T H E S I S

on

The Origin and Character of Electro-magnetic

Radiations from High-Voltage Pin Type Insulators

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Lawrence Thomas Fisher

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APPROVED:

Redacted for privacy

Research Professor of Electrical Engineering

In Charge of Major

Redacted for privacy

Director of Engineering Experiment Station

Redacted for privacy

Chairman of Committee on Graduate Study

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INTRODUCTION

The introduction of new inventions has always reacted upon the older customs in use--sometimes unfavorably for a time--and this has given rise to problems in adjusting the old and the new. The introduction of radio broadcasting in the last decade has been no exception and we are still faced with the problem of harmonizing it with the industries which existed prior to its advent. There are many examples in the past history of such adjustments and the principles to be followed are, in general, similar. The trend in such adjustments has been towards directing matters so that the public will have the maximum advantage of all types of up-to-date service with the minimum disruption of existing utilities.

The public has been insistent in their demands for better entertainment, better reproduction from radio receivers, and reception free from interference. Broadcasting companies are making advances in the production of programs and their presentation from the broadcasting stations, manufacturing companies and research laboratories are constantly improving radio receivers, and electrical manufacturing companies are expending a great deal of effort in producing interference-free machines and devices. Operating companies in both the power and the communication fields are making improvements in the equipment they have in service and in the construction of new plant apparatus.

In spite of the progress that has been made there are still many problems that are unsolved. One of these with which the people of the western part of the United States are particularly interested is the radio interference from high voltage insulators, especially those of the pin and pedestal types. This type of interference is not necessarily peculiar to any geographic location, but is more troublesome in the western part of the United States for two reasons: First, the extensive hydroelectric development requires a large network of high-voltage transmission lines to transmit the power to the centers of population and second, the broadcasting stations are few in number and operate at relatively low power. The result is that the ratio of the field strength of the broadcasting station to the field strength of the interference is low compared to that of other sections of the country. This results in unsatisfactory reception.

There are two methods by which this ratio can be improved. One is to increase the number and power of the broadcasting stations, thereby increasing their field strength and the other is to reduce the field strength of the interference or to eliminate it entirely.

The Northwest Electric Light and Power Association with the assistance of the National Electric Light Association began an investigation of the nature of this interference and methods for preventing it in 1929. The Engineering Experiment Station of the Oregon State College was invited to conduct the investigation and the invitation was accepted. It was in connection with this work that the present thesis subject and material was obtained.

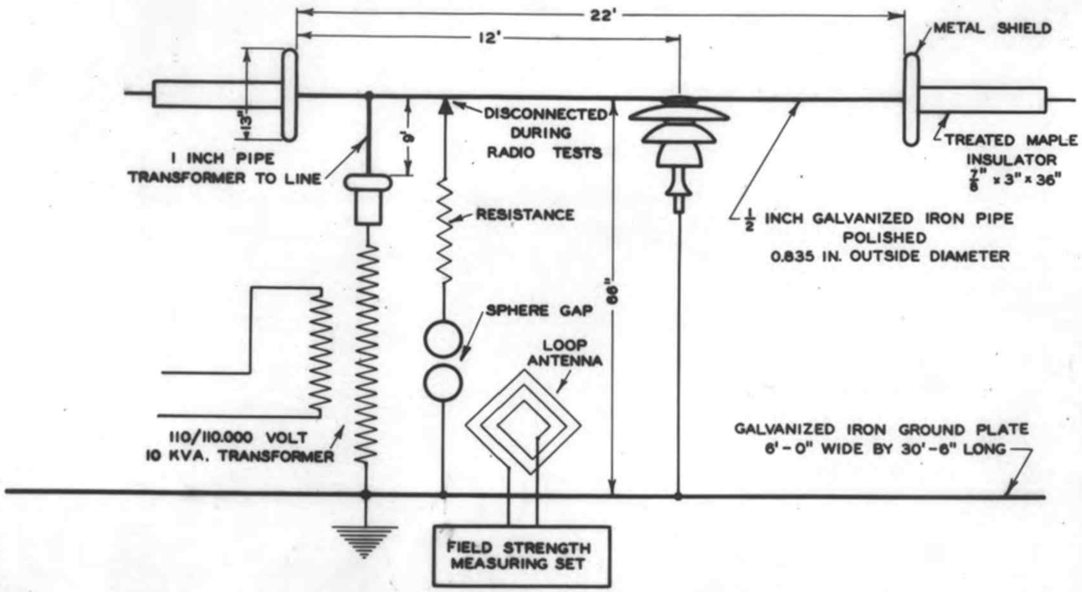


FIG. 1 - ELECTRICAL CONNECTIONS AND DIMENSIONS FOR LABORATORY INVESTIGATION OF PIN TYPE INSULATOR RADIO INTERFERENCE AND CORONA FORMATION VOLTAGES

THE CAUSE OF RADIO INTERFERENCE FROM INSULATORS

Laboratory tests show conclusively that radio interference from high voltage insulators is caused by corona discharges occuring at locations on the insulator where the air is ionized by excessive dielectric flux concentration. Large numbers of tests conducted in a darkened room show that the start of corona formation and radio interference are coincident. A diagram of the circuit used in determining this relationship is shown in Figure 1 and Figure 4 shows the arrangement of the apparatus used in the laboratory investigation. Numerous tests were made to eliminate interference from the circuit without the insulator in place over the range of voltages at which the tests were made. The conductor is a polished 1/2 inch pipe well shielded at the ends by grading rings and supported by strain insulators of treated maple wood. Tests proved this equipment to be free of corona for all voltages up to 100 kilovolts. The transformer is a standard 60-cycle General Electric 10-k.va. Testing Transformer with a voltage rating of 110/220 volts to 110,000 volts. This piece of apparatus was found free of interference at voltages up to 50 kv. The insulators tested were nominally rated at from 63 to 70 kv. These ratings are line to line values hence for these tests it is necessary to use only the voltages to neutral. Therefore, the voltages necessary to test the insulators under actual operating potentials are never more than 40.5 kv. This leaves an ample factor of safety for running these particular tests. All metal objects near the test line were bonded and either grounded or connected to the high voltage circuit to prevent interference originating on such objects associated with or adjacent to the test circuit.

A small motor generator set was used for a source of potential for these tests. The voltage from the shop had some pronounced harmonics in it that caused trouble in determining the voltage ratio of the transformer and also in the balancing circuit used for measuring the changes in the charging current flowing through the insulators under test. The large motor generator set in the laboratory has a D.C. machine connected to it that gives radio interference from its commutator and could not be used. The 10 kv-a. alternator used as a source of power was driven by an induction motor and the field for the generator was obtained from the storage battery in the shop so that it was not necessary to run any D.C. machines in the laboratory while making the tests. Voltage on the generator was controlled by means of a rheostat in series with the battery so good voltage control was possible. The stator winding of the generator is an interconnected star winding so that most of the harmonic currents are eliminated in the winding itself. This source of voltage for the tests gave no radio interference that could be noticed on the receiving set used.

The voltage on the line was determined by means of a calibrated potential coil. The calibration was obtained by connecting the transformer to the shielded conductor with a test insulator in place and measuring the voltage by means of a 6.25-cm. sphere gap. The ratio of the potential coil to the high-voltage winding is approximately 1000 to 1 but more accuracy is obtained by taking a ratio curve with the sphere gap. This ratio curve is included in the appendix.

The radio set used in these tests is a field strength measuring set developed by the Bell Laboratories for measuring the field strength of broadcasting stations. The receiver circuit of this set is a standard superheterodyne circuit consisting of an oscillator, a high frequency detector, three stages of intermediate frequency amplification, a low frequency detector and one stage of audio frequency amplification. The antenna is a center grounded loop. A set of head phones is provided for listening to the output of the set. A special audio transformer was built for the output circuit of this set to complete some tests that are described later in this report.

The procedure for running the tests is to darken the room or to work at night with all light off while looking for visual corona on the surface of the insulator. Voltage is applied to the line while an observer, standing as close to the insulator as possible with safety, which for these tests is approximately two or three feet, watches for the first appearance of corona on a particular part of the insulator. This may be the head of the insulator, the pin, or between the shells. There are cases where it is impossible to see the first appearance of corona as it may occur under the tie wire or, in the case of pin holes without thimbles or conducting coatings, it may appear between the pin and the solid dielectric of the insulator in such a position that it cannot be seen from the outside. Insulators so designed and treated that there was no corona formed under the tie wires or in the pin hole were used for this part of the tests so that there could be no doubt about the first appearance of corona and radio interference being coincident. When the voltage at which visible corona first appears has been definitely determined and read on the voltmeter in the potential coil of the transformer the radio set is connected so that the loop is well coupled with the line or with the ground circuit of the insulator and the voltage at which the first evidence of radio interference is heard is read on the voltmeter. This point is checked several times for accuracy.

Tests were made on several insulators of different makes and of different designs and the fact that initial radio interference is coincident with initial formation

TABLE I
PIN TYPE INSULATOR RADIO INTERFERENCE AND CORONA FORMATION VOLTAGE DATA

INSULATOR NUMBER	NOMINAL RATING KV	INITIAL RADIO INTERFERENCE DATA		INSULATOR VISIBLE CORONA DATA					REMARKS
		INSULATOR POTENTIAL KV	LOCATION ON INSULATOR	HEAD KV	PIN KV	SHELLS* 1–2 KV	SHELLS* 2–3 KV	SHELLS* 3–4 KV	<u>MEAN ATMOSPHERIC CONDITION</u> BAROMETRIC PRESSURE 757.2 MM. OF HG. TEMPERATURE 21.3 DEGREES CENTIGRADE WET BULB TEMPERATURE 55.3 DEGREES FAHRENHEIT DRY BULB TEMPERATURE 70.4 DEGREES FAHRENHEIT RELATIVE HUMIDITY 36 PER CENT
A-4	66	20.4	PIN	20.4	18.4	30.5	25.7	–	Solder coating in conductor and tie wire grooves.
B-5	66	23.0	HEAD	23.0	32.7	62.2	86.6	–	Silver and Bismuth coating on head. Zinc thimble in pin hole.
B-6	66	23.5	HEAD & PIN	23.5	23.5	67.6	75.0	–	Silver and Bismuth coating on head and in pin hole.
D-4	66	8.1	HEAD	8.5	52.0	53.6	42.9	–	Standard porcelain insulator with $\frac{3}{4}$ in. malleable thimble.
D-5	66	29.3	CAP TO PORC.	30.2	37.1	50.3	NOT TAKEN	–	Malleable cap on head $\frac{3}{4}$ in. malleable thimble, discharge cap to porcelain.
D-6	66	32.1	CAP TO PORC.	32.1	40.4	54.4	58.9	–	Malleable cap on head $\frac{3}{4}$ in. malleable thimble, discharge cap to porcelain.
D-6a	66	42.4	BETWEEN SHELLS 2&3	47.6	45.7	43.4	42.4	–	Crevices head and thimble filled with Portland Cement.
D-6b	66	17.9	HEAD	17.9	71.5	97.1+	70.7	–	Crevices head and thimble filled with Portland Cement, between shells with Pothead Compound.
D-7	66	25.2	PIN	27.0	25.2	46.5	51.9	–	Malleable cap on head $\frac{3}{4}$ in. malleable thimble, discharge cap to porcelain.
D-7a	66	60.7	HEAD	60.7	86.7	53.8	56.8	–	Crevices head and thimble filled with Pothead. Comp'd. Discharge at head.
D-7b	66	38.7	HEAD	38.7	64.1	91.6+	91.6+	–	Crevices at head, shells, and thimble filled with Pothead Compound. <u>Discharge over compound at head 45.3 KV.</u>
F-4	70	25.2	HEAD	25.5	38.3	44.7	41.1	37.4	Sanded head coated with electrolytic copper $\frac{3}{4}$ in. malleable thimble.
F-5	70	9.5	HEAD	9.5	← NOT TAKEN →				Same as F-4. Discharge in fault in metal coating.
G-1	70	12.3	HEAD	12.3	38.5	81.1+	81.1+	–	Standard Insulator. Corona on head at tie and in pin hole around metal.
G-2	70	50.3	HEAD	50.3	81.1+	81.1+	81.1+	–	"Nostatic" coating on head and in pin hole.
G-2a	70	40.3	HEAD	40.3	← NOT TAKEN →			–	After 10 A.I.E.E. Std thermal test cycles, 35 impulse flashovers at 450Kv. maximum, and five hours heavy conductor and tie wire vibration, corona first formed where impulse arcs destroyed the conducting <u>coating on the head.</u>
G-3	70	59.	HEAD	59.0	80.0+	80.0+	80.0+	–	"Nostatic" coating on head and in pin hole.

*SHELLS NUMBERED FROM HEAD TO PIN

of visual corona was definitely determined.

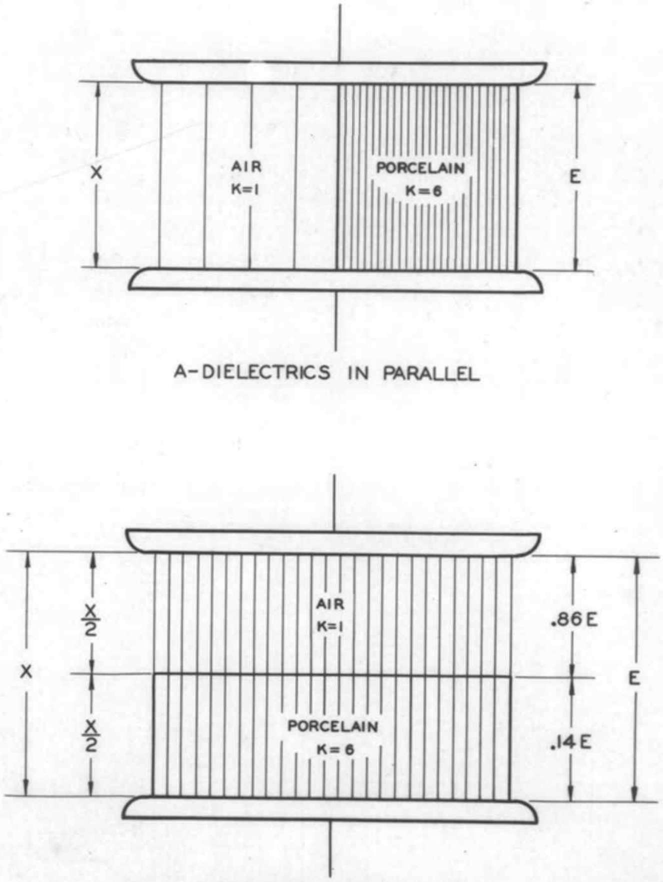
A DISCUSSION OF THE THEORY OF THE FORMATION OF CORONA

A consideration of the theory of the ionization by collision for gases and the formation of corona in air lead to the conclusion that radio interference should be associated with corona formation. The electron theory assumes that there are free ions in the atmosphere at all times due to ionizing radiations of various kinds, one of the most important of which is probably cosmic radiation. These ions or charged particles have both positive and negative polarities. Under the influence of the electric field of a charged body these particles are either attracted to the body or repelled, depending upon the relation of the charges. Under the influence of the electric field the particles are given uniform acceleration until they strike other particles or atoms in the space. During this acceleration period they acquire kinetic energy due to their mass and acceleration. Upon collision with other particles all or a part of this energy is lost in the impact to the larger particle. The Bohr atom, which probably gives the best available conception of the model of a true atom, assumes that the atom consists of a central nucleus of positive and negative charges containing an excess of positive charges. Electrons rotate around this positive nucleus in various orbits representing different energy levels. It is in reality a miniature solar system, the centrifugal force of the revolving electrons just compensating for the electrostatic attraction of the positive nucleus. An energy change in the atom causes a change in the arrangement of these electrons in their orbits. An electron may be removed from its orbit by imparting sufficient energy to the atom. If a free electron acquires enough energy under the influence of a dielectric field during its acceleration period and collides with an atom it will remove an electron from the atom. This will leave two negatively charged electrons and one atom with a positive charge in the space. This action is cumulative and the space surrounding the charged body is soon filled with charged particles. The heavy positive particles are relatively immobile while the electrons with their relatively small mass are easily accelerated and are the ones that cause most of the ionization. The fact that the positive charges are relatively immobile is important in connection with the formation of a space charge around conductors carrying high voltages and will be considered later in this report.

The particles carrying the positive and negative charges are coming together at various velocities at all times. At the higher velocities electrons are knocked out of the atoms as we have seen. Energy is given to the atom. When the charges come together at low velocities there may be a recombination and the atom be restored to its original state. When this happens energy is given up by the atom. This energy appears in the form of radiations at various frequencies.

Conductors carrying high voltages may cause ionization by collision since the dielectric fields are concentrated at their surfaces. This phenomenon depends on the size of the conductor, the crest value of the line voltage, the mean spacing between the atoms of the atmosphere which depends on the atmospheric pressure and temperature, on the spacing of the line wires and the condition of the conductor surface. The formation of corona causes a line loss since energy is lost in the form of light, heat, chemical action, and noise. There is also an increase in the conduction losses.

Energy storage is associated with the formation of corona around conductors. When the voltage builds up on the positive half of the cycle to the ionization potential of air electrons are attracted to the conductor from the space ionized. This leaves a preponderance of positive ions that have absorbed energy. Other investigations show that this extraction of electrons persists until the crest of the voltage wave is reached. As the voltage decreases to zero these positive ions are left in the space. On the negative half of the cycle there is another energy transfer. The positive space charge is partly neutralized but a certain amount is accumulated near the surface of the conductor and subtracts from the negative potential of the line and retards the formation of the negative space charge. In the process however, there is a change in the energy storage. It has been demonstrated that this storage of energy can be simulated by two condensers in series one of which is shunted by a sphere gap in series with a high resistance. By the use of this circuit characteristics very similar to actual corona are obtained. The similarity of the characteristics proves conclusively that the corona energy storage and discharge can be compared to the charging and discharging of the above circuit. This is important in this study because the change in the stored energy and the changing of the constants of the circuit cause line oscillations that are radiated by the conductors in the same manner that antennae of broadcasting stations radiate their signals. These radiations cover a wide band of frequencies from the audible to beyond 1500 kilocycles the upper limit of the broadcast band. It is the radiation in the broadcast frequency band that causes interference in radio receivers.



B-DIELECTRICS IN SERIES

FIG. 2-DIELECTRIC FLUX AND VOLTAGE DISTRIBUTION IN DIELECTRICS

THE DIELECTRIC CIRCUIT OF AN INSULATOR

A consideration of the dielectric circuits of insulators of conventional design will show that there are over stressed regions on the present types of high voltage insulators where corona appears at relatively very low voltages.

When two parallel conducting electrodes of opposite electrical polarity are separated by a non-conducting medium of dielectric, a field of dielectric flux exists between them. This field originates in one electrode and terminates in the other. The total amount of the flux ψ, in this field is directly proportional to the difference in potential between the electrodes E, the cross-sectional area A of the fields, the absolute permittivity or the ability of the material to transmit the dielectric flux k K, and inversely proportional to the distance between the electrodes X. Therefore

$$\psi = \frac{E}{X} A\,k\,K \qquad (1)$$

where k is the relative permittivity of the dielectric with respect to air and K is the absolute permittivity of the air.

$$K = \frac{10^9}{4\ V^2} \qquad (2)$$

V is the velocity of light, 3×10^{10} centimeters per second.

The flux density D is

$$D = \frac{\Psi}{A} = \frac{E}{X} k K \qquad (3)$$

Part A, Figure 2 illustrates how parallel dielectrics having different permittivities have different flux densities when the impressed voltages are the same. In a uniform field such as is being considered, the voltage gradient g, or potential per unit distance in the field is,

$$g = \frac{E}{X} \qquad (4)$$

Putting g in equation (3) and solving for g, we have,

$$g = \frac{D}{k K} \qquad (5)$$

Equation (5) shows that the voltage gradient or stress on a dielectric transmitting dielectric flux is directly proportional to the flux density and inversely proportional to the ease with which the dielectric transmits the flux. It is therefore obvious that when two dielectrics are transmitting the same dielectric flux in series, the dielectric having the lower permittivity will be subject to the higher voltage gradient per unit thickness. A very simple case of porcelain and air in series is shown in part B, Figure 2. For the condition shown, that is equal thickness of air and porcelain, the air is subject to 86 per cent of the voltage between electrodes and the porcelain to only 14 per cent. If the thickness of the porcelain is increased and that of the air decreased the unit stress or gradient in the air becomes very much worse than that shown in the illustration. These are the conditions that are present when air is used as a dielectric in series with high permittivity solid dielectrics of all kinds. The equations derived above are limited to the uniform electric field for simplicity. The principles are the same for the non-uniform field.

The insulation of high voltage lines consists of two dielectrics, air and some other solid insulating material such as porcelain or glass. In the practical application of these gaseous and solid materials, they are combined in series and parallel combinations in the dielectric circuit. The air and solid materials have widely different dielectric characteristics. High voltage insulator porcelain transmits the dielectric flux approximately six times as readily as air and has a dielectric strength several times greater. The glass used in modern high voltage glass insulators has a permittivity of approximately four and one half times that of air and like porcelain has a dielectric strength several times that of air. Because of the widely different abilities to transmit dielectric flux, it requires very careful design to use air and porcelain, or air and glass, in series combinations with high impressed voltages. Thin air gaps in series with thick sections of porcelain or glass must be avoided in regions of strong electric field to prevent failure of the air by ionization. This condition of excessive flux concentration is found in three places on many of the conventional multi-shell pin-type insulators as now designed.

a. At the point where the conductor and the tie wire are not in intimate contact with the head of the insulator.

b. At the point of imperfect contact between the pin hole and the pin or thimble.

c. Between the shells of multi-part insulators.

When insulators designed in this manner are used on high voltage lines, the air in these thin gaps fails due to ionization by collision and results in radio interference at relatively very low voltages. Tests conducted in the laboratory indicate that in the case of ordinary glass or porcelain insulators designed for an insulator operating voltage of 40 kv. cause trouble at voltages as low as 8 kv. when used without any sort of treatment for the prevention of radio interference.

INSULATOR CORONA CURRENT

An insulator in service on a transmission line forms part of the dielectric circuit between the line and ground. When used on an alternating current line a charging current will flow through the insulator to ground as current flows in any condenser in an alternating current circuit. Energy is required to establish the dielectric field on one quarter of the cycle and this energy is returned to the circuit the next quarter cycle. This constitutes the charging current that is in quadrature with the voltage. We have seen that there is a change in the energy storage of the line due to the space charge formed around the conductor when corona occurs. There is also a power component of current that is caused by the energy loss in the ionization phenomena and the conduction of the dielectric. The current that flows as a result of the corona phenomena is highly oscillatory and in general is different on the positive and negative half waves. When corona appears on insulators this current will flow through the capacitance of the insulator to ground. A study of this current was made by using a low voltage cathode ray oscillograph. The results of this study show that radio interference is associated with corona formation.

The low voltage cathode-ray oscillograph used in this investigation depends for its operation upon a jet of electrons moving at a high velocity, within a tube containing argon gas at low pressure and impinging upon a fluorescent screen. The argon gas is introduced to produce a positive space charge for focusing the cathode stream and make it possible to use low velocity electrons for producing this stream. This electron stream can be deflected from its normal course by transverse dielectric or magnetic fields, or by a combination of the two and thereby made to trace a definite figure on the fluorescent screen which becomes luminous at the point at which the electrons strike.

The figure is representative of the electric phenomena taking place within the circuit being investigated, and can be accurately interpreted when the various tube and circuit constants are known. These figures are traced irrespective of the frequency of the voltage or current producing the deflection of the beam, because this beam has practically no mass and hence, no natural period of oscillation, at least in the limits of the usual radio frequencies. However, due to the relative immobility of the positive ions which are depended upon for focusing in the low voltage oscillograph, the beam begins to lose sharpness of focus at about 1,000,000 cycles per second for the usual amplitudes.

This low voltage type of instrument is especially useful for this investigation because the low anode cathode voltage gives low electron velocities in the cathode stream and a resulting high sensitivity. High sensitivity is obtained with low electron velocity because the sensitivity is inversely proportional to the electron velocity. The magnitude of the currents and voltages studied are so small that any other type of oscillograph would upset the circuit constants to such an extent that it is doubtful if dependable results could be obtained. The deflecting forces used in this investigation were dielectric fields for both the current and time scales. To measure the corona current the voltage drop across a resistance through which the corona current was flowing was applied to the deflector plates and a trace directly proportional to the current in the resistance is the result obtained. The deflector plates of the oscillograph tube have a capacitance of approximately 10 m.m. farads which, for the connections used, did not materially alter the corona current values.

The low voltage cathode ray used in this investigation is a Western Electric Vacuum Tube No. 224-B. It is mounted in a dark box for viewing in a brightly lighted room and also arranged so that pictures can be taken. A film in a standard film holder is placed in the box and the tube moved up until the fluorescent screen is in intimate contact with the film. There is some bending of the film as the end of the tube is slightly convex. Imperfect contact prevents good definition on a part of the film but the results are quite good as can be seen by referring to Figures 5, 6, and 7. The best definition is obtained by exposures of from one quarter to one half second when using super-speed portrait film. Panchromatic portrait films were also tried but very little difference was found in the negatives obtained, probably because the radiation from the fluorescent material covered only a small part of the spectrum.

For these investigations it was necessary to place the oscillograph quite close to the line carrying the

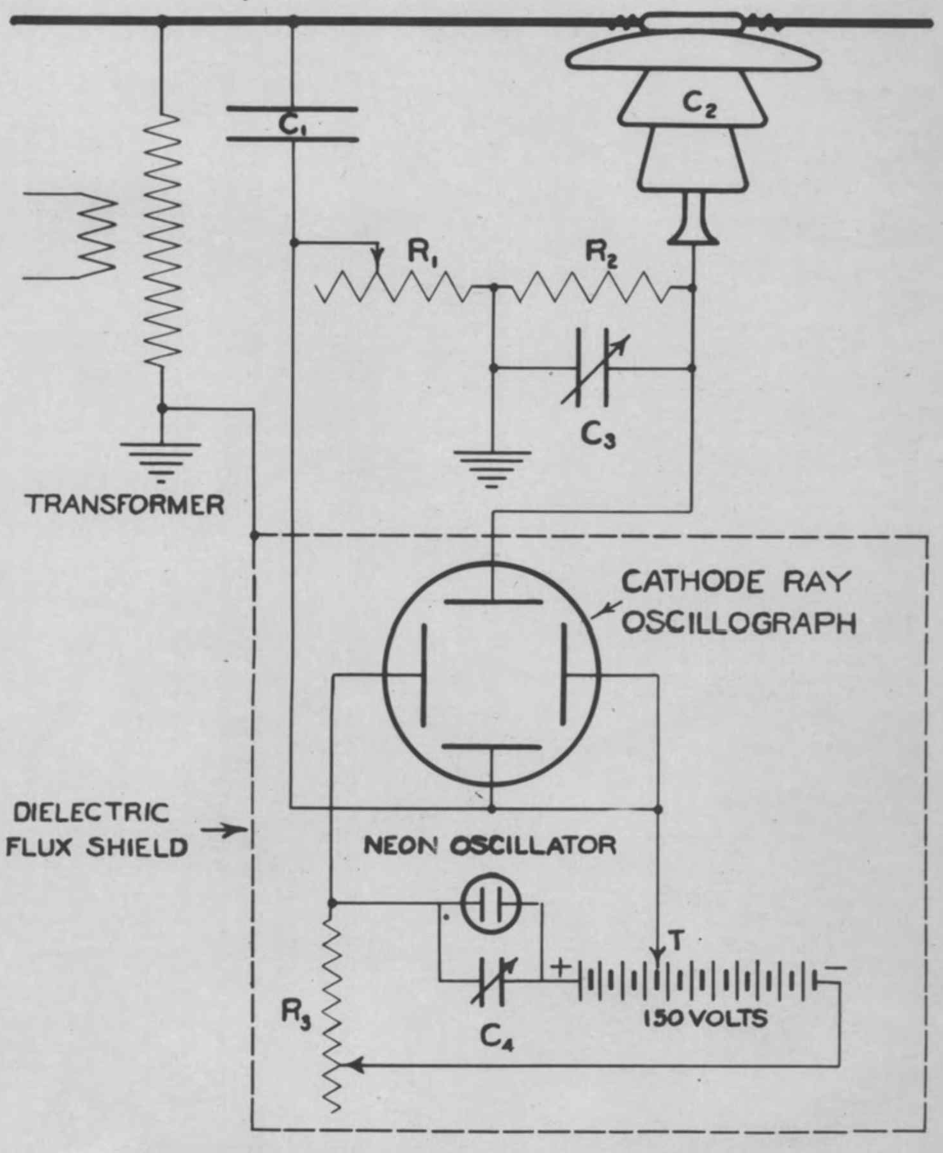


FIG. 3. - CIRCUIT FOR OBSERVING AND TAKING CATHODE RAY OSCILLOGRAMS OF THE CORONA CURRENT ON INSULATORS BY BALANCING OUT THE CHARGING CURRENT.

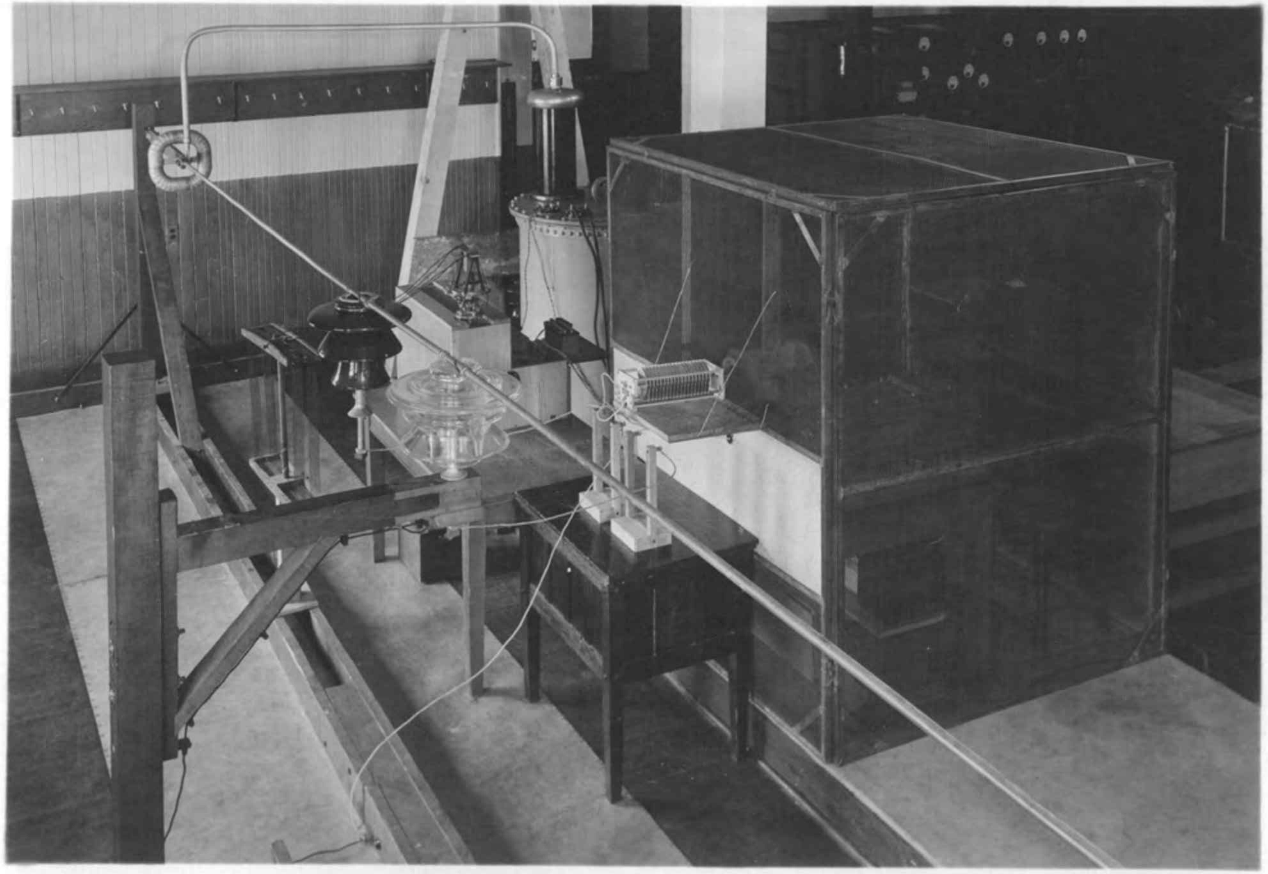


FIG. 4. ARRANGEMENT OF APPARATUS FOR MEASURING INSULATOR CORONA CURRENT.

voltage for testing the insulators. Because of the sensitivity of the oscillograph it was necessary to construct a shielding cage so that no stray dielectric fields could affect the beam. The very great sensitivity of the oscillograph is shown by the fact that an open wire lighting circuit in the ceiling affected the beam before the shielding cage was installed.

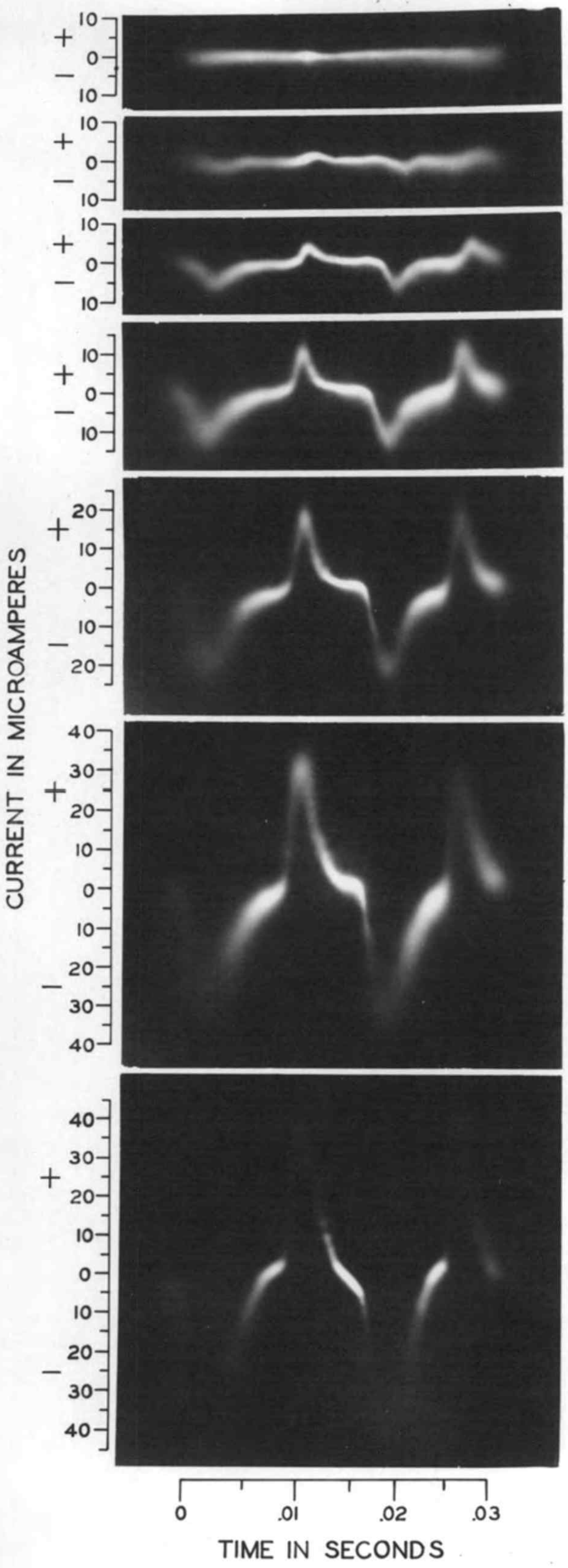
The circuit for studying the corona current flowing through an insulator is shown in Figure 3. The arrangement of the apparatus as it was set up in the laboratory is shown in Figure 4. The insulator to be studied is placed on the line with a tie wire the same as it would be in actual service in the field. A balancing condenser, C_1, is placed on the line as shown in Figure 3. In these tests a treated glass insulator that was free of corona up to 50 kv. was used for this balancing condenser. Two resistances R_1 and R_2 were connected in series with the insulator under test and the insulator used for a balancing condenser to ground. The resistance R_1 in series with the balancing condenser was variable to make the voltage drop across R_1 and R_2 exactly the same when the insulator is free of corona. One pair of deflector plates of the oscillograph were connected across the circuit on the insulator side and the balancing condenser side of the resistances. These resistances, R_1 and R_2, were of the order of one megohm. A variable air condenser, C_3, was connected across the resistance in series with the insulator under test in order to balance the capacitance to ground of the anode cathode batteries and other apparatus connected to the opposite deflector plate of the oscillograph.

Voltage is impressed on the line and a charging current flows through the insulator and the balancing condenser to ground. This current flowing through the resistance R_1 and R_2 causes a resistance voltage drop. If the insulator capacitance C_2 equals the capacitance of the balancing condenser C_1 and the resistances R_2 and R_1 are equal the voltage across the deflector plates of the oscillograph will be zero. If there is a difference in the capacitance of the insulator C_2 and the balancing condenser C_1 this voltage can still be made to equal zero by adjusting the variable resistance R_1 in series with the balancing condenser C_1. However it will be impossible to balance these voltages and obtain zero voltage on the oscillograph unless the phase relations of the two voltages are the same. Without the use of the variable air condenser C_3 across the resistance R_2 in series with the insulator this balance can not be obtained because the capacitance of the circuit to ground on the other deflector plate changes the phase relation of the voltage across R_1. By connecting the variable condenser C_3 across R_2 and adjusting it to the proper value the phase relation of the voltages across R_1 and R_2 can be made the same. The resistance R_1 and condenser C_3 are adjusted until the voltage across the deflector plates is equal to zero at a voltage below the corona formation voltage on the insulator under test. With this adjustment any change in the current of the insulator C_2 due to the formation of corona will then cause a current to flow in R_2 that does not flow in R_1 and the voltage across the oscillograph plates will no longer be zero but equal to the voltage drop caused by the corona current flowing in R_2. The cathode beam will then be deflected by an amount proportional to the corona current flowing.

The horizontal deflector plates of the oscillograph are placed across the output of a neon tube oscillator as shown in Figure 3. This neon oscillator impresses a sweeping voltage on the deflector plates of the oscillograph that increases exponentially as the condenser C_4 and the plates of the neon tube are charged by the 150 volt oscillator battery through the high resistance R_3. This sweeping voltage is quickly reduced to the starting value when the condenser C_4 is charged to the ionization potential of the neon tube. At this point the tube suddenly becomes conducting and discharges C_4 down to the extinction voltage. This operation is repeated by the oscillator at a frequency that can be accurately synchronized with the phenomena being observed or photographed by the adjustment of either R_3 or C_4. This oscillator voltage sweeps the cathode beam across the tube from right to left rather slowly as the voltage builds up on the neon tube and condenser and then as the neon tube discharges the beam is quickly returned to the starting point and the cycle is repeated.

The ordinary cyclograms obtained with the cathode ray oscillograph are difficult to visualize without replotting to rectangular coordinates. By using this sweeping device it is possible to obtain oscillograms in the ordinary rectangular coordinates directly.

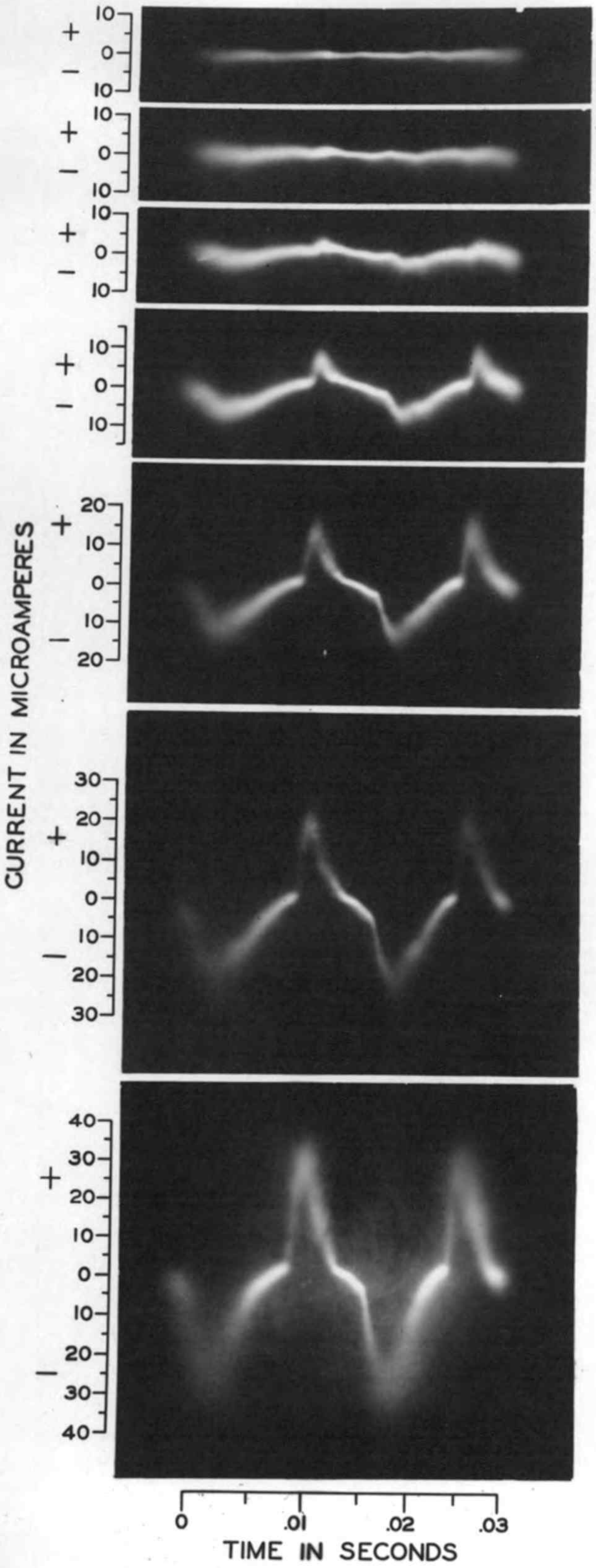
The method of procedure to determine the corona current of an insulator at various voltages is to connect the apparatus and the insulator to be tested as shown in Figure 3. Voltage is applied to the line through the transformer and regulated by changing the series resistance in the field circuit. This voltage is first brought up to a value just below the voltage at which the insulator will give radio interference. At this voltage the resistance R_1 and the condenser C_3 are adjusted to make the voltage applied to the vertical deflector plates of the oscillograph zero. These adjustments are made while looking at the oscillograph with the neon oscillator sweeping the beam across the screen on what corresponds to the X axis in rectangular coordinates. The resistance and capacitance are adjusted so that the result on the viewing screen of



OSCILLOGRAM	KILOVOLTS CONDUCTOR TO PIN R.M.S.	KILOVOLTS CONDUCTOR TO PIN MAXIMUM
A	10	14.1
B	15	21.2
C	20	28.3
D	25	35.4
E	30	42.5
F	35	49.5
G	40	56.6

BAROMETRIC PRESSURE ....763.4 MM.
TEMPERATURE, DEG. CENT., DRY BULB 21.5
WET BULB 16.0
RELATIVE HUMIDITY..........56 PER CENT
ABSOLUTE HUMIDITY......10.6 GRAMS PER CUBIC METER

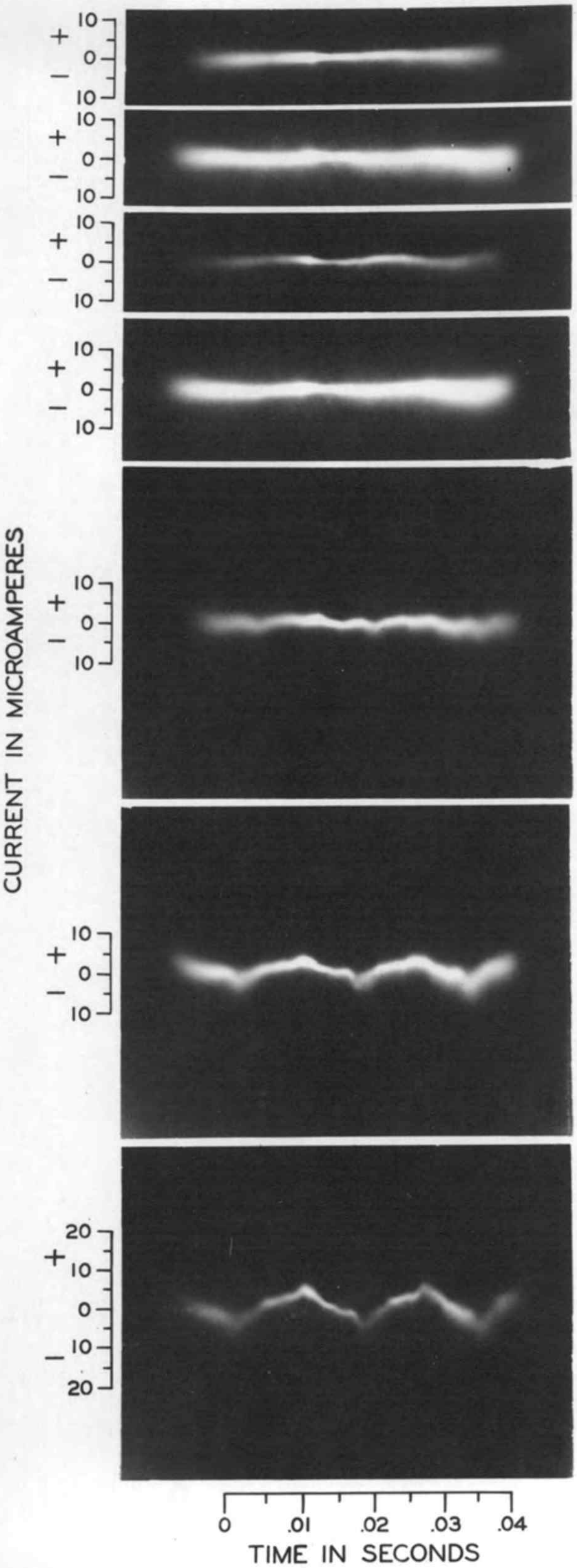
FIG. 5 CATHODE RAY OSCILLOGRAMS OF THE CORONA CURRENT FOR STANDARD 70 KV. GLASS INSULATOR NUMBER G-1



OSCILLOGRAM	KILOVOLTS CONDUCTOR TO PIN R.M.S.	MAXIMUM
A	10	14.1
B	15	21.2
C	20	28.3
D	25	35.4
E	30	42.5
F	35	49.5
G	40	56.6

BAROMETRIC PRESSURE ....756.0 MM.
TEMPERATURE DEG. CENT., DRY BULB.. 21.6
WET BULB...15.3
RELATIVE HUMIDITY...... 50 PER CENT
ABSOLUTE HUMIDITY.... 9.4 GRAMS PER CUBIC METER

FIG. 6 CATHODE-RAY OSCILLOGRAMS OF THE CORONA CURRENT FOR STANDARD 66 KV. PORCELAIN INSULATOR NUMBER B-41



OSCILLOGRAM	KILOVOLTS CONDUCTOR TO PIN R. M. S.	KILOVOLTS CONDUCTOR TO PIN MAXIMUM
A	10	14.1
B	15	21.2
C	20	28.3
D	25	35.4
E	30	42.5
F	35	49.5
G	40	56.6

BAROMETRIC PRESSURE..........760.0 MM
TEMPERATURE, DEG. CENT., DRY BULB..21.5
WET BULB..16.0
RELATIVE HUMIDITY............56 PER CENT
ABSOLUTE HUMIDITY.......10.6 GRAMS PER CUBIC METER

FIG. 7 CATHODE RAY OSCILLOGRAMS OF THE CORONA CURRENT FOR SPECIAL 66 KV. PORCELAIN INSULATOR NUMBER B-6. SILVER AND BISMUTH COATING ON HEAD AND IN PIN HOLE.

the oscillograph is a straight line. As long as the capacitance of the insulator and the balancing condenser used on the line remain the same as when this adjustment is made the voltage can be varied and the line on this viewing screen will remain straight because the charging current through the insulator and the balancing condenser are proportional to the applied voltage and the voltage drop across the series resistances R_1 and R_2 will balance. However, if there is a change in instantaneous impedance of one condenser as when corona occurs on C_2 there will be a corresponding change in the current flowing through R_2 and the difference in the voltages across the series resistances will deflect the cathode beam of the oscillograph. Figures 5, 6, and 7, give examples of this change in current for three types of insulators at different applied voltages. In all cases radio interference was coincident with the first appearance of corona current as seen on the screen of the oscillograph.

A study of these oscillograms of corona current bring out some interesting facts about the formation of corona on insulators. Other investigators have studied the formation of corona on conductors but as far as is known no investigations have been made on insulators. The same theory of ionization applies in both cases but the phenomena on insulators are modified because of the presence of the solid dielectric.

The formation of corona is an ionization by collision phenomenon as previously explained. When the voltage is increased on the alternating current wave the free ions are accelerated under the influence of the dielectric field until they acquire enough kinetic energy to liberate other ions from atoms or molecules when they collide. On the positive half of the wave the electrons or negative ions are attracted to the conductor. The heavy and relatively immobile positive ions remain in the space around the conductor, a longer time, adding their positive field to the positive field of the conductor which extends the ionizing gradient to a greater distance than would obtain for the conductor field alone. In this way the formation of corona around a positive electrode is a growing process that removes electrons from a relatively large space and establishes a large positive space charge. On the surface of an insulator an action similar to that on conductors takes place. The dielectric flux near the surface of the insulator produces ionization by collision when the voltage is sufficiently high and the positive space charge is spread over the surface of the insulator adjacent to the region of ionization. The ionization phenomenon causes a current to flow. This current transfers the energy stored in the space charge and dissipated in the various forms of radiation and loss associated with ionization by collision. During the positive half of the cycle the corona current increases rather abruptly at the initial corona starting voltage and then dies away to zero at the crest of the wave. The positive space charge then falls back towards the conductor as the potential decreases producing a high voltage gradient near the conductor and the corona starts at a very low voltage on the negative half cycle. In the case of extremely high voltage gradients the corona actually starts before the voltage reverses.

On the negative half of the cycle the residual positive space charge in the air and on the surface of the insulator greatly increases the voltage gradient to the negative conductor and when the critical gradient is reached discharges occur between the negative conductor and the positive space charges. These discharges produce sudden changes in energy storage and produce high frequency oscillations on the line conductor that are radiated as radio interference. The breakdown paths thus formed also act as sharp conducting points from which corona streamers extend producing further oscillations and radio interference. These long streamers form at somewhat regular intervals along the conductor.

The oscillograms shown in Figures 5, 6, and 7 are of corona current caused by ionization on insulators. The time scale is plotted in seconds and the current flowing in the insulator as a result of the formation of corona is shown in microamperes. The current calibration was readily determined because the voltage necessary to produce a certain deflection on the tube was measured and the value of the resistance R_2 in the insulator circuit was known. From these data the current calibration for the oscillograph was calculated. The curve of the voltage calibration for the tube is given in the appendix. The series resistance R_2 was one megohm. One volt impressed on the plates of the tube gives one mm. deflection, hence the deflection of one mm. when the insulator is in the circuit is equal to one microampere flowing through the resistance R_2.

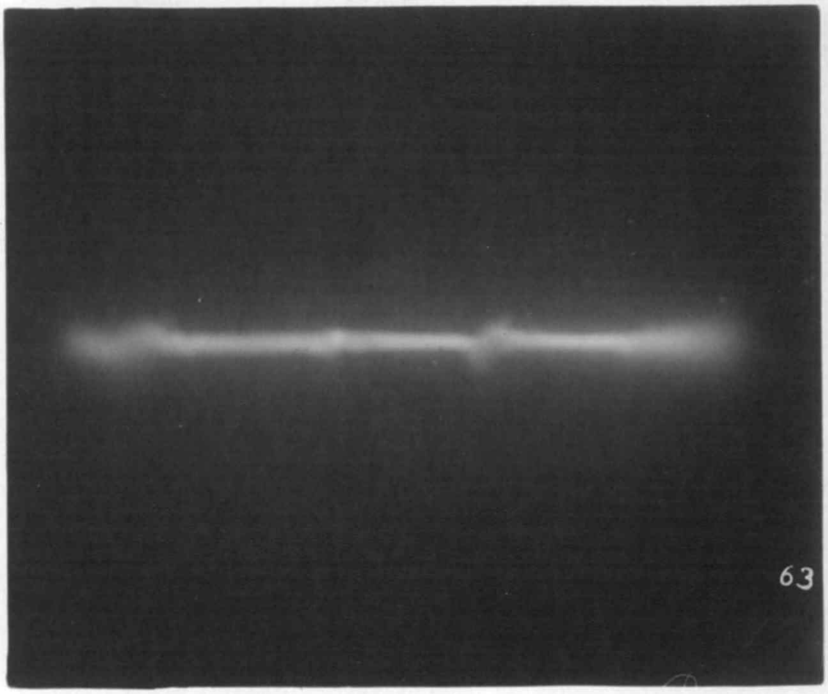
Figure 5 is a series of oscillograms of the corona current for a glass insulator at various voltages of from 10 to 40 kv., r.m.s. The circuit was balanced at 10 kv. and the beam traced a straight line as shown in Figure 5A. The effect of ionization begins to appear at 15 kv., Figure 5B. As the voltage is increased to 40 kv. a difference is noticed in the character of the positive and negative currents. The positive half of the wave is relatively distinct for all values of voltage. The negative half of the wave is blurred at the higher current values. The distinct trace of the positive half shows that the positive phenomenon repeats quite faithfully on successive cycles. The corona current rises very abruptly and gradually dies out near the crest of the voltage wave. On the negative half of the cycle the badly blurred trace shows that the current is oscillating at high frequency and is much more erratic in its formation. These oscillations are larger in amplitude and are sustained for a longer period of time on the negative than on the positive half cycle. The oscillating and erratic character of the negative half of the wave tends to make the image more blurred since each oscillogram is the result of two or more traces of the cathode beam.

Figure 6 is a series of oscillograms of the current caused by corona on a porcelain insulator under the same voltage conditions as for the glass insulator. In this set of oscillograms the same considerations hold as before. Here, however, the negative half of the wave is even more erratic and the positive half more oscillatory than in the case of the glass insulator.

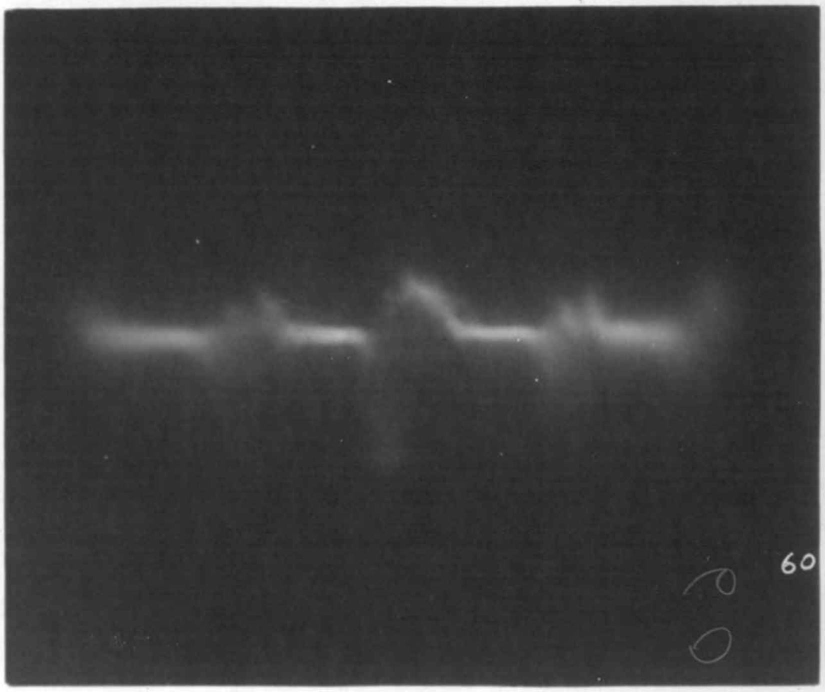
Figure 7 is a series of oscillograms made of the corona current on a porcelain insulator treated on the head and in the pin hole with a silver and bismuth alloy to give a conducting coating that will eliminate the overstressed areas around the tie wire and the conductor and in the pin hole. Corona forms on the edges of this coating at the higher voltages away from any confining spaces and since it is not confined it has more nearly the character of corona formed on smooth conductors. Corona does not occur until the voltage has been increased to 25 kv. r.m.s. As in the previous two cases the corona on the negative half of the cycle causes greater circuit disturbances than it does on the positive largely because of its more suddenly disruptive character.

In the case of the untreated insulators the first formation of corona occurs in confined spaces between the conductor and the porcelain or between the pin and the porcelain, on account of this fact the character of the disturbance on the negative and the positive halves of the wave are more nearly the same.

The use of the low voltage cathode ray oscillograph proved quite successful for studying the formation of corona on insulators and some very interesting facts were found that could not be recorded on films. By visual observations it was possible to see the oscillations quite distinctly and notice any changes that take place that cannot be recorded on a film because it is necessary to sweep the beam over the film several times to make a record. The highly oscillatory nature of the corona currents on the negative half of the cycle was particularly noticeable during visual operation. It was also discovered that in general the ionization appeared first when the conductor was positive. The difference in the applied voltage between the appearance of the ionization on the two halves of the cycle was so small that it was impossible to measure with the apparatus used in the tests. The formation of the corona on the negative half of the cycle is abrupt and almost immediately became worse than corona on the positive

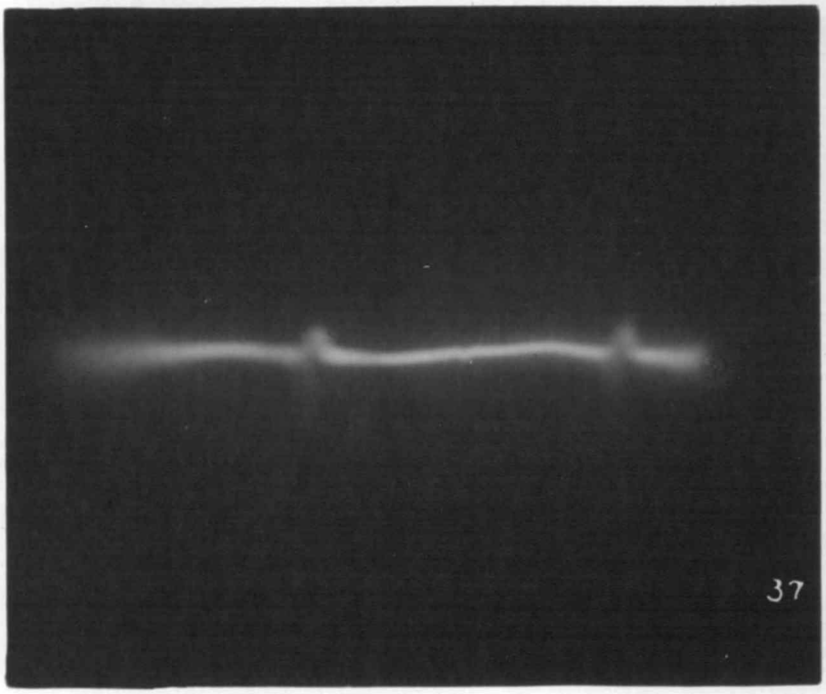


A

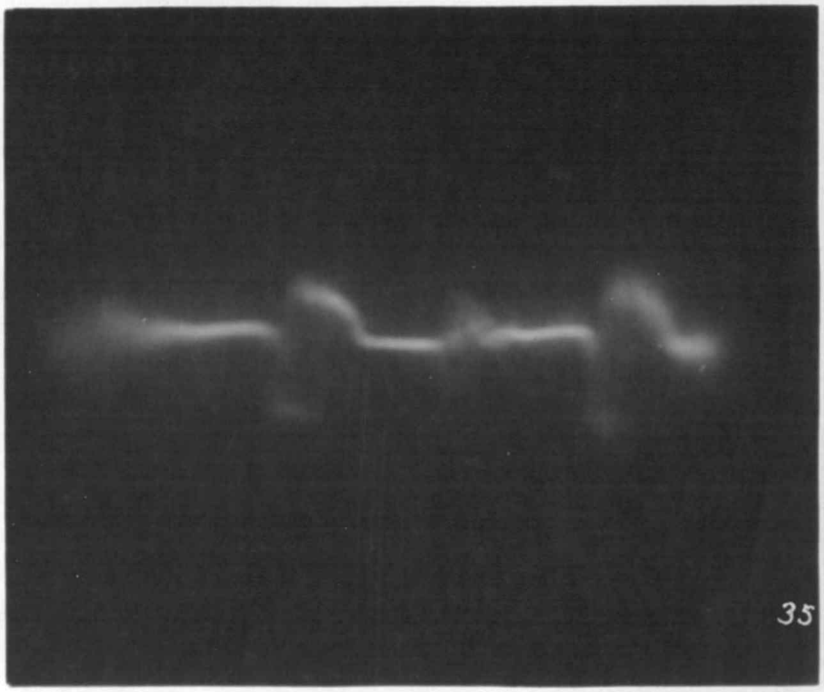


B

FIG. 18. CATHODE RAY OSCILLOGRAMS OF RADIO INTERFERENCE FROM A GLASS INSULATOR.



A



B

FIG. 9. CATHODE RAY OSCILLOGRAMS OF RADIO INTERFERENCE FROM A PORCELAIN INSULATOR.

half. Records to show these phenomena satisfactorily could not be obtained photographically with the cathode ray oscillograph although repeated attempts were made.

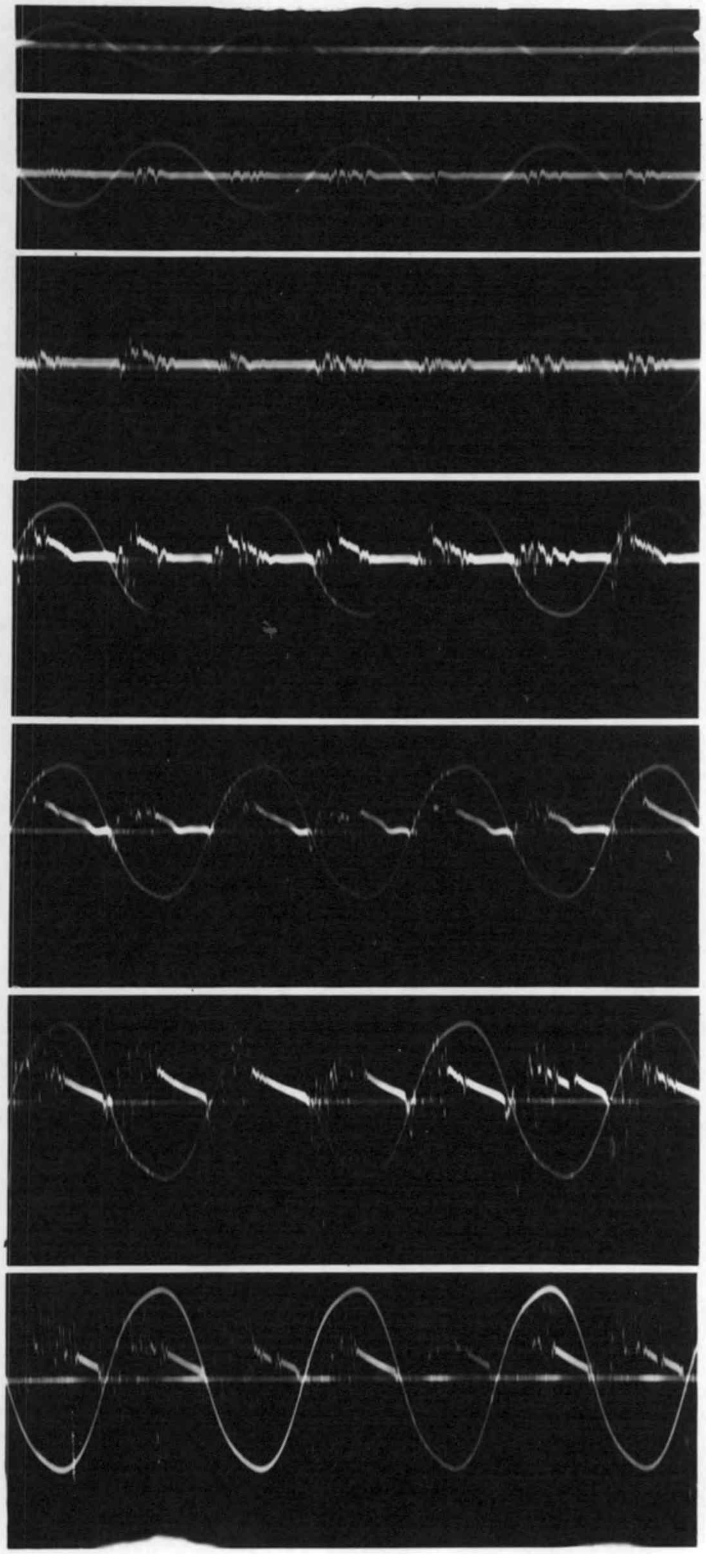
This method suggests itself for the use in ascertaining the first appearance of corona on insulators in laboratory or field tests. At the present time there is considerable lack of agreement in determining the first appearance of corona by observation in a darkened room. Different observers obtain widely different results unless the observations are very carefully made by experienced observers. This oscillographic method would eliminate the possibility of error.

A STUDY OF THE EFFECT OF CORONA INTERFERENCE ON A RADIO SET

A series of oscillograph were taken of the audio-frequency output of a super-heterodyne receiver tuned for a frequency of 1000 kilocycles and receiving only the radiations from a laboratory line equipped with one insulator. Figures 8 and 9 are the oscillograms obtained for two of the characteristic insulators tested. These oscillograms were made to observe the appearance of the oscillations on an oscillograph that has no natural period in the frequency band studied. The amplification of the set was different for Figure 8 than for Figure 9 and therefore comparisons of amplitude cannot be made. However, the difference in the character of the signal from the positive and the negative half of the line voltage wave can be easily observed. The negative half of the wave causes the largest disturbance in all cases. To be absolutely certain that this polarity was correct the voltage wave was superimposed on the audio-frequency output of the radio set and it was found that the worst disturbance occurred on the negative half of the voltage wave. The highly oscillatory character of the negative wave is particularly noticeable. In this case the disturbance appeared on the positive half of the wave first but as soon as the negative corona appears it is much worse than the positive.

The Duddell type of oscillograph was used for a more extensive study of the output of the radio receiving set. This type of oscillograph uses vibrating galvanometers suspended in a strong magnetic field. A beam of light is reflected from the galvanometer mirror on a photographic film. As the changes in the current flowing in the loop of wire causes the mirror to vibrate the film is rotated at a constant speed and a record of the current is made. This type of oscillograph has a sensitivity of approximately 0.006 amperes per mm. It was therefore necessary to construct a special audio-frequency transformer for the output of the radio receiving set to obtain satisfactory vibrator amplitude.

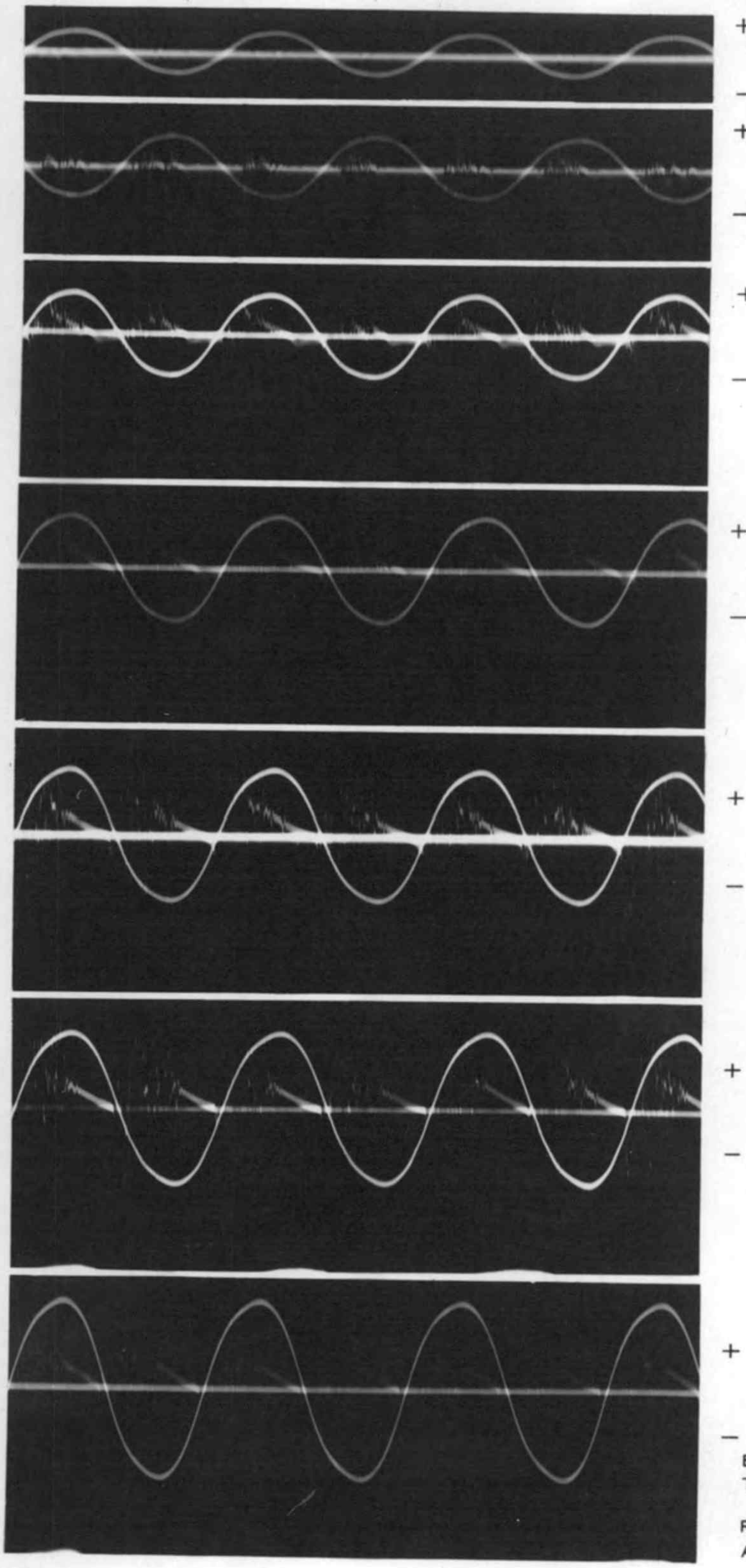
The 60-cycle voltage wave was put on the same film to



OSCILLOGRAM	KILOVOLTS CONDUCTOR TO PIN R.M.S.	KILOVOLTS CONDUCTOR TO PIN MAXIMUM
A	10	14.1
B	15	21.2
C	20	28.3
D	25	35.4
E	30	42.5
F	35	49.5
G	40	56.6

BAROMETRIC PRESSURE .... 763.4 MM.
TEMPERATURE, DEG. CENT., DRY BULB.... 21.5
WET BULB.... 16.0
RELATIVE HUMIDITY............ 56 PER CENT
ABSOLUTE HUMIDITY...... 10.6 GRAMS PER CUBIC METER

FIG. 10 60-CYCLE VOLTAGE AND INSULATOR-CORONA RADIO NOISE FOR STANDARD 70 KV. GLASS INSULATOR NUMBER G-1.

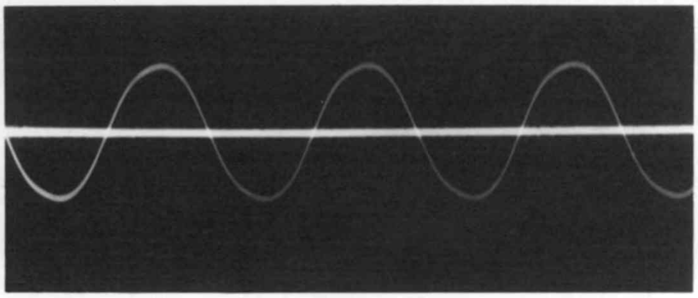


OSCILLOGRAM	KILOVOLTS CONDUCTOR TO PIN R.M.S.	MAXIMUM
A	10	14.1
B	15	21.2
C	20	28.3
D	25	35.4
E	30	42.5
F	35	49.5
G	40	56.6

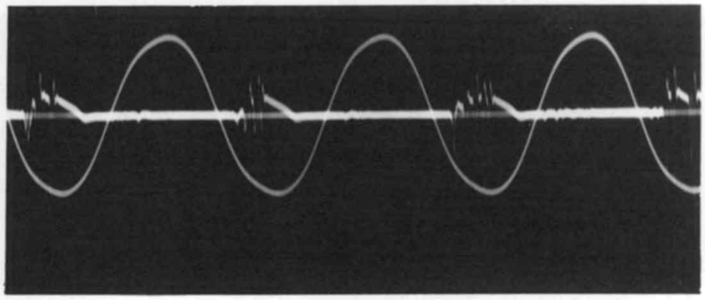
BAROMETRIC PRESSURE..........756.0 MM.
TEMPERATURE. DEG. CENT.. DRY BULB...21.6
WET BULB...15.3
RELATIVE HUMIDITY............50 PER CENT
ABSOLUTE HUMIDITY......9.4 GRAMS PER CUBIC METER

FIG. 11 60-CYCLE VOLTAGE AND INSULATOR-CORONA RADIO NOISE FOR STANDARD 66 KV PORCELAIN INSULATOR NUMBER B-41.

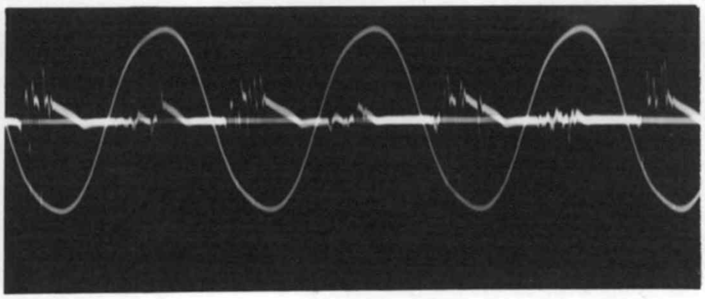
OSCILLOGRAM KILOVOLTS
CONDUCTOR TO PIN
R. M. S. MAXIMUM



\+
A 30 42.5
−



\+
B 35 49.5
−



\+
C 40 56.6
−

BAROMETRIC PRESSURE............760.0 MM.
TEMPERATURE, DEG. CENT., DRY BULB......21.5
WET BULB......16.0
RELATIVE HUMIDITY............56 PER CENT
ABSOLUTE HUMIDITY.......10.6 GRAMS PER CUBIC METER

FIG. 12 60-CYCLE VOLTAGE AND INSULATOR-CORONA RADIO NOISE FOR SPECIAL 66 KV. PORCELAIN INSULATOR NUMBER B-6 SILVER AND BISMUTH COATING ON HEAD AND IN PIN HOLE.

record the relation between the radio interference and the impressed voltage. This voltage is taken from the potential coil of the testing transformer which, due to its position with respect to the high voltage winding of the transformer, gives a true indication of the voltage impressed on the line. The polarity of this winding with respect to the high voltage winding was carefully checked and connected to the oscillograph in such a manner that a deflection above the zero axis corresponds to a positive potential on the line conductor.

Records were made on the three insulators previously tested for corona currents. The radio receiving set was tuned for a frequency of 1000 kilocycles which is at the center of the broadcast band. The amplification of the set was kept at a maximum at all times. The natural vibration period for the vibrator used in this case is approximately 5000 cycles per second. This fact is important because the audio-frequency interference noise currents from the radio set are of that order of frequency. This causes an overshooting of the galvanometer that records excessive values of output current, in spite of the fact that damping liquid is used in the vibrator cell, and this may give a wrong impression of the results. Therefore great care must be exercised if quantative measurements are attempted with this type of oscillograph.

Figure 10 is a series of Duddell oscillograms of the output of the radio set with a 70 kv. glass insulator in place on the test line. In general the radio noise on the two halves of the cycle is the same. The natural period of oscillation of the vibrator exaggerates the current amplitudes but the general character of the radio interference is shown very clearly and its relation to the line voltage is very well shown. The voltage at which corona starts is lower as the voltage is increased above the critical corona voltage due to the space charge that is formed around the surface of the insulator. At 30 kv. interference starts at zero voltage on the conductor. At 35 and 40 kv. it starts before the voltage has reached zero. A comparison between these oscillograms and those taken on the same insulator with a cathode ray oscillograph where the natural period of the instrument does not enter into the cycle will give a better idea of the actual magnitude of the disturbance.

Figure 11 is a series of oscillograms of the output of the radio receiving set with a standard 66 kv. porcelain insulator on the test line. In this case as in the case of the glass insulator the general appearance of the corona is the same on the positive and the negative half of the cycle. There is not much difference in the interference produced by the standard glass and the standard porcelain insulators.

Figure 12 is the output of the radio receiving set with a treated porcelain insulator on the test line. Corona does not start on this insulator until the voltage has been increased to 23.5 kv. In this case the difference in the character of the corona formation on the two half cycles is pronounced. The difference in the interference produced by the positive and the negative corona is very clearly shown in Figure 12B.

The confined area in which the corona forms in the case of the standard glass and the standard porcelain insulator would cause the two halves of the voltage wave to produce more nearly the same disturbance in a radio receiving set. The varying air gap between the tie wire and the insulator surface and also between the conductor and the insulator and in the pin hole cause corona discharges on both the positive and the negative half of the voltage cycle that do not have the space charge effect that corona forming on an unconfined surface would have on any radiations. The character of the disturbance obtained on the treated porcelain insulator demonstrates clearly that corona forming on an unconfined surface has the directional effect that corona forming on a smooth conductor would have.

Oscillograms were not taken of the radio set output with a treated glass insulator on the line because it was free of interference for voltages well above 40 kv. which is the normal operating voltage for 70 kv. insulators.

CONCLUSIONS

The formation of corona on the head, in the pin hole or between the shells of high voltage pin type insulators causes oscillations on transmission lines that are radiated and interfere with radio reception in the broadcast band.

The present standard insulators have regions of over-stressed air where corona forms producing radio interference at approximately 25 per cent of the normal operating voltage.

Corona free and hence interference free insulators can be made by the use of dielectric flux distributors.

The corona currents for insulators can be observed and measured by means of the low voltage cathode ray oscillograph.

The cathode ray oscillograph can be used as an indicator of the corona starting voltage by eliminating the personal element in visual observation.

In general the corona formed on the negative half of the voltage cycle is more disturbing than that formed on the positive half of the cycle.

CALIBRATION CURVE

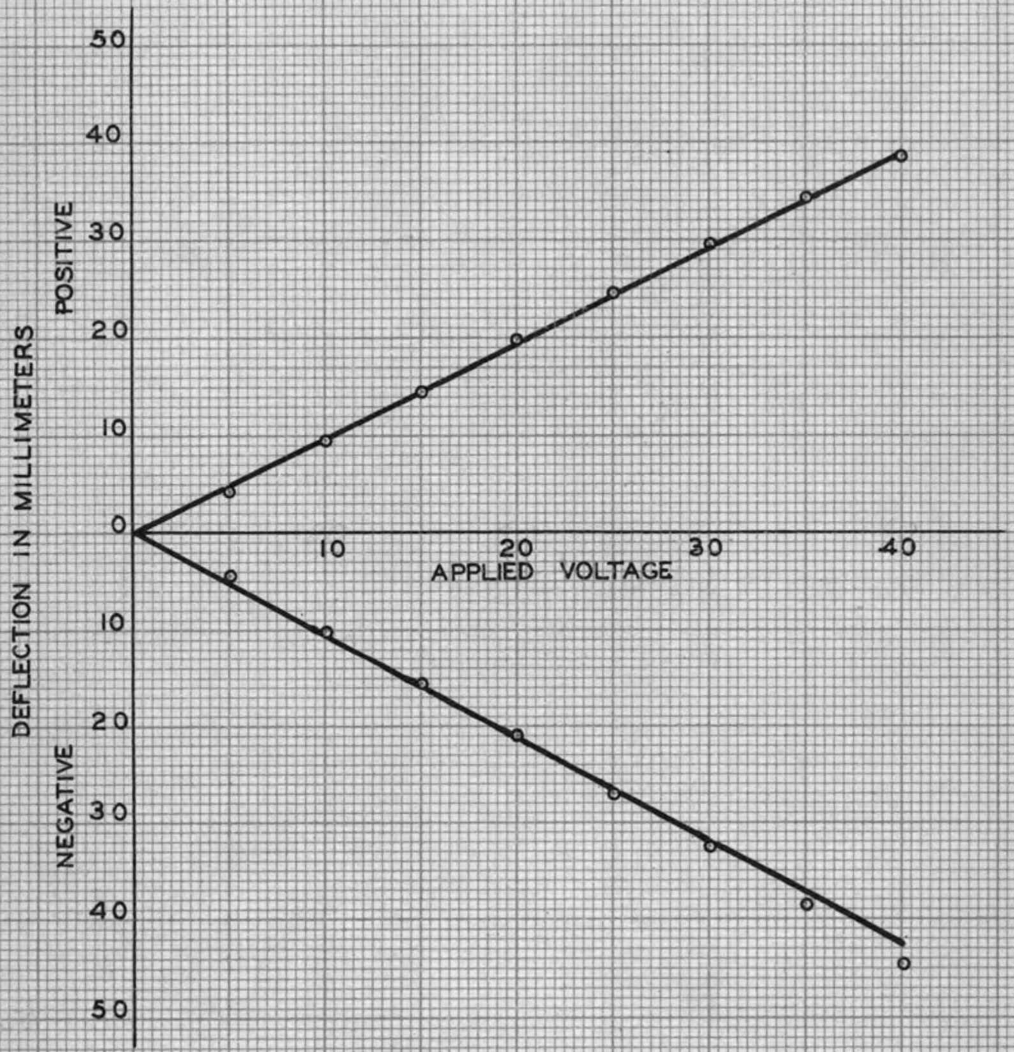
FOR

VERTICAL DEFLECTOR PLATES

LOW VOLTAGE CATHODE RAY OSCILOGRAPH

WESTERN ELECTRIC VACUUM TUBE 224-B

ANODE CATHODE VOLTAGE 313 VOLTS



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