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THE EFFECT OF TRANSIENT VOLTAGES ON DIELECTRICS II

The Effect of Lightning Voltages on Arrester Gaps, Insulators and Bushings on Transmission Lines

BY F. W. PEEK, JR.

ABSTRACT OF PAPER

This paper treats of some of the practical applications resulting from an investigation of the effect of lightning voltages on insulators, bushings and protective gaps.

There is a great difference in the relative lightning spark-over voltages of various gaps as well as a great difference in the settings imposed by operating conditions. Both of these factors must be considered in comparing the relative protective values.

A gap must be set so that the normal line voltage does not cause it to spark-over. Gaps are generally used out of doors. Rain lowers the 60-cycle spark-over voltage of all uncovered gaps and thus imposes a greatly increased setting and decreased protective value since the lightning spark-over voltage is not changed by rain.

The covered sphere gives the maximum protection. The protective value is constant under all conditions.

The sphere-horn, having electrodes of points, horns and spheres, gives very good protection over the whole range of frequency and wave front. The spheres discharge the very steep waves, the horns the moderate ones, and the points continuous high-frequency waves of slanting front and static.

The protective value of selective gaps varies with the wave front. Its protective value is a minimum for very steep wave fronts and for waves of slanting front. Over a certain range its protective value is very good.

The relative protective values of various gaps for steep and slanting wave fronts and high frequency are shown graphically in Figs. 14, 15, 16 and 17. The relative protective values are approximately independent of the point on the 60-cycle wave at which the discharge occurs.

Data are given on the steepness of lightning waves actually occurring on transmission lines in practise.

Bushings and insulators with equal 60-cycle spark-over voltages may have entirely different lightning spark-over voltages. A bushing should be designed for a high lightning spark-over voltage.

The lightning wet spark-over voltage of a bushing or insulator is the same as the dry spark-over voltage.

IN 1915 I presented a paper covering an extensive investigation on the effects of transient or lightning voltages on air, oil and solid insulations, line insulators and the discharge voltages of various gaps.¹ An exact study was made possible

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by the development of the "impulse generator," which was also described in the paper referred to above, and as a result some very important fundamental relations were discovered.

It is the purpose of this paper to treat in more detail a few of the important practical applications which have been made of these relations within the last few years. The present discussion will be concerned principally with lightning arrester gaps, bushings and line insulators. It is hoped in particular, to make clear the advantages and disadvantages from a strictly practical standpoint of the various arrester gaps.

The fundamental relations referred to above, bearing on the present discussion, will be briefly reviewed:

When a 60-cycle voltage is slowly applied to a gap and gradually increased, spark-over will occur at some definite voltage. This is the minimum voltage that will cause sufficient ionization for the gap to discharge and it requires a relatively long time.

Lightning voltages, or voltages of relatively steep wave front start at zero or line voltage and increase at the very rapid rate of millions or billions of volts per second. When such voltages are applied across a gap or insulator, spark-over does not occur at the instant the minimum or 60-cycle voltage is reached, as considerable time is required at this voltage. When this voltage is reached the spark begins to form but is only completed after the rapidly rising voltage has reached some higher value. The "slower" the gap the higher the voltage will rise. In a uniform field, break-down takes place over a relatively short path, everywhere, at the same time. In the case of a non-uniform field represented, for instance, by the needle gap, corona forms around the electrodes before spark-over. A vast amount of air must be ionized. The condition is equivalent to putting the corona or arc resistance in series with an ever increasing capacity represented by the unbroken dielectric. Time is thus required to bring all of the space between the electrodes up to the break-down gradient and during this time, the lightning voltage rises higher and higher.

To summarize: (1) Two gaps or insulators with equal 60-cycle spark-over voltages may have entirely different lightning or impulse spark over voltages because of the time lag.

1. "The Effect of Transient Voltages on Dielectrics," F. W. Peek, Jr., A. I. E. E., Vol. XXXIV, 1915, page 1857.

"Lightning," *General Electric Review*, July 1916.

(2) The time lag is the greatest in a non-uniform field or for electrodes where corona precedes spark-over; it is minimum for a uniform field.

(3) The time lag for any given electrodes and spacing is not constant, but depends upon the steepness of the wave or the rate at which the voltage is applied. The spark-over voltage increases and the time lag decreases with increasing steepness of wave front.

(4) Lightning or impulse spark-over voltages, unlike 60-cycle spark-over voltages, are not appreciably lowered by rain.

The above discussion means, of course, that certain gaps and insulators which have equal 60-cycle spark-over voltages may have entirely different lightning spark-over voltages. The ratio between the impulse and 60 cycle spark-over voltage was termed the impulse ratio. When there is no time lag the impulse ratio is unity; the greater the time lag, the higher the impulse ratio. Under certain conditions selective gaps may have an *apparent* impulse ratio of less than unity.

It is very important to utilize these principles in design; protective gaps should have an impulse ratio of unity or low lightning spark-over voltage, while insulators and insulation should have a high impulse ratio or high lightning spark-over and puncture voltage.

The practical application of these principles to various protective gaps will first be discussed.

PROTECTIVE GAPS

General. The lower the voltage at which a given arrester gap can be set the greater is its protective value. In practise, the setting must be such that the gap does not discharge under any normal operating condition. The 60-cycle spark-over voltage of a gap is very much decreased if the electrodes become wet. The decrease in voltage due to moisture differs greatly with the shape of electrodes. It is minimum for points and maximum for plane surfaces. The 60-cycle spark-over voltage of a gap may be affected by other surface conditions, but by far the greatest effect is that caused by moisture. See Table I. Practically all high voltage arrester gaps are installed out of doors. These gaps must, therefore, be set so that the line voltage does not cause spark-over during a rain storm. This means that with any gap with "fast" electrodes the setting

must be approximately doubled and the protective value thus reduced.

The wet and dry 60-cycle spark-over voltages of 6.25 cm.

TABLE I
SPHERE GAP
The Approximate Effect of Rain, Ice, Dust, etc. on the 60 Cycle
Spark-over Voltage of Sphere Gap.

Foreign material on sphere surface.	Voltage per cent of normal
Thin coating of dust.....	98
Coating of oil.....	100
Heavy coating of oil and sand.....	75 - 90
Thin coating of ice.....	75 - 90
Thick coating of ice.....	75 - 80
Surface oxidized.....	100
Ordinary pitting.....	90 - 100
Rain 0.2 in. precipitation per min. Polished spheres.....	40 - 50
Rain 0.2 in. precipitation per min. Pitted spheres.....	40 - 50

spheres is given in Fig. 1. That the lightning spark-over voltage is not appreciably changed by rain is shown in Fig. 2. In comparing the relative protective value of lightning arrester

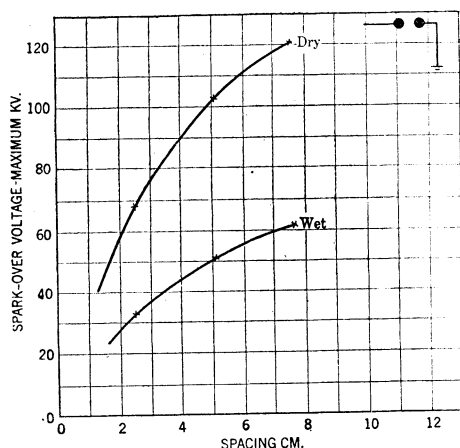


FIG. 1—SPHERES—WET AND DRY SPARK-OVER VOLTAGES
6.25 cm. spheres—60 cycles—one sphere grounded—0.2 in. rain—data Table II

gaps it is, thus important to make the comparison on equal wet 60-cycle spark-over voltages or by the setting imposed by the operating conditions.

Operating conditions other than rain or inherent properties of the arrester proper may make it necessary to increase the setting of certain types of gaps and not of others. Rain is, however, the chief factor in non-selective gaps. As an example of the effect of rain on the setting, assume a 66,000-volt line with grounded neutral. The voltage to ground is

$$\frac{66,000}{1.73} = 38,000$$

The arrester gap must be set at about 25 per cent above this or 47 kv. wet. Referring to Fig. 2, if the gap is protected

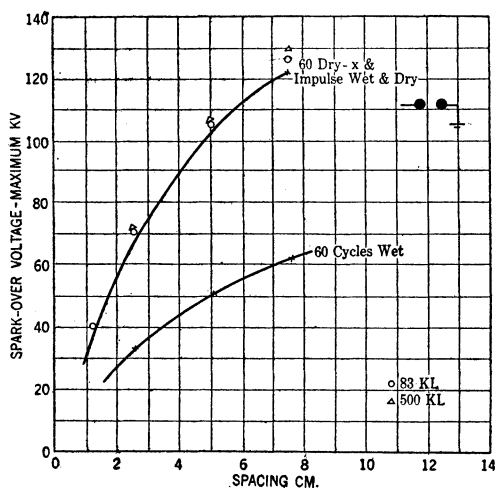


FIG. 2—SPHERE—WET AND DRY SPARK-OVER VOLTAGES

6.25 cm. spheres—60 cycles and impulses—0.2 in. rain—one sphere grounded—data Table II

from the weather the lightning spark-over voltage is 47 kv., wet or dry; if the gap is not protected from the weather the dry 60-cycle spark-over voltage must be 94 kv. in order to make the wet 60-cycle spark-over voltage 47 kv. and the apparatus is thus subjected to double the stress which would obtain if a covered gap were used. This follows because the lightning spark-over voltage approximately corresponds to the dry setting. There may be no gain in protection with a gap discharging at very low lightning voltages if in practise it must be set at a wide spacing to prevent line voltages from continually causing it to spark over.

The horn gap is not affected by the weather to as great an

extent as the sphere gap. If a sphere and a horn are adjusted for equal wet 60-cycle spark-over voltages, the dry 60-cycle spark-over voltage of the horn will be lower. For low-frequency surges the horn would thus discharge at a lower voltage. For steep wave front lightning voltages however, the lag of the horn, which may easily have an impulse ratio of 2, will cause it to give inferior protection. See Fig. 3.

THE SPHERE GAP—THE SPHERE HORN

The sphere gap has an impulse ratio of unity. It thus offers equal protection for all sorts of transient voltages, and is with-

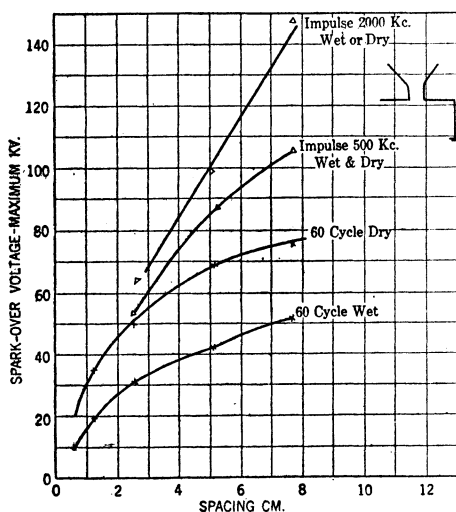


FIG. 3—HORNS—WET AND DRY SPARK-OVER VOLTAGES
60-cycle and impulse—wet and dry—data Table IV

out time lag when set at not greater than diameter spacing. When exposed to the weather, however, the setting must be high enough so that the line voltage will not spark-over during rain. See Figs. 1 and 2.

In the practical gap the sphere and horn were combined; the horn being used to assist in breaking the dynamic arc and for the gain in discharging low-frequency surges due to the smaller difference between the wet and dry spark-over voltages. The difference between the wet and dry spark-over voltage of points is less than with the horn. A point is sometimes added to further increase the protection at low-frequency surges.

This gap has proved very successful in its several years of practical use, very greatly increasing the protective value of arresters. See Fig. 4. Take for comparison equal wet settings of 50 kv. at 2000 kilocycles the spark-over voltage of the horn is 135, the sphere 100. For impulses below 500 kilocycles, the spark-over voltage of the horn is lower than the sphere. Thus, when a sphere horn is used the discharge takes place across the sphere for steep wave fronts and across the horn for low-frequency surges. The gain due to the sphere is greater at higher voltages and steeper wave fronts. The

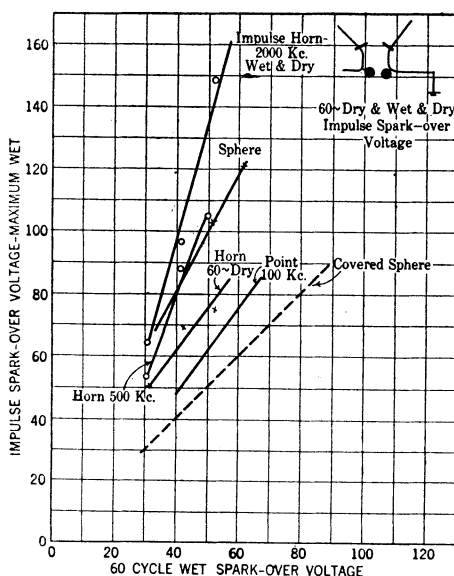


FIG. 4—SPHERE—HORN

Relative protective values of the component parts—data Tables II, IV, and V

covered gap, shown by the dotted line is superior at all wave fronts.

The Covered Sphere. If a sphere gap is covered and shielded from the weather its protective value is greatly increased since the setting imposed by the condition that the normal line voltage must not discharge over the gap is cut in half. Such a gap, therefore, discharges lightning voltages of half the value of the uncovered sphere. This gap gives the highest degree of protection. It is not possible to use it with all types of arresters since a horn is often necessary to assist in breaking

the dynamic arc. See Fig. 5. A properly designed hemisphere may also be used in this type of gap.

A gap not appreciably affected by the weather and still providing an arc breaking horn may be built as shown in Fig. 6. The way this accomplishes the desired results will be described later.

Since the gap requires two spheres in series, it is necessary to determine if such an arrangement has appreciable time lag and, therefore, high lightning-discharge voltages. Two 6.25-cm. spheres connected in series are shown in Fig. 7. If gap *A* is set at approximately 25 kv. and gap *B* at approximately 75

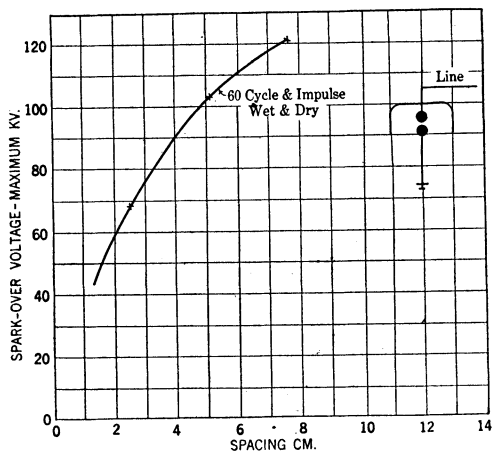


FIG. 5—SPHERES—WET AND DRY SPARK-OVER VOLTAGES

6.25 cm. spheres—covered gap—60 cycle and impulse—wet and dry—one sphere grounded
—data Table V

kv. the 60-cycle spark is not $(25 + 75) = 100$ kv. but is 75 kv.; the lightning or impulse spark-over is 91 kv. See Fig. 7.

The two gaps break down at 75 kv., 60 cycles, instead of the sum of the two or 100 kv. because the applied voltage does not divide evenly between them. The voltage reaches 25 kv. across the low-voltage gap and breaks that gap down before it reaches 75 kv. on the high-voltage gap. All of the stress is thus transferred to the high voltage gap and it breaks down as soon as a total voltage of 75 kv. is reached. If, now, capacities are adjusted across *A* and *B* so that the voltage divides in proportion to their relative break down voltages both gaps will break down simultaneously. The break down voltage will

be equal to their sum. This is called the "balanced" gap. When two sphere gaps each without appreciable lag are placed in series it is found that unless the gaps are "balanced" there is considerable lag. This would be expected because one gap breaks down first and puts resistance in series with the capacity of the other similar to the corona in the needle gap. Balancing the gaps causes simultaneous spark-over and there is no appreciable lag. See Fig. 7.

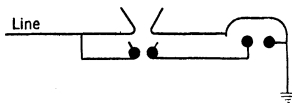


FIG. 6

If two gaps are placed in series as in Fig. 6 and balanced by properly adjusting their relative capacities there will be no appreciable lag. The rain affects only the outside gap. For example, if the outside gap is set at 10 kv. and the inside gap at 50 kv. the outside gap may be reduced to 5 kv. by rain. If balanced wet, the total wet spark-over is 55 kv. while the dry spark-over voltage is about 60 kv. This gap is thus without appreciable lag and not appreciably affected by rain. The only object of the outside gap is, of course, to

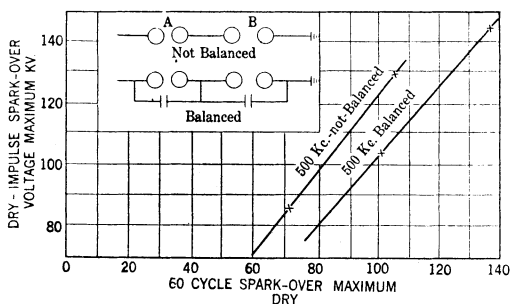


FIG. 7
Data Table III

transfer the dynamic arc to the horn where it rises and breaks.

The impulse and 60 cycle characteristics of this gap are shown in Fig. 8.

The advantage of the sphere gap is that it gives equal protection under voltages of all frequencies and wave front and is practically without lag.

Selective Gaps. Various forms of selective gaps have been proposed from time to time. Probably the most interesting and important of these is that investigated by Mr. Allcutt

and shown in Fig. 9.² In this gap the division of voltage is not greatly affected at 60 cycles by the auxiliary electrode. The auxiliary electrode is held at mid-potential because it is connected at the mid-point between two equal condensers. The capacity current is too small at 60-cycles to cause any appreciable "drop" across the resistance. If the condenser circuit were opened on one side, the gap on that side would break down at about half voltage. This is exactly what happens under impulse.

For steep wave fronts the resistance has the effect of opening

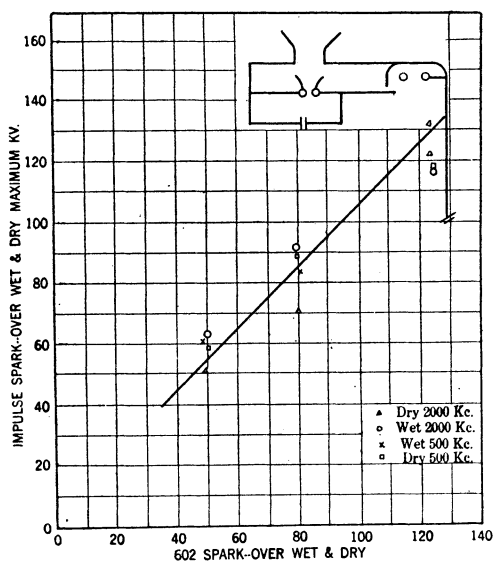


FIG. 8—WET AND DRY SPARK-OVER COVERED DOUBLE GAP BALANCED
Data Table VI

the condenser circuit on that side. See Fig. 10. The gap on that side breaks down. The voltage does not immediately disappear across the arc. The gap has lag for the same reason as the double unbalanced gap discussed above. Whether it is above or below the 60-cycle setting depends upon the impulse. The effect is similar to that which would result from a needle gap which could be set at, for instance, 100 kv. for 60-cycle operation and instantly and automatically reduced

2. "Lightning Arrester Spark Gaps," C. T. Allecutt, A. I. E. E., May 1918.

Discussions F. W. Peek, Jr., A. I. E. E., Atlantic City, June 1918.

to a 50 kv., 60-cycle setting whenever an impulse came on the line. For moderately steep wave fronts the spark-over voltage would be greater than 50 and less than 100 kv.; but for very steep wave fronts, the impulse ratio of the 50 kv. gap would be greater than two, or the spark-over voltage would be greater than 100 kv. The impulse ratio of the selective gap is always greater than unity; the "apparent" impulse ratio is greater or

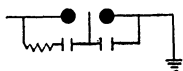


FIG. 9

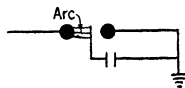


FIG. 10

less depending upon the steepness of the wave front. The reason this distinction is made is discussed elsewhere.³ The apparent impulse ratio should be used in comparing protective values. This characteristic for the selective gap is shown in Fig. 11 and compared with a sphere gap for the same dry 60-cycle settings. The sphere gap spark-over voltage is practically constant for all wave fronts. The spark-over voltages are the same for 60 cycles. At moderate wave fronts the selec-

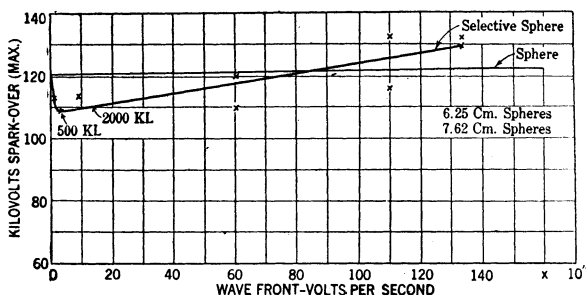


FIG. 11—VARIATION OF SPARK-OVER VOLTAGE WITH WAVE FRONT—
SPHERE AND SELECTIVE SPHERE—

Data Table VII

tive gap has about 5 to 20 per cent lower spark-over voltage than for spheres, while for steeper wave fronts the voltage is higher on the selective gap. The protective value of a gap, as already pointed out, depends not only on its lightning discharge voltage for a given 60-cycle setting, but also upon the setting which is imposed upon it by operating conditions. Fig. 11 shows the relative protective values of spheres and

3. A. I. E. E. Discussion, June 1918, F. W. Peek, Jr.

selective spheres assuming equal dry 60-cycle settings are possible. The settings must be such that the line voltage does not frequently spark-over and cause the destruction of the energy absorbing device under certain operating conditions. The effect of rain makes it necessary to set a non-shielded selective gap at about double the voltage that would be necessary in the protected gap. See Fig. 12.

Other forms of selective gaps have been devised and it is possible to extend the selective principle to a number of gaps in series, theoretically (neglecting lag) making it possible to discharge an impulse at a small fraction of line voltage. Such

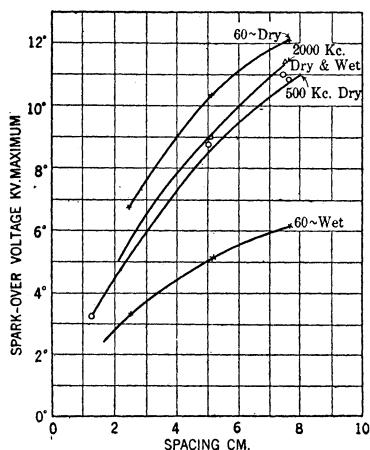


FIG. 12—SELECTIVE SPHERE
60-cycle and impulse—wet and dry—Data Table VIII

a gap would of course necessitate high initial setting and give very little protection against lightning impulses.

The selective principle may also be readily applied to covered gaps if it is deemed advisable.

RELATIVE PROTECTIVE VALUES OF THE GAPS ALREADY DISCUSSED

The following comparison of the different gaps is the result of extensive research. The tests were made with the impulse generator. The methods of conducting the tests, the precautions, accuracy, etc. are the same as discussed in the former paper.⁴ For convenience the connection diagrams are shown in Fig. 13—(a) is used when the impulse only is ap-

plied to the gap; (b) when the impulse is superposed on the 60-cycle wave.

There are three cases which require consideration.⁵

Case A. Where the impulse occurs at the zero point of the 60-cycle wave and is thus not affected thereby.

Case B. Where the impulse occurs at the maximum of the 60-cycle wave and is additive.

Case C. Where the impulse occurs at the maximum of the 60-cycle voltage wave, but in the opposite direction.

Case C is naturally the most dangerous case. Case A is equivalent to applying the impulse without 60-cycle voltage.

In making impulse tests it is found that there is a certain minimum impulse voltage that will spark-over the gap only occasionally and that the voltage must be increased to cause

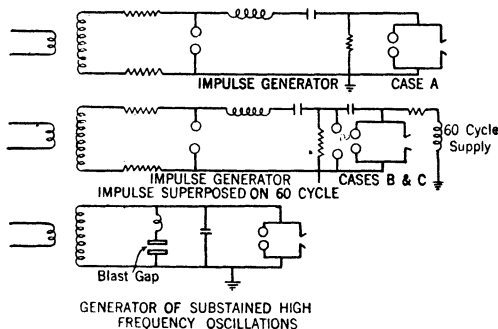


FIG. 3—CONNECTIONS USED IN MAKING TESTS

spark-over at every application. This difference between minimum spark-over and spark-over at every application may be inappreciable for some gaps and quite appreciable for others. This is discussed in my former paper. It is, thus, obviously necessary to record the method of making the tests. The data for all of the curves with description of method of making measurements will be found in the tables. Unless otherwise stated, the impulse voltage was increased until the gap sparked once in five applications. "Frequency" is used for convenience only. It means, unless otherwise stated, that an impulse approximating a single half sine wave of the frequency stated has been used. By applying a super-voltage or a voltage higher than the discharge voltage of the gap the steepness of

4. "The Effect of Transient Voltages on Dielectrics," A. I. E. E., F. W. Peek, Jr., 1915.

5. "Lightning Arrester Spark Gaps," C. T. Allcutt, A. I. E. E., May 1918. Discussion, F. W. Peek, Jr., A. I. E. E., June 1918.

the wave or rate of application is increased. For instance a super-voltage at 100 kilocycles might be steeper than a lower voltage at 2000 kilocycles. In making measurements by adjusting two gaps in parallel for equal spark-over, as is done in the case of super voltages, it is important to arrange the gaps symmetrically with equal length of leads; otherwise inconsistent results will be obtained. With steep waves and unsymmetrical leads it is possible to short-circuit one gap and still obtain sparks on the other.

The over-voltages that cause insulation failures in practise may be divided into three classes:

1. Gradual increase of voltage on the line due to static or low frequency surges.

2. Very high frequency oscillations of voltages generally too low for any gap arrester to discharge, but which may cause very high internal voltages in apparatus.

3. The form of voltage with which we are principally concerned—lightning voltages of very steep wave fronts where the voltage across the apparatus increases from normal to a very high value in perhaps a millionth of a second.

Condition. (1) is readily taken care of by any gap and need not be further discussed; (2) is of some interest but is a condition generally not taken care of by a gap arrester—some results of tests will be given however; (3) is the steep wave front condition that represents lightning proper and with which we are mostly concerned.

Relative Protective Value of the Horn, Sphere-horn, Selective Sphere Gap and Covered Gap.

Impulse Voltages of Steep Wave Front. The spark-over voltages of various types of gaps are plotted with equal wet 60-cycle settings in Fig. 14. Values are plotted for both wet and dry electrodes. The wave applied was a single half-cycle of a 2000 kilocycle wave with a 340-kv. maximum; that is, at super-voltage. The rate of application of voltage of the wave front was thus about 70×10^{11} volts per second. I believe that waves steeper than this occur on lines in practise. In fact, I first noted that there was a difference between the 60-cycle and lightning spark-over voltages of various electrodes by the existence of such waves on an operating line. The bushings on the line always protected the lightning arrester horns although the horns had a lower 60-cycle spark-over voltage. By measuring the impulse spark-over voltages of the bushing

and the arrester gap in the laboratory it was found that the bushing protected the horn for a wave front at which the impulse ratio of the horn was over (2); this corresponds to a steeper wave than the one under immediate discussion.

It will be noted that the covered gaps give by far the best protection under this condition. For example, when all the gaps are set on the line at 100 kv., lightning voltage discharges respectively at 100 kv. on the covered gap, 115 kv. on the bal-

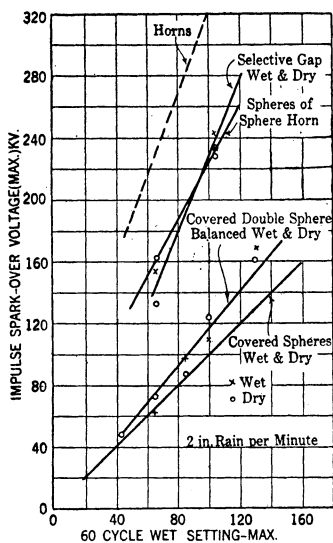


FIG. 14—RELATIVE PROTECTIVE VALUES OF HORNS, SPHERE-HORNS, SELECTIVE SPHERES. COVERED SPHERES—STEEP WAVE FRONTS

2000 kilocycles—340 kv.—impulse—data Tables IX, X and XI

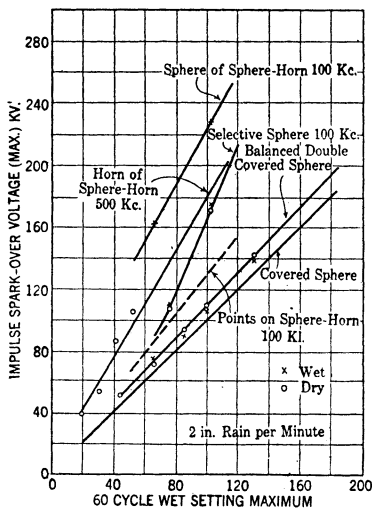


FIG. 15—RELATIVE PROTECTIVE VALUES OF SPHERE-HORN, SELECTIVE SPHERES, COVERED SPHERE—MODERATE WAVE FRONTS

Impulse—single half-cycle 100 kilocycles—non-grounded—data Tables IX, X and XI

anced covered gap, 225 kv. on the sphere of the sphere horn, 225 kv. on the selective sphere, and 320 kv. on a horn.

Moderate Wave Fronts. A similar comparison is given in Fig. 15 for moderate wave fronts. The impulses being single half cycles of 100 kilocycle waves, the average fronts ranging from 0.5 to $1. \times 10^{11}$ volts per second.

It will be noted that here, also, the covered spheres give the best protection. For example, at a 100-kv. line setting the impulse spark-over voltages are respectively 100 kv. for the covered sphere, 110 kv. for the balanced covered sphere, 170 kv. for the selective sphere, 178 kv. for a horn or the horn of

the sphere horn, 130 kv. for points of the sphere-horn, and 222 kv. for the sphere. If this data is compared with that in Fig. 14 the value of the sphere horn combination is well illustrated. For the steep wave fronts the sphere affords the better protection, while for the moderate waves the horn affords the better protection and a still greater gain is made by adding points. This comes about, of course, due to the difference between the wet and dry setting.

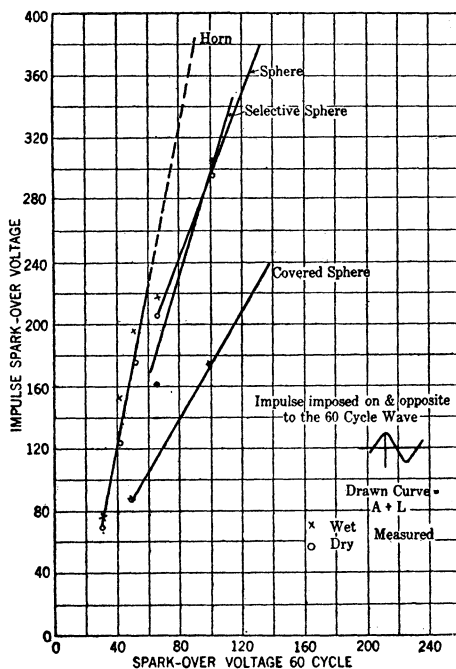


FIG. 16—RELATIVE PROTECTIVE VALUES OF VARIOUS GAPS

Impulses imposed on and opposite to the maximum of the 60-cycle wave—data Table XII

Ratio for Comparing the Relative Protective Value of Various Gaps. From the above discussion it is readily seen that in order to compare the relative protective value of various gaps two factors must be considered.

1. The increased 60-cycle setting imposed by operating conditions to prevent the gap from continuously discharging *due to rain or harmless surges*. Let the ratio of the actual operating setting to the normal setting be called α where the normal setting is the setting that just prevents the line voltage from arcing over under ideal conditions.

2. The impulse ratio (or apparent impulse ratio for the selective gap) for the wave under consideration. Let the impulse ratio be called β

The relative protective value of two gaps is then $\frac{\alpha_1 \beta_1}{\alpha_2 \beta_2}$

For example:—a gap must be set at 50 kv. (max.) to prevent the 60-cycle line voltage from causing it to spark-over under ideal conditions. The relative protective values of a horn and

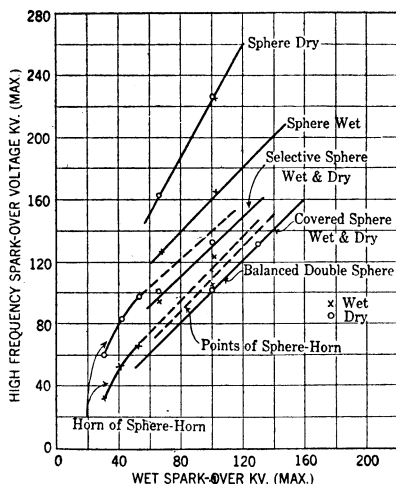


FIG. 17—RELATIVE DISCHARGE VALUES SPHERES, SELECTIVE SPHERES, COVERED SPHERES,—50,000 CYCLE SUSTAINED OSCILLATION—
Data Table XIII

a covered sphere for the 2000 kilocycle wave are obtained as follows from Figs. 3 and 5.

Horn	Covered Sphere
$\alpha_1 = 75/50 = 1.50$	$\alpha_2 = 50/50 = 1$
$\beta_1 = 133/75 = 1.77$	$\beta_2 = 50/50 = 1$
$\alpha_1 \beta_1 = 1.50 \times 1.77 = 2.65$	$\alpha_2 \beta_2 = 1$
$\alpha_1 \beta_1 / \alpha_2 \beta_2 = 2.65$	

The horn permits the lightning voltage to rise to 2.65 times the value of the voltages permitted by the covered sphere.

Combination of Lightning and 60-cycle Voltages. The lightning spark-over voltage is a minimum when it occurs at the maximum of the 60-cycle wave and in an additive direction (case B). The lightning voltage is a maximum when it occurs at the maximum of the 60-cycle wave but in the opposite direction (Case C). The relative effects are approximately the same for all of the

types of gaps discussed. If the lightning voltages for case A, Case B, Case C and the 60-cycle line voltage are called A, B, C and L respectively the lightning spark-over voltages are approximately:

Case A. A
 Case B. $A - L$
 Case C. $A + L$

Data for Case C are plotted in Fig. 16.

High Frequency Oscillations. The effect of sustained high frequency oscillations not very highly dampened is shown in Fig. 17. For connections see Fig. 13 (c). It is probably very rarely that oscillations with such a low damping factor occur on a transmission line. The arcing ground condition is more nearly approximated by a series of the impulses discussed above. Note that the horn and points give good protection for sustained oscillations.

LINE INSULATORS, BUSHINGS AND INSULATION

General. Line insulators and bushings should have a high impulse ratio or lightning arc-over voltage. The bushing mentioned above as protecting the horn had a low impulse ratio. The 60-cycle and lightning spark-over voltages were nearly equal. The horn would have given protection in this case if the impulse ratio had been higher. Bushings are now designed with a high impulse ratio.

The 60-cycle spark-over voltage of a bushing or insulator is often very appreciably lowered by rain. It is fortunate, however, that the lightning spark-over voltage is not appreciably changed by rain.

The data below were taken on different lengths of strings of Hewlett disk insulators. The impulse was a single half-cycle of a 200-kilocycle wave, or of very moderate wave front.

SPARK-OVER VOLTAGES—DISK INSULATORS
 (One side Grounded—Dry)

No. of units	60-cycle spark-over	Impulse spark-over 200 kc.	Impulse ratio	String efficiency 60-cycle	String efficiency impulse 200 kc.
1	80	85	1.06	....	....
2	142	167	1.18	0.87	0.98
3	204	262	1.28	0.85	0.99
4	261	345	1.36	0.81	1.01
5	317	410	1.30	0.79	0.97
6	368	....	....	0.77	....

Measured spark-over of string

String efficiency = $\frac{\text{Measured spark-over of string}}{\text{Number of units in string} \times \text{spark-over voltage of one unit}}$

It is interesting to note that even with this moderately steep wave front the lightning spark-over voltage is approximately the product of the spark-over voltage of a single unit and the number of units in a string. The impulse voltage increases with increasing steepness of wave front.

The wet impulse spark-over voltage is approximately the same as the dry.

Impulse ratios of three or more have been obtained on bushings. More complete data on line insulators have been published elsewhere.⁶

CONCLUSIONS

1. There is a great difference in the relative lightning spark-over voltages of different gaps as well as a great difference in the settings imposed by operating conditions. Both of these factors must be considered in comparing the relative protective values. It is shown that if the lightning spark-over factor is represented by the impulse ratio β , and the setting factor by α , the relative protective value of two gaps are

inversely as $\frac{\alpha_1 \beta_1}{\alpha_2 \beta_2}$.

2. β is due to time lag; α to the fact that the gap must be set so that the normal line voltage will not cause it to spark-over. Rain lowers the 60-cycle spark-over voltage of all gaps, and thus affects the ratio α . Rain does not lower the lightning spark-over voltage.

3. All uncovered gaps require a high setting factor, because rain lowers the spark-over value at 60 cycles. The effect is much less for points than it is for spheres.

4. The covered sphere gives better protection than any uncovered gap, because both α and β are low. The protective value is constant under all conditions.

5. The sphere-horn, having electrodes of points, horns, and spheres, gives very good protection over the whole range of frequency or wave front, due to the different values of α and β for its various electrodes. The spheres discharge the very steep waves, the horns the moderate ones, and the points continuous high frequency, waves of very slanting front and static.

6. The protective value of the selective gaps, as the name

6. "Factors Determining the Safe Spark-over voltage of Insulators and Bushings for High Voltage Transmission Lines," F. W. Peek, Jr., *General Electric Review*, June 1916.

implies, varies with the wave front. Its protective value is a minimum for very steep wave fronts, and for waves of slanting front. Over a certain range its protective value is very good.

7. The relative protective values of various gaps are shown in Figs. 14, 15 and 16.

8. The relative protective values of various gaps are approximately independent of the point on the 60-cycle wave at which the discharge occurs, as shown in Figs. 14, 15 and 16.

9. Data are given on the steepness of lightning waves actually occurring on transmission lines in practise.

10. Bushings and insulators with equal 60-cycle spark-over voltages may have entirely different lightning spark-over voltages. A bushing or insulator should be designed for a high impulse ratio or lightning spark-over voltage.

11. The lightning wet spark-over voltage of a bushing or insulator is the same as the dry spark-over voltage.

APPENDIX

TABLE II
SPHERE GAP

Wet and dry 60-cycle and impulse spark-over.
6.25-cm. spheres—One grounded 2 in. rain per minute.

Spacing		Spark-over voltage (maximum)			
		60-cycle and impulse dry	60-cycle wet	Impulse 8 $\frac{1}{2}$ kc. wet	Impulse 500 kc. wet
Inch	Cm.				
0.5	1.27			40	
1.	2.54	68	33	71	72
2.	5.08	103	51	105	106
3.	7.62	121	61	126	130
CASE B					
Impulse assisting and at maximum of 60-cycle wave.					
		Impulse dry 500 kc.			
1	2.54	52			
2	5.08	60.5			
3	7.62	86			
CASE C					
Impulse opposing and at maximum of the 60-cycle wave.					
1	2.54	108			
2	5.08	148			
3	7.62	160			

No parallel gap—one discharge in five applications 60-cycle voltage $\frac{1}{2}$ dry discharge voltage of the gap in cases B and C.

TABLE III
60-CYCLE AND IMPULSE SPARK-OVER OF TWO GAPS IN SERIES.
6.25-cm. spheres.
One sphere grounded.

Spacing gap				60 cycle spark-over				Impulse spark-over	Impulse ratio
A		B		A	B	Sum A and B	Measured A and B	500 kc.	
Inch	Cm.	Inch	Cm.						
		Gaps not balanced for simultaneous spark-over							
0.45	1.19	1.02	2.59	35	68	103	72	86	1.20
0.45	1.19	2.15	5.46	33.7	107	140	106	129	1.21
		Gaps balanced for simultaneous spark-over							
0.45	1.19	1.02	2.59	35	67	102	101	103	1.02
0.45	1.19	2.15	5.46	33.7	107	140	136	144	1.06

Impulse voltages applied and increased in values until one spark-over occurred in five applications. No. 60 cycle voltage on the gap.

TABLE IV
HORNS
Wet and dry 60-cycle and impulse spark-over
Voltage of horns (3/8 in.)
0.2 in. rain—one horn grounded.

Spacing		Spark-over voltage—maximum					
		Dry			Wet		
Inch	Cm.	60 cycle	500 kc.	2000 kc.	60 cycle	500 kc.	2000 kc.
0.25	0.63	19	....	....	9.2	....	....
0.5	1.27	35	39.7	44.5	19.7	....	....
1	2.54	50	53	63.5	31.0	....	45
2	5.08	69	88	96.5	41.5	....	99
3	7.62	74.5	105	148	52	117	148

No parallel gap.—One discharge in five applications. 2000 kc (b) wave Table XIV.

TABLE V
COVERED SPHERES
Wet and Dry—60-cycle and Impulse Spark-over Voltage
6.25-cm. spheres—One sphere grounded.

Spacing		Spark-over Voltage—Maximum					
Inches	Cm.	60 cycles dry	500 kc. dry	2000 kc. dry	60 cycles wet	500 kc. wet	2000 kc. wet
Case A—No. 60-cycle voltage on the gap.							
0.50	1.27	....	....	....	....	....	....
1.00	2.54	68	68	68	68	68	68
2.0	5.08	103	103	103	103	103	103
3.0	7.62	121	121	121	121	121	121
Case B—Impulse assisting and at maximum of the 60 cycle voltage.							
1	2.54	....	52	....	....	....	....
2	5.08	....	60.5	....	....	....	....
3	7.62	....	86	....	....	....	....
Case C—Impulse opposed to and at maximum of the 60 cycle voltage.							
1	2.54	....	108	....	....	....	....
2	5.08	....	148	....	....	....	....
3	7.62	....	160	....	....	....	....

No parallel gap—One discharge in five applications—60 cycle voltage $\frac{1}{2}$ dry discharge voltage of the gap applied in cases B and C. 2000 kc (b) wave Table XIV.

TABLE VI
Double Covered Sphere Gap—Balanced
Balanced Wet
(0.2 in. Rain—6.25-cm. spheres—One sphere grounded)

Total 60-cycle spark over max.	Gap setting Kv.max. dry		Impulse spark over total kv. max.	
	A	B	Wet	Wet
			500 kc.	2000 kc.
50	14	42	59	63
79	23.5	71	89	91
124	35	105	118	117
			Dry	Dry
48	14	42	61	51
80	23.5	71	83	71
123	35	105	132	122

Average measured voltages. 2000 kc (b) wave Table XIV.

TABLE VII
SELECTIVE SPHERE-HORN
(6.25-cm. Spheres with Auxiliary Electrode). One side grounded.

Gap setting		60-cycle spark- over kv max.	60-cycle spark- over ½ gap kv. max.	Impulse spark- over total gap	Apparent impulse ratio	Impulse ratio
In.	Cm.					
Single half cycle 83 kilocycles						
½	1.27	38	23	28	0.74	1.21
2	5.08	105	67	81	0.77	1.20
3	7.62	121	88	113	0.94	1.29
Single half cycle 500 kilocycles						
½	1.27	38	23	32	0.84	1.40
2	5.08	105	67	87	0.83	1.30
3	7.62	121	88	109	0.90	1.24
Single half cycle 2000 kilocycles (a) wave						
½	1.27	38	23	34	0.90	1.48
3	7.62	121	88	114	0.94	1.30
				Impulse spark- over total gap	Apparent impulse ratio	Wave front volts sec.
3	7.62	121	88	113	0.94	0.4 × 10 ¹¹
3	7.62	121	88	109	0.90	2.1 × 10 ¹¹
3	7.62	121	88	114	0.94	9.1 × 10 ¹¹
3	7.62	121	88	110-120*	.91-1.00	60 × 10 ¹¹
3	7.62	121	88	106-133*	0.88-1.10	110 × 10 ¹¹
3	7.62	121	88	130-132*	1.07-1.10	133 × 10 ¹¹

Above data for Case A—Impulse applied at zero of 60 cycle wave.

(*Range of equal spark-over.—Super Voltages, (b) wave Table XIV.)

TABLE VIII
SELECTIVE SPHERES
Wet and Dry 60-cycle and Impulse spark-over 6.25-cm sphere—One Grounded
0.2 in. Rain per minute

Case A							
Spacing		60-cycle spark-over Kv. max.		Impulse spark-over kv. max.			
Inches	Cm.	Dry	Wet	Dry		Wet	
				500 kc.	2000 kc.	500 kc.	2000 kc.
0.5	1.27	....	....	32	34	....	....
1	2.54	68	33	49	....	41	48.5
2	5.08	103	51	87	....	74	89
3	7.62	121	61	109	114	104	113
Case B—Impulse assisting and at the maximum of the 60-cycle wave.							
1	2.54	....	....	54	....	....	....
2	5.08	....	....	54	....	....	....
3	7.62	....	....	67	....	....	....
Case C—Impulse opposing and at max. of 60-cycle wave.							
1	2.54	....	....	97	....	....	....
2	5.08	....	....	115	....	....	....
3	7.62	....	....	147	....	....	....

Applied 60-cycle voltage $\frac{1}{2}$ dry 60-cycle voltage of the gap and impulse one discharge in five applications. (2000 kc (a) wave Table XIV.)

TABLE IX
SELECTIVE SPHERES
12.5-cm. Spheres—Non-Grounded Impulses
Case—A

Setting		60-cycles spark-over Kv. (max.)		Impulse		Spark-over	
Inches	Cm.			2000 kc. 340 kv. (max.)		100 kc. single-half cycle.	
		Dry	Wet	Dry	Wet	Dry	Wet
2.80	7.10	162	66	133	153	107	109
5.34	13.5	227	102	233	242	170	174

Super Voltage Impulses measured at equal spark-over. 2000 kc (b) wave.

TABLE X
COVERED DOUBLE SPHERE GAP—BALANCED
7.6-cm. spheres—Non-grounded

Total 60-cycle spark-over kv. (max.)		Setting—60-cycles kv. (max.)				Impulse spark-over kv. max.			
						2000 kc. 340 kv.		100 kc.	
Dry	Wet	Outside dry	Outside wet	Inside dry	Sum wet	Dry	Wet	Dry	Wet
....	130	63.0	34	101	136	160	168	142	138
....	100	51.0	25.3	75	100.2	123	109	109	105
....	85	38.3	19.8	61	80.8	85.5	96.7	93	88
....	65.5	29.6	....	49.6	....	71	62	71	73
....	44	14.1	....	31.1	....	46.5	46.5	50.5	....

Super-voltage impulses measured at equal spark-over. (2000 kc (b) wave Table XIV.)

TABLE XI
SPHERES—IMPULSES
12.5-cm. Spheres—Non-grounded

Spacing		Spark-over kv. max.		Impulse Spark-over voltage kv. max.			
Inch	Cm.	60-cycle	60-cycle	(2000 kc.) 340 kv. max.		100 kc.	
		Dry	Wet	Dry	Wet	Dry	Wet
2.80	7.10	162	66	164	....	162	....
5.34	13.5	227	102	227	227	....	....

Super-voltage impulses measured at equal spark-over.
2000 kc (b) wave Table XIV.

TABLE XII
IMPULSE SPARK-OVER VOLTAGES WHEN THE 60-CYCLE LINE VOLTAGE
IS ON THE GAP.—CASE C.

Spacing		60-cycle spark-over		Ap-plied 60-cycle	Impulse spark-over kv. max. 2000 kc.						
Inches	Cm.	Kv. max.			Kv. L.	Case A No. 60-cycle		Sum A & L.		Case C measured impulse	
		Dry	Wet			Dry	Wet	Dry	Wet	Dry	Wet
Selective spheres 12.5-cm.											
2.80	7.10	162	66	50	138	135	188	185	160	161	
5.34	13.5	227	102	76.5	227	....	303	303	296	305
Spheres 12.5 cm.											
2.80	7.10	162	66	50	....	164	214	....	204	217
5.34	13.5	227	102	76.5	227	227	303	303	305	305	
Covered Spheres 6.25-cm.											
0.70	1.8	50	50	37.5	50	50	87.5	87.5	87.5	87.5	
1.58	4.0	100	100	75	100	100	175	175	175	175	
Horns											
1	2.54	51	30.7	23	58.5	60	81.5	83	69	76	
2	5.08	40.6	67.5	30.5	105	110	135.5	140.5	124	153	
3	7.62	52	75	39	145	150	184	189	175	196	

Case C—Impulse applied opposed to the maximum of the 60-cycle wave.

Applied 60-cycle kv. 75 per cent of wet 60-cycle spark-over.

Gaps not grounded. One discharge in five impulses.

2000 kc (b) wave Table XIV.

TABLE XIII
SPARK OVER VOLTAGES OF GAPS FOR SUSTAINED HIGH FREQUENCY
OSCILLATIONS.

Gap-setting		Frequency of oscillations— Spark-over kv. max.									
Inches	Cm.	19,600		50,000		100,000		200,000		160,000 from high freq. coil	
		Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Selective Spheres 12.5-cm.											
2.80	7.10	112	105	100	95	77	90	77	92	108	125
5.34	13.5	200	143	131	123	126	127	120	122	170	186
Spheres 12.5 cm.											
2.80	7.10	162	106	162	126	163	106	162	118	163	....
5.34	13.5	227	173	227	164	12.27	173	227	169	227	....
Double gap—Balanced—Covered											
Setting Kv.-60 cycles											
	Wet										
	100	....	98	....	105	....	102	93	100	112	112
	130	....	107	....	126	....	128	132	124	147	150
Covered Spheres											
....	50	50	50	....	....	....	50	50	50	50	50
....	100	100	100	....	....	....	100	100	100	100	100
Inches Cm.		Horns									
1	2.54	....	....	58	33.5	....	....	....	....	....	....
2	5.08	....	....	82	54	....	....	....	....	....	....
3	7.62	....	....	97	67	....	....	....	....	....	....
Points											
1	2.54	....	....	28.5	28.5	....	....	....	....	....	....
2	5.08	....	....	46	46	....	....	....	....	....	....
3	7.62	....	....	64	64	....	....	....	....	....	....
4	10.2	....	....	74	74	....	....	....	....	....	....
5	12.7	....	....	88	88	....	....	....	....	....	....

TABLE XIV
IMPULSE GENERATOR CONSTANTS

Impulse	Wave	Capacity farads	Inductance henrys	Resistance
83	Single Half Cycle—Sine	1.25×10^{-9}	3.73×10^{-3}	1000
100	Single Half Cycle—Sine	1.25×10^{-9}	3.73×10^{-3}	2000
500	Single Half Cycle—Sine	0.62×10^{-9}	0.28×10^{-3}	750
2000	Single half Sine (a)	0.625×10^{-9}	3.34×10^{-5}	450
2300	(b) wave	1.25×10^{-9}	8.7×10^{-5}	3000