the maximum possible gradient of 100 kilovolts per foot or 100,000 volts per foot times the height of the line in feet. This extreme condition seldom occurs because it requires the discharge to take place at a very rapid rate in the immediate vicinity of the line, practically a direct stroke. The chances of this condition are remote because when the storm center is only a quarter of a mile away the gradient is reduced to one-third. It may also be reduced by a slow discharging cloud permitting a considerable dispersal of the charge along the line. Apparent gradients of 20,000 to 30,000 volts per foot are fairly common on actual lines. The tabulation in Figure 14 shows the induced lightning voltages on a 20-foot transmission line at different distances from the rapidly discharged cloud.

Practically, this shows that a high transmission line is undesirable from the lightning standpoint. It also affords a means of determining the maximum lightning voltage that can appear on a transmission line.

The maximum voltage induced on the line is 1 or 2 per cent of the cloud voltage. The energy is of the order of 1,350 watt-seconds. The character of the discharge is generally impulsive and reaches its maximum in a few microseconds. In fact, it corresponds closely to the discharge from the lightning generator in voltage, energy, and duration.

TRAVEL OF LIGHTNING ON TRANSMISSION LINES

A lightning disturbance travels over the line at the velocity of light, and is dissipated to a considerable extent by losses; it may

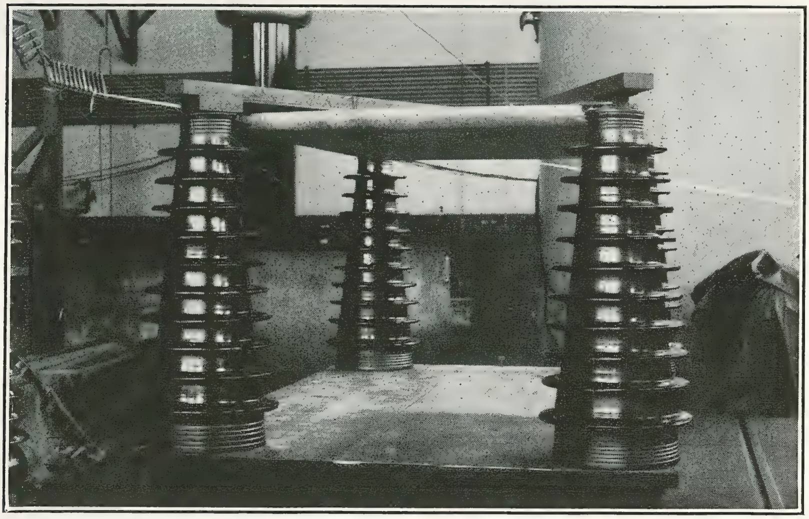


FIG. 18.—STUDY OF THE VOLTAGES INDUCED UPON TRANSMISSION LINES

Photograph shows overhead cloud and a section to scale of one of the lines studied during the investigation

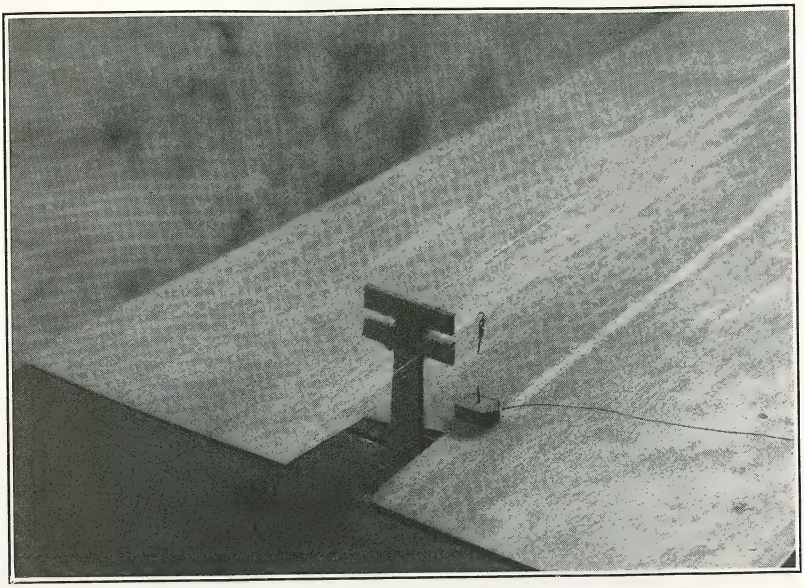


FIG. 19.—SHORT SECTION OF A THREE-PHASE LINE WITH OVERHEAD GROUND WIRE UPON WHICH A STUDY WAS MADE OF INDUCED VOLTAGES BY LIGHTNING

Photograph shows one of the "towers" and one of the spark-gaps used to measure voltage at this point

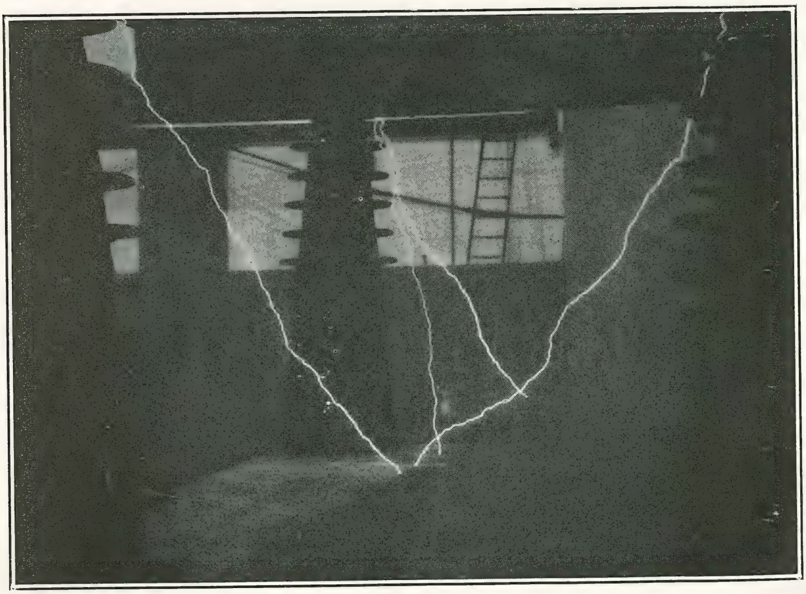


FIG. 20.—LIGHTNING STROKES HITTING THE OVERHEAD GROUND WIRE OF A TRANSMISSION LINE DURING STUDY OF LIGHTNING VOLTAGES INDUCED ON A THREE-PHASE LINE DURING A STORM

double in value when it strikes the end of the line where it starts back. If the voltage is high enough it may break down insulators or discharge over an arrester. If no break occurs it is eventually dissipated by losses. The change in shape and voltage of lightning waves traveling along transmission lines at 186,000 miles per second has been measured in the laboratory.

The strength of the insulation of lines operating at various voltages was determined by measurements with artificial lightning. By comparing the insulation strength with the maximum lightning voltage the ability to withstand lightning was determined.

THE GROUND WIRE

When a grounded wire is placed near and parallel to the transmission wires it has a marked effect on the induced voltages. The effect of the ground wire was studied on models to scale. The diagrammatic arrangement is shown in Figure 17, while the actual models are shown in Figures 18, 19, and 20.

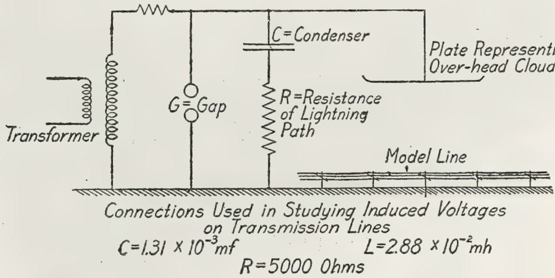


FIG. 17

The method of making the test was to measure the induced voltages on the model line with and without a ground wire. In general the single ground wire reduces the induced lightning voltage to one-half, two to one-third, and three to one-fourth. Very good connections must be made to ground. The ground wire thus offers an important practicable means of reducing lightning voltages. It is also important in case of a direct stroke, when the ground wire is struck 98 per cent of the time.

INSULATING A TRANSMISSION LINE TO WITHSTAND LIGHTNING

The investigation has shown the maximum lightning voltages that can occur on transmission lines with and without a ground wire. It is of interest to compare these voltages with the lightning insulator arc-over voltages for modern transmission lines.

The lightning spark-over voltage for insulators and the lightning breakdown voltage for insulation is always higher than for steady voltages. In fact, this is true for all transient voltages that can occur on transmission lines. Rain lowers the arc-over voltage of insulators at 60 cycles, but does not reduce the lightning spark-over voltage. The curves of insulator spark-over voltages for transient and operating conditions are given in Figure 21.

The transient voltage curves cover the range of lightning, switching surges, and surges due to arcing grounds. The surges other than lightning are limited in value by the line voltage. Except as it is affected by the height of tower, lightning is independent of line voltage. It is the determining factor in insulation.

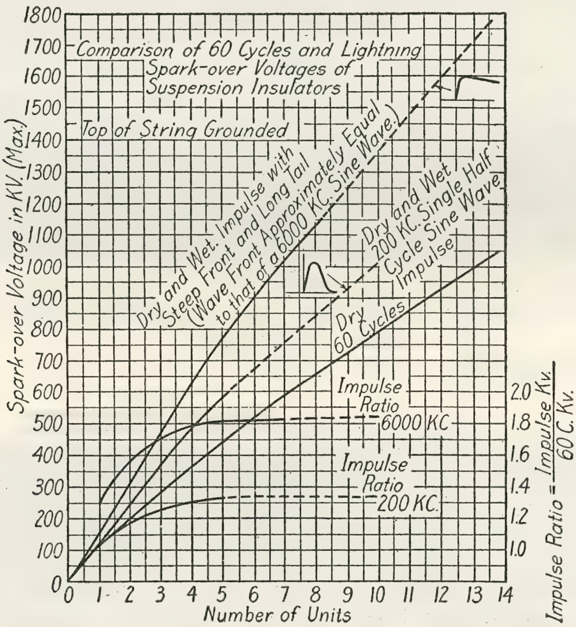


FIG. 21

The lightning flash-over voltage of insulators is plotted with operating voltage in Figure 22. On this same figure are plotted curves of the probable highest lightning voltage for lines with and without ground wires. A direct stroke on a line without a ground wire causes voltages much higher than the insulator arc-over voltage. The second curve down represents the usual highest voltage on a line without a ground wire. It happens that this same curve corresponds to the voltage by a direct stroke on a line with one ground wire. This curve crosses the insulator spark-over voltage of 220 kv. This indicates that a 220-kv. line without a ground wire is not likely to have insulator trouble from lightning except in case of direct stroke. It further indicates that a 220-kv.

line with a favorably installed ground wire is not likely to have trouble from lightning under any circumstances, unless the towers are very high. The next curve gives the usual highest voltage for a line with one ground wire. Under usual conditions, very little trouble should be expected for lines insulated for over 100-kv. operation. The lowest curve shows that three ground wires reduce the probability of lightning to still lower operating voltages. The probability of trouble with direct strokes would be reduced in proportion.

The values of voltages taken in the above curves are for the most severe storms directly over exposed lines. Such conditions might not occur during a year or several years. It is a well-established fact that during any storm there are likely to be induced many low-voltage impulses, a less number of moderate-voltage impulses, and frequently none at high voltage.

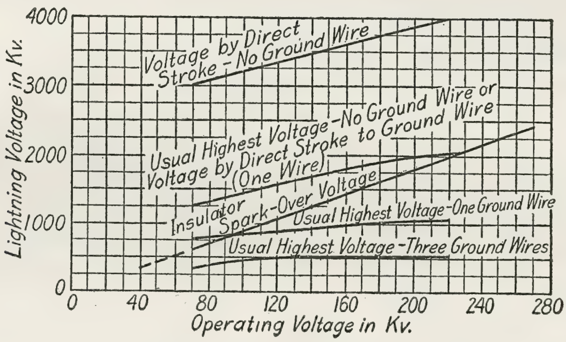


FIG. 22.—Insulator spark-over voltage compared with maximum lighting voltage for severe storms directly over the line

Lightning voltages are likely to cause high local stress in inductive apparatus such as transformers. In designing inductive apparatus to withstand lightning voltages, it is important to prevent concentration of stress. This can be done by means of shields. Like the ground wire, the action of the shield is preventative. Shields have been used on both line insulations and transformers.

LIGHTNING ARRESTERS

Preventive methods of guarding against lightning on transmission lines, such as the ground wire, shields, and extra insulation, have already been discussed. The remaining method is the lightning arrester.

The object of the arrester is to permit transient or other excess voltages to discharge to earth and to suppress the dynamic arc that follows. Since transient currents are generally high, the arrester must have a low resistance. It must also have a low time lag, otherwise the transient voltage may rise to high values before the discharge occurs.

Figure 22 shows that the need of an arrester becomes less as the operating voltage increases.

Corona and other losses also rapidly reduce lightning voltages.

OTHER CAUSES OF TROUBLE ON TRANSMISSION LINES

Most troubles on transmission lines are caused either by lightning voltages in excess of the insulation breakdown voltage or to some form of dirt that lowers the normal breakdown voltage to such an extent that failure occurs under normal conditions.

Certain transient voltages are produced in lines during switching, etc., but these are usually quite harmless.

CORONA AND SPARK OVER OF LIGHTNING VOLTAGES

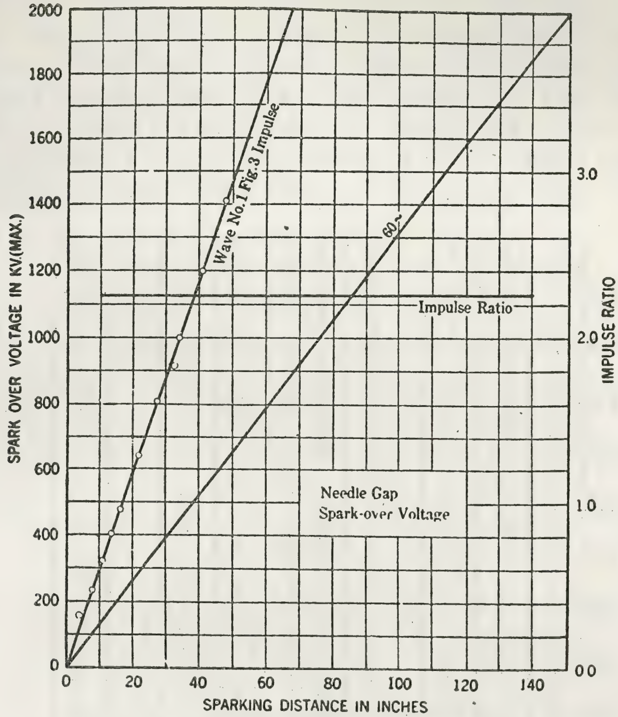
The corona and spark-over voltages due to lightning are usually quite different from the continuously applied 60-cycle or direct-current voltages. This also applies to liquid and solid insulation. The lightning voltage is a transient or impulse and in effect is applied at an extremely rapid rate. The insulation does not have time to break down when its usual breakdown voltage is reached but the break is completed at a later time when the voltage has risen to a higher value. The time lag will be discussed in more detail later.

CORONA

Lightning voltages cause corona in the same manner as continuously applied voltages. Corona produced by lightning voltages of less than a microsecond duration (millionth of a second) can be readily seen. It is also easy to tell whether the impulse is positive or negative. In general, corona produced by impulse voltages follows the same law as corona produced by continuously applied voltages. It is of interest that the eye can readily see corona produced by voltage of a microsecond duration.

SPARK-OVER OF NEEDLE GAPS

A typical discharge from the lightning generator at 1,500,000 volts between points is shown in Figure 10. The discharge has a zigzag path and characteristic side flashes of lightning. The lightning spark-over curve for needle gap is given in Figure 23. This curve shows that for the particular impulse used (fig. 24) a voltage is required approximately 2.25 times the 60-cycle voltage to spark over a given gap. The factor 2.25 is called the impulse ratio.



LIGHTNING SPARK-OVER CURVE BETWEEN POINTS

FIG. 23

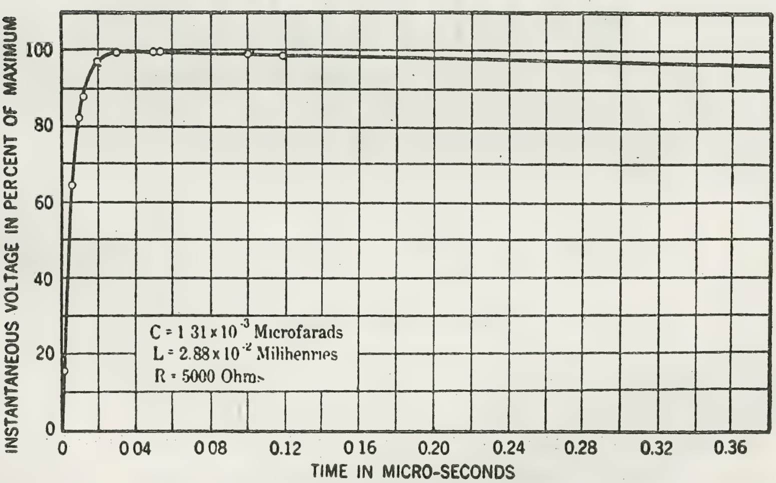


FIG. 24.—Wave shape of lightning used in the tests. Wave shape No. 1. Two million-volt impulse generators

THE SPHERE GAP

While the impulse spark-over voltage of the needle gap varies with the wave shape of the impulse and is always higher than the 60-cycle spark over, the sphere gap is very little affected, even for quite steep waves. The sphere gap thus offers a means of measuring transient voltages over a considerable range. Figure 12 shows a typical sphere gap spark, and Figure 25 shows that the spark-over

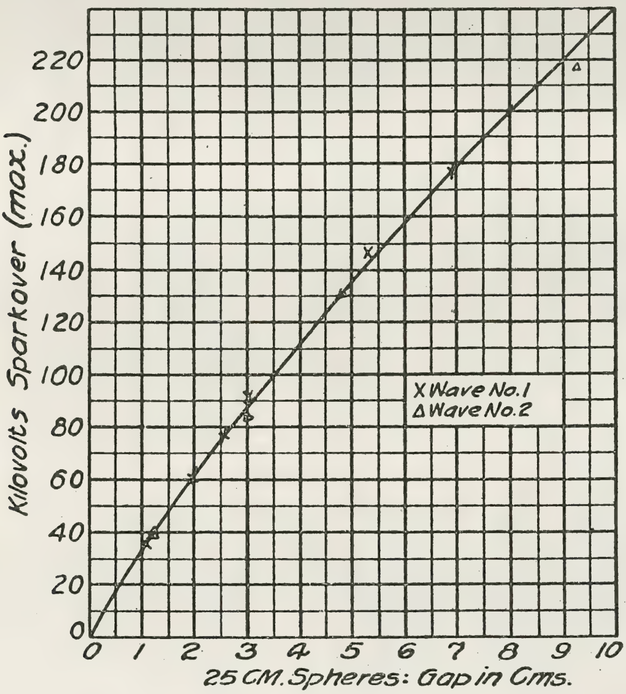


FIG. 25.—Sphere gap spark-over curves for 60 cycles and for impulse waves Nos. 1 and 2. Wave No. 1, single half sine wave impulse; wave No. 2, impulse with steep front, but with a long tail. (Drawn curve is for 60 cycles; points are for waves Nos. 1 and 2, as noted.)

voltages for a given gap do not vary over a very wide range of transients.

LINE INSULATORS

Investigation at the lower voltages showed that the wet and dry lightning spark-over voltages of insulators were equal. Tests made at the higher voltages confirm these data. Typical 60-cycle and lightning arcing characteristics for shielded and nonshielded insulator strings are shown in Figures 27 and 28. The shield consists of a metal ring at the line end of the string. It serves to distribute the voltage evenly between the units as well as to direct the arc away from the string.

These tests are of practical importance, since lightning voltages higher than these rarely occur on operating transmission lines. The lightning spark-over voltage was found to be twice the 60-cycle spark-over voltage. The impulse ratio was increased by the shield. The wet and dry lightning flashes clear the shielded string while on the nonshielded string the flash cascades and is likely to rip off the skirts.

It will be noted that the three typical gap arrangements have different characteristics. Both the needle gap and the insulators require a lightning voltage about double the 60-cycle voltage to

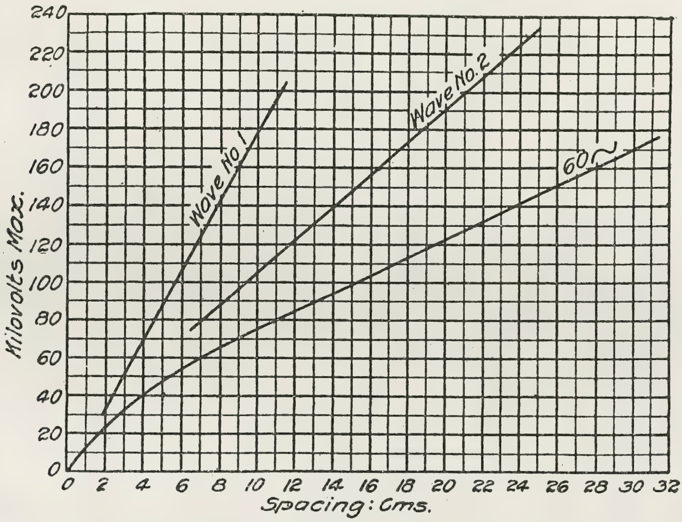


FIG. 26.—Needle-gap spark-over curves for 60 cycles and for impulse waves Nos. 1 and 2. Wave No. 1, single half sine wave impulse; wave No. 2, impulse with steep front, but with a long tail

cause spark over, while the sphere spark-over voltage is the same for 60-cycle and a wide range of impulse voltages. This characteristic is of great practical importance, since it is desirable to have an arrester gap that discharges at a low lightning voltage and to design insulators that have a high lightning spark-over voltage. The reason for this is time lag, and it seems worth while to discuss it briefly.

TIME LAG

A fixed minimum voltage is required to spark over a given gap when the time of application is not limited. Energy is necessary to rupture gaseous, liquid, and solid insulation; this introduces a time element.

Referring to Figure 29 the spark-over voltage of a given needle gap is e_1, and always practically constant if the time of application is not limited. Spark over may take place after the continuously applied voltage e_1 has been on for some time t_1. If a voltage increasing at a rapid rate, as represented by A in Figure 29, is applied, spark over will not take place when the continuously applied spark-over voltage e_1 is reached, as the time t_1 is required at this voltage. The spark will begin to form when the voltage reaches the value e_1, however. The voltage will, therefore, rise above e_1, and spark over will take place after the time t_2 has elapsed and the voltage has risen to e_2. When the voltage is applied at a more rapid rate along wave B, the spark, as before, will begin to form when voltage e_1 is reached. The voltage will continue to rise and reach some

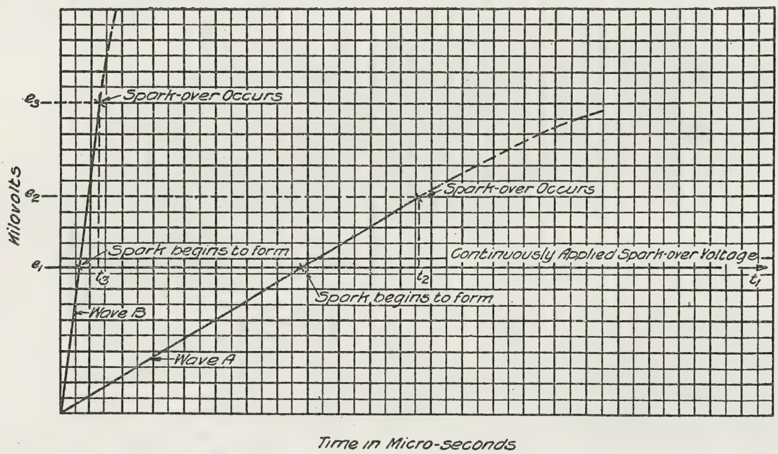
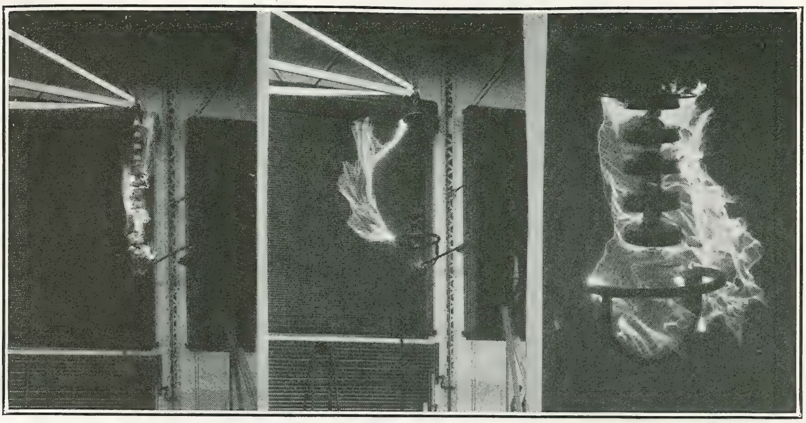


FIG. 29.—Diagrammatic illustration of why the lightning or impulse spark-over voltage is higher than the continuously applied

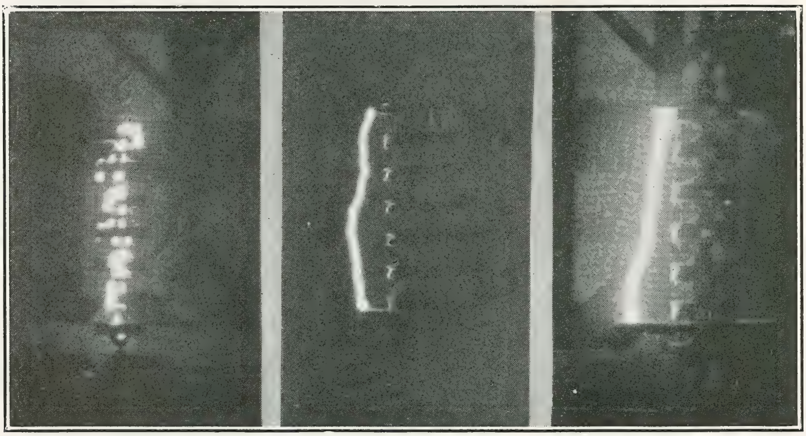
value e_3 during the time t_3 before the spark over occurs. Thus, on account of the time lag, when voltage is applied at a very rapid rate, as by an impulse, spark over does not occur when the continuously applied breakdown voltage is reached. The voltage "overshoots" this value during the time that rupture is taking place. The excess in voltage is greater, and the time lag less, the greater the rate of application. The time lag for any given gap or insulation has thus not a fixed value but depends on the wave shape of the impulse or rate of application of the voltage. In making a study of such phenomena it is necessary to use certain definite wave shapes. Figure 30 shows the impulse voltage-time characteristic for needle gaps. The impulses used in this test were single half cycles of sine waves. Note that the impulse spark-over voltage is not greatly above the continuously applied or 60-cycle voltage when the time is over 5 microseconds; that is, when the time of application is comparatively



A *B* *C*

FIG. 27.—SIXTY-CYCLE SPARK-OVER OF SUSPENSION INSULATOR STRINGS

A, Dryspark-over on a nonshielded string. Note that arc cascades badly along the entire length of string. *B*, Dry spark-over on a string shielded with the ring shield. Note that arc clears string. *C*, Wet spark-over on a string shielded with the ring shield. Arc starts through drip then immediately transfer itself clear of string



A *B* *C*

FIG. 23.—LIGHTNING SPARK-OVER OF SUSPENSION INSULATOR STRINGS

A, Dry spark-over on a nonshielded string. Note that the arc cascades badly along the entire length of string. Voltage=1,200,000 volts. *B*, Dry spark-over on a string shielded with the ring shield. Note that the arc clears the string. Voltage=1,200,000 volts. *C*, Wet spark-over on a string shielded with the ring shield. Note that arc clears the string. Voltage=1,200,000 volts. Note, also, the drip along the string and the raindrops which appear stationary in space since the light of the arc lasted less than a millionth of a second

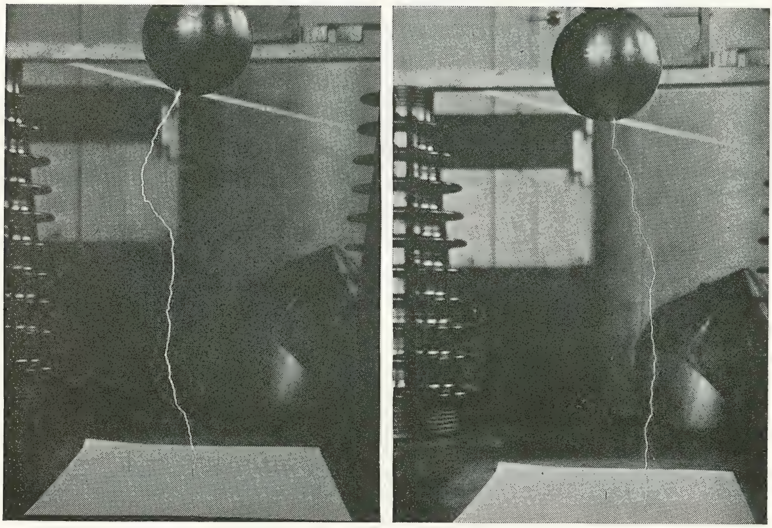


FIG. 32.—LIGHTNING DOES NOT ALWAYS HIT THE HIGHEST POINT

FIG. 39.—ARTIFICIAL LIGHTNING STROKE FROM THE 2,000,000-VOLT LIGHTNING GENERATOR STRIKING HOUSE AND CHURCH OF MODEL VILLAGE DURING STUDY OF LIGHTNING PROTECTION OF BUILDINGS

long there may be a considerable variation of this time without an appreciable change in the spark-over voltage. The continuously applied (60-cycle, or *d—c*, where heating does not occur) spark-over voltage is the lowest voltage at which spark over can take place.

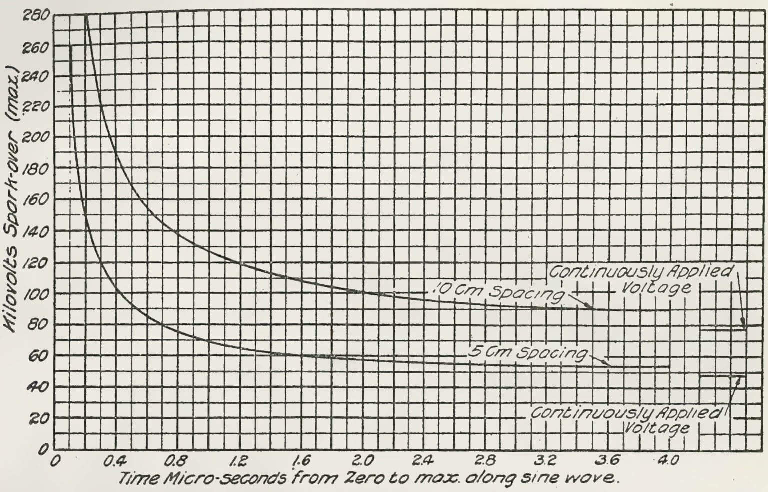
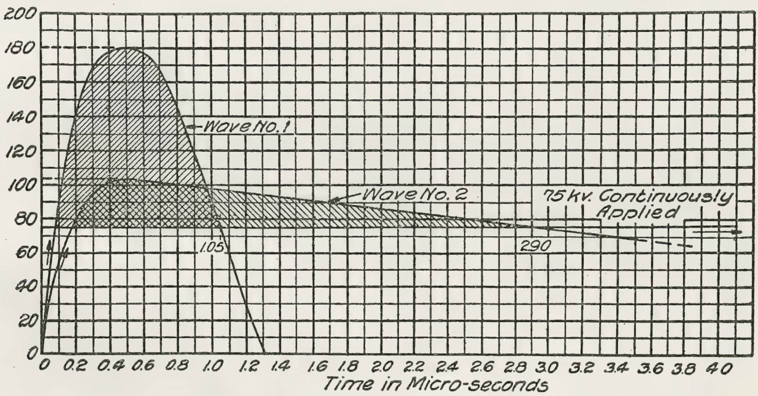


FIG. 30.—Time and voltage to spark over needle gaps with a sine wave impulse

Waves (1) and (2) (fig. 31) show actual wave shapes used in obtaining data given in Figures 25 and 26. Wave (1) is equivalent to a single half cycle of a sine wave; wave (2) rises to a maximum



F|7. 31.—Continuously applied and impulse voltages to just cause spark over of a 10-cm. gap between needles

at the same rate as wave (1) but has a flat top, or is of much longer duration. Of the two waves shown in Figure 31 the voltage required to spark over a given gap is higher for the one of shorter duration or for wave (1). In this figure, where actual test data are given for a 10-cm. gap between needles, spark over results at 180 kv. for wave (1), while for wave (2) spark over results at 104 kv. The spark over at 60 cycles is 75 kv. The time that wave (1) is above the continuously applied breakdown voltage is 0.95 microseconds, wave (2), 2.70 microseconds. The impulse and continuously applied needle gap spark-over curves are given in Figure 26. An examination of Figure 26 shows that the impulse spark-over voltage of needles is always higher than the continuously applied spark-over voltage, for a 10-cm. gap is 180 kv., or 2.4 times the 60-cycle or continuously applied voltage.

The time to spark over a gap varies with the spacing and shape of the electrodes. For a given 60-cycle voltage setting the time re-

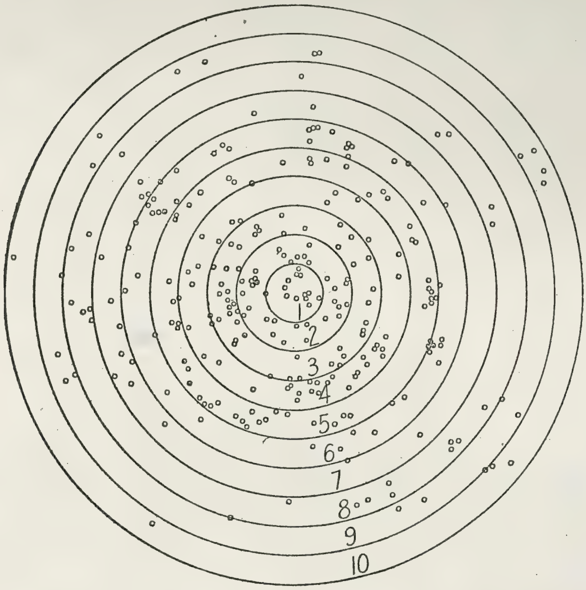


Fig. 33.—Target made by lightning. No needle

quired to form a spark is greatest for gaps between points and least for gaps between well-rounded surfaces. For spheres, the time lag is so small that discharge takes place before the impulse voltage can rise appreciably above the continuously applied or 60-cycle spark-over voltage. This is shown in Figure 25, where the drawn curve is the 60-cycle curve, while the impulse spark-over voltages for waves (1) and (2) are represented by crosses and triangles.

The needle gap requires the maximum time of any gap, as considerable air must be ionized before spark over can result. Another way of considering it is that the corona increases the capacity and places resistance in series with it as it forms. It requires time to charge a condenser through resistance.

On the other hand, spheres are very little affected because corona does not precede spark over, and the discharge is small and confined to a short path. The field is very nearly uniform, and ruptures start everywhere along the path between the electrodes at approximately the same time.

THE LIGHTNING ROD

A study was made, using models built to scale, to determine the protective value of lightning rods. In making these tests, voltages varying from 60 cycles to oscillations and impulses were used. The "clouds" were also varied from a point to a large flat plane.

FIG. 34.—Target made by lightning. ½-inch needle

It seems that all possible conditions were covered by this range, and since the general behavior of the discharges was the same in all cases, it is believed the results apply to actual lightning discharges.

In making the tests the rod was placed in the center of a large piece of drawing paper on a flat plane. Unless otherwise stated, the plane was of metal. The cloud was placed above the rod. The tests show that lightning from a cloud overhead does not always strike the highest object. The discharges either took place to the rod or to the plane. When the discharge hit the paper a small hole was made. A record was thus obtained of the distribution of the discharges. When the cloud was a plane, a small point was placed at its center to represent the storm center. The apparatus is shown in Figure 32, while sample charts are shown in Figures 33 and 34.

AREA PROTECTED BY A ROD

The general character of the division of hits between a rod and the surrounding ground is shown in Figure 35. In this specific

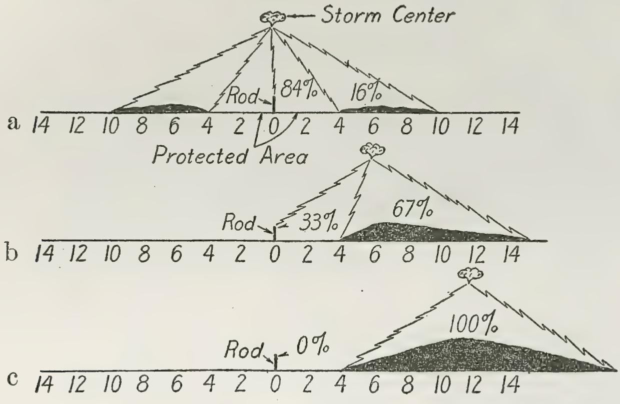


FIG. 35.—Protected area and distribution of hits between rod and ground for different positions of storm center

example, taken for illustration, the rod is located on a conducting plane and is 1.85 per cent of the cloud height. In (a), Figure 35,

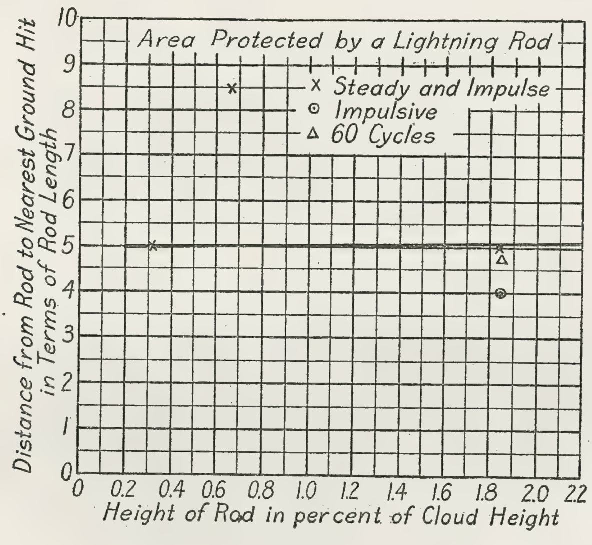


FIG. 36

the storm center is located directly above the rod. Under this condition 84 per cent of the strokes hit the rod, while 16 per cent hit the ground approximately as shown in the shaded portion.

There are no ground hits in an area between the rod and four rod lengths away. This protected area is well illustrated in Figure 34 and seems to hold for all conditions as shown in Figure 36.

The division of hits as the storm center moves away from the rod is illustrated in (b) and (c) Figure 35. Eventually, a distance is reached when the rod is no longer struck. This occurs for this particular rod when the projection of the storm center is about 30 per cent of the cloud height away from the rod. There are no ground hits closer to the rod than four times its height for the extremes given in Figure 35.

DIVISION OF HITS BETWEEN ROD AND GROUND FOR DIFFERENT HEIGHTS OF ROD

The division of hits between a lightning rod and ground, when the rod is located directly under the storm center, is shown in Figure

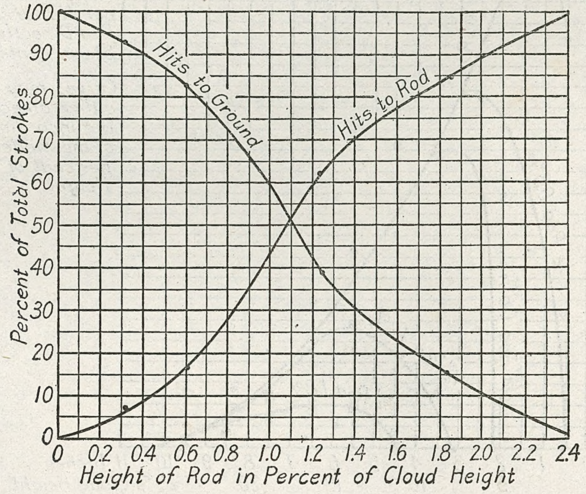


FIG. 37.—Division of hits between rod and ground for different heights of rod

37. When the rod has zero length, 100 per cent of the hits, of course, must strike the ground. When the height of the rod is 1.1 per cent of the cloud height, the division of hits is equal, while all of the strokes go to the rod when it is about 2.5 per cent of the cloud height. Over this range the ground was never hit nearer to the rod than four times its height.

HITS PER UNIT AREA UNDER A STORM CLOUD

Figure 38 shows the ground hits per unit area at various distances from rods of different heights. The rods are directly under the storm center. With rods of zero height 1 per cent of the hits per unit area occur directly under the storm center. The number of hits per unit area decreases rapidly until there are no hits at about 25 per cent of the cloud height away from the center. With a rod 0.6 per cent of the cloud height, 16 per cent of the strokes strike the rod (fig. 37). There is a protected area where no ground hits occur (fig. 38). The maximum ground hits per unit area, 0.7 per cent, occur at about 8 per cent of the cloud height from the center. No ground hits occur at 25 per cent of cloud height from the center.

CHANCE OF BEING STRUCK

The above data offer a means of estimating the relative chance of objects of different heights being struck during a thunderstorm

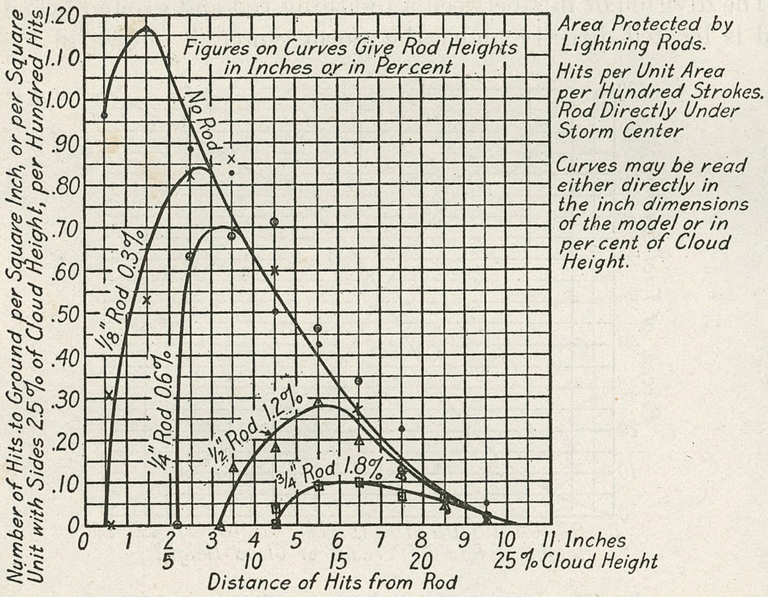


FIG. 38

when the cloud is overhead and of sufficient voltage to discharge to earth.

Assume a cloud 1,000 feet high. A 6-foot man on a plane directly under the storm center (from fig. 37) would be hit 15 times out of every 100 strokes, while a 25-foot building would be hit every time. A man flat on the ground (from fig. 38) would be struck about once for every hundred strokes. An 18.5 foot building directly under the storm center would be struck 84 times out of 100 hits. However, with the storm center moved only 296 feet this building would not be struck.

These data are useful in determining the best methods of protection, because they tell what will happen when conditions are such that discharges can take place to the house or rod under consideration. In other words, the data give the chance of an object being struck when it is directly under a cloud at sufficient potential to cause a discharge. To determine the chance of any object being struck during a year, it is also necessary to know the chance of a cloud of sufficiently high potential passing over the object. It is apparent that this chance is usually quite small even when the object is located on a plane. When mountains, hills, and trees are added the chance becomes still less.

PROTECTION OF BUILDING

The lightning rod is of real value in preventing or limiting damage when a building is struck. Whether or not it increases the chance of being struck depends upon circumstances. It is rather doubtful if it often does, as a chimney, grounded gutter, or water pipe may be sufficiently conducting to determine the direction of the stroke.

In deciding upon a lightning rod the economic factor or the cost of protection must be considered in connection with the probability of being struck. It seems that the best results can be obtained with plain inconspicuous rods. Ornate rods or rods with special points appear to have no advantage. A grounded metal roof would seem almost ideal protection. Rods should be installed so that side flashes are not likely to occur to conducting objects inside or outside of the building. When a building is in an exposed position and storms frequently pass over it, a more elaborate outlay for protection would be justified than in the case of an unexposed building. For instance, a building on a cliff over a valley followed by storms would be in much greater danger from lightning than a building located in the valley. This would be especially so if connections were made from the upper building to water level. Lightning rods can be arranged to give almost ideal protection when the expense is warranted. In the case cited above, a lightning rod located on the cliff would give good protection to buildings in the valley. It is probable that except for buildings in exposed positions and for special cases as magazines or oil tanks, the cost of even an inexpensive rod is not warranted from the standpoint of the cost of insurance.

SPARKS INSIDE OF METAL TANKS

Tests have been made to determine if it is possible to cause sparks inside of metal tanks or cans by direct stroke or by electromagnetic

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induction or electrostatic induction. It has not yet been possible to obtain sparks between points within a completely closed metal tank. Under certain conditions small sparks have been obtained by electromagnetic induction between points in partly inclosed metal structures. Sparks are readily obtained within tanks from a grounded conductor brought in from the outside when it is slightly insulated from the tank by oxide or otherwise. The spark occurs by electrostatic induction or when either the wire or tank is struck. This is interesting in that sparks may be obtained from a grounded conductor.

The above experiments have a practical value, because they show the danger of any lead-in conductors to oil tanks or magazines. They also illustrate the importance of having no projections within a tank. For instance, a metal rivet insulated from a tank by oxide might cause a sufficient spark to ignite gases within the tank. Grounded gauge chains could readily cause internal sparks.

FIRES BY LIGHTNING

It is quite possible to cause fires by lightning by sparks between isolated metal parts even when direct strokes do not occur. Some model bales of cotton were placed under the model cloud. It was found that the cotton could be ignited by sparks electrostatically induced between the metal bonding strips.