T H E S I S

on

RADIO INTERFERENCE FROM CONDUCTOR CORONA

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INTRODUCTION

Prior to 1910 the knowledge of corona was very meager. The period following that date was marked by intense activity in the investigation of corona phenomena by the manufacturing and operating companies and in the laboratories of the various colleges and universities. This research work has resulted in the accumulation of a large amount of data and a working knowledge of the laws governing corona.

All of the phenomena that have been observed in connection with corona can be very satisfactorily explained by Townsend's theory of ionization by collision, first presented in 1900. The formation of large numbers of ions in a gas under the influence of an electric field where the gradient exceeds a certain critical value is explained by a chance free electron receiving sufficient kinetic energy through acceleration in the field to enable it to expel an outer electron from an atom or molecule when this kinetic energy is delivered to a particle by collision. The kinetic energy delivered to the particle by the collision is transformed to the potential energy of the electron and the positive ion resulting from the collision. When recombination takes place this potential energy is liberated in the form of electromagnetic radiations, some of which are in the visible spectrum. It is this radiation which gives to corona its characteristic luminous appearance.

Empirical equations have been developed from which it is possible to calculate the potential required to just initiate corona on various types of electrodes with a fair degree of accuracy. In the case of polished cylindrical and spherical electrodes it is necessary to know only the dimensions of the dielectric circuit. Thus it can be shown by mathematics that when the ratio of S/r is large the maximum gradient at the surfaces of two parallel cylindrical conductors is

$$g = \frac{E_n}{r \log_e \frac{S}{r}} \qquad (1)$$

when E_n is the voltage to neutral, r the radius of the conductors and S the spacing between them. In the case of stranded cables and weathered conductors it is necessary to use empirical factors to correct for surface irregularities.

Empirical equations have also been developed from which it is possible to calculate the power loss resulting from corona on conductors. These equations give results in good agreement with the experimental values for voltages greater than the visual critical corona values but lose their accuracy below this potential because conductor irregularities are the predominating influence in this range. Because of the excessive power loss voltages very near the visual critical potential may not be exceeded if a transmission line is to be efficient, therefore corona power loss calculations in the practical range of potentials are inaccurate.

There is, however, one phase of conductor corona phenomena that has not been investigated, namely the radio frequency electromagnetic radiations that interfere with radio reception. The need for knowledge in this field is becoming more and more urgent as radio transmission and reception continues to grow in importance.

Conductor corona discharges are inherently a source of radio interference as will be shown later in this paper. High-voltage insulators have been particular offenders in the past and much work has been done and is being done to eliminate interference from this source. Corona on conductors can, however, create interference of a much higher order of field strength due to the greater amount of energy involved and little is known of the nature of the interference from conductor corona. With an alternating line voltage it has, in fact, been a moot question whether the interference originates when the conductor is positive or negative or shows no polarity effect at all.

The public utilities are recognizing the importance of eliminating radio interference because of its undesirable effect on public relations and the reduction in revenue resulting from the reduced use of radio receiving sets under conditions of unsatisfactory reception. The Pennsylvania Railroad Company in the recent electrification of their lines installed, at greatly increased cost, hollow conductors for the express purpose of eliminating radio interference.

The National Electric Light Association and the Northwest Electric Light and Power Association are cooperating with the Oregon State College Engineering Experiment Station in the investigation of radio interference from high-voltage transmission lines, and it is through this cooperation that the work presented in this thesis was made possible.

LABORATORY EQUIPMENT

Alternating Current Generator.

The source of power for the laboratory tests was a 15 kva., 220 volt alternator driven by an induction motor operated from the laboratory power supply. The alternator was used with an interconnected star arrangement of the windings during all of the experimental work to obtain the best voltage wave form possible. Exciting current for the alternator was obtained from the laboratory storage battery supply to eliminate the necessity of operating direct current machines all of which produced undesirable interference. The alternator voltage was controlled by field rheostats. Through the use of this equipment a much better wave form and a more constant source of voltage were obtained than were available from the alternating current mains in the laboratory. The equipment also possessed the advantage that it was free from radio interference at all voltages and loads.

High-Voltage Transformer.

The high-voltage transformer was a General Electric, Type K, Form EV, 110/220-110,000 volt Testing Transformer. The transformer was equipped with a voltmeter coil having a nominal ratio of 1000 to 1 with the high voltage winding. This voltmeter coil ratio was checked with sphere gaps and for the wave forms used was found to be within the limits of accuracy required for this investigation. The voltmeter coil also provided a means of obtaining a very close approximation of the high voltage wave form by examination with a Duddell type of oscillograph.

The influence of polarity on corona and the resulting radio interference is of so much importance in this investigation from both theoretical and practical considerations that very great care was exercised in determining the polarity of both the high voltage winding and the voltmeter potential coil. The direct current method of determining polarity was applied to both of these coils and their relative polarities carefully determined. This was necessary because the voltmeter coil potential was used on the Duddell oscillograph to measure and indicate the instantaneous polarity of the test conductor voltage. These polarity determinations were not made for the transformer alone but were carried back to the photographic record on the Duddell oscillograph to eliminate any possible error in interpreting the experimental data.

Wave Form Correction.

The wave form was investigated at the beginning of the experimental work and it was found that the current drawn by the corona on the test conductor caused pronounced harmonics in the voltage wave. The rate of change of current during the first burst of corona is so very rapid that although the maximum current is only a few milliamperes the instantaneous reactance voltage drop is large enough to badly distort the voltage wave. The ideal method of correcting this difficulty would be to connect a condenser across the high voltage winding of sufficient capacitance to supply this energy consumed by the corona. This method of correction was tried by connecting a high voltage condenser of 0.004 microfarads capacitance across the high voltage winding. This gave a very good wave form at all voltages, however, corona formation at the edges of the plates caused so much radio interference that it was impossible to use it during the radio interference tests.

Another method of correction is to load the transformer so that the impedence drop in the windings due to the corona current is a small fraction of the total voltage drop. A water tube resistance consisting of thirty six feet of three-fourths inch rubber hose through which water circulated continuously was used as such a load. The resistance consisted of two eighteen foot sections of hose with the mid-point connected to the high voltage conductors and the inlet and discharge ends grounded. This arrangement provides two water tube resistances in parallel for the load. With tap water circulating through the hose the load on the transformer was about ten kilowatts at one hundred ten kilovolts or full load at the maximum potential of the transformer. This method of correction was found to give a very good wave form for voltages up to eighty kilovolts and one that could be used up to one hundred ten kilovolts. Other methods of eliminating the harmonics which were tried consisted of loading the alternator with a non-inductive resistance and with a low voltage condenser but both were found to be unsatisfactory.

The high voltage condenser could not be used during the radio interference tests and it was desirable to have all tests performed under similar conditions, therefore, it was decided to use the water tube resistor for all of the investigations. The resulting wave form is shown by the Duddell oscillograms of the voltmeter coil voltage.

Cathode Ray Oscillograph.

The low voltage cathode ray oscillograph was used extensively in the tests. The oscillograph tube was the Western Electric Company 224 B type and is so well known that no description is required. The particular tube used throughout the tests was calibrated in order that quantitative data might be obtained. A variable alternating potential was applied to the vertical deflector plates of the tube and the total deflection on the fluorescent screen measured. The potential was then removed and the zero location of the beam determined. From these data the deflection in both the positive and negative directions was obtained. The alternating potential was measured with voltmeters which were later compared with laboratory standard instruments. The effective values of the potentials applied to the plates were then multiplied by the crest factor of a sine wave and these values of voltage taken as the true deflecting potential. Direct current check points were taken and found to agree with the alternating voltage calibration. The anode-cathode potential of the tube was kept constant at 310 volts throughout the investigation. The tube was mounted in a light proof box with an opening in one end for visual observation of the fluorescent screen. The box was equipped with a slide for receiving a standard five by seven inch cut film holder. After the holder was inserted in the box the slide could be removed and the oscillograph tube moved forward until the fluorescent screen was in contact with the film. The film holder was especially selected for flexibility to allow some bending of the film to obtain a greater area of intimate contact between the convex screen and the film. When exposing oscillograms the filament of the oscillograph tube was left burning and the anode-cathode circuit was closed and opened by a telegraph key. Exposures of the order of one-fourth second are necessary, when using this arrangement, on Super-speed Portrait Films.

Sweeping Oscillator.

The sweeping oscillator used in conjunction with the cathode ray oscillograph tube to give the image an approximately linear axis was constructed in conjunction with this work. It consists essentially of a gas filled thermionic tube in parallel with an adjustable condenser which is charged through a variable high resistance from a battery of approximately three hundred volts. The method of operation is as follows. When the battery potential is applied to the oscillator the voltage across the condenser and tube rises exponentially with time until it reaches the ionizing potential of the tube. The tube then breaks down and immediately changes from an insulator to a conductor with a constant voltage drop of about fifteen volts. This discharges the parallel condenser, the tube deionizes and restores itself when the potential drops below the extinction value, and the cycle then repeats. The voltage drop across the series resistance is applied to the horizontal deflector plates of the oscillograph tube and sweeps the beam across the tube from left to right as the condenser charges and when the tube ionizes it returns from right to left so rapidly that the trace is invisible. Other refinements and additions were incorporated

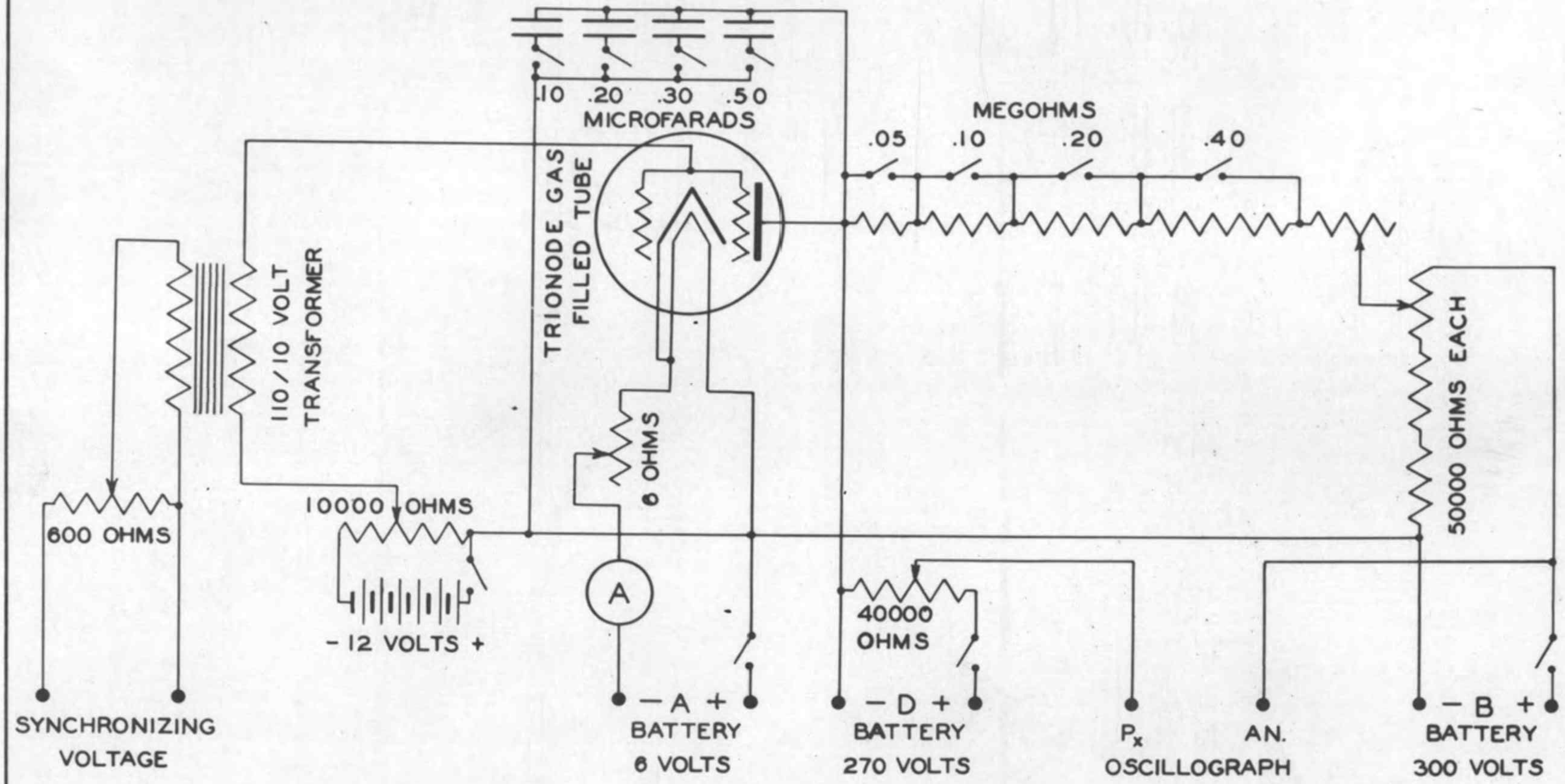


FIG. I. WIRING DIAGRAM FOR CATHODE RAY OSCILLOGRAPH SWEEPING OSCILLATOR in the oscillator which have proven to be very useful. The addition of an extra battery shown as D in Fig. 1 and controlled by a potentiometer in the output circuit was extremely useful. Their function is to place an adjustable permanent potential on the horizontal deflector plates of the oscillograph tube. By the use of this potential the portion of the exponential sweeping voltage may be selected which gives the best time axis. Another feature of the oscillator was the use of a 110 to 10 volt synchronizing transformer in the grid circuit of the gas-filled tube. The 110 volt winding of this transformer was connected through a potentiometer to the voltmeter coil of the high-voltage transformer. The secondary of the synchronizing transformer impresses a ripple on the direct current grid bias of the trionode. This alternating current grid voltage initiates the ionization and synchronizes the oscillator with the voltage under investigation which prevents the image on the fluorescent screen from shifting. The direct current negative grid bias may be changed from zero to twelve volts by a potentiometer. Through the use of this potentiometer the ionizing potential of the tube can be changed from approximately 20 to 300 volts. This enables the operator to lengthen or shorten the charging period of the condenser which changes both the frequency and the length of sweep. The tube used in the oscillator is a Western Electric 256A trionode . This is a three element gas-filled thermionic tube so designed that for any given anode-cathode potential there is a critical grid potential. If the grid is more negative than this critical value the space current through the tube is zero. If it is less negative the tube ionizes, becomes conducting and the space current depends only on the anode-cathode battery potential, the series resistance in the circuit and the constant anode-cathode drop. The grid losses all control of the discharge once it is started and it may be extinguished only by decreasing the voltage across the tube to a value less than its extinction potential.

It was found that the frequency of the completed oscillator could be controlled from two or three cycles per second to near the upper limit of the audible range. A detailed wiring diagram of the oscillator is shown in Fig. 1 and the right-hand instrument on the table in Fig. 5 is the completed device.

It was found necessary to completely shield the cathode ray oscillograph, oscillator, and all batteries connected with them to eliminate the influence of extraneous electric fields. The shielding was accomplished by housing the equipment in a cage made of one-quarter inch mesh, heavy steel wire screen.

Radio Receiving Set.

The radio receiving set used in the tests was a set constructed by the Bell Telephone Laboratories for measuring the field strength of radio broadcasting stations. It employs a standard superheterodyne circuit containing an oscillator, high frequency detector, three stages of intermediate frequency amplification, a low frequency detector and one stage of audio frequency amplification. The eight tubes used in the set are of the Western Electric 215-A type. The tuning condensers of the set were accurately calibrated and were adjusted to 1000 kilocycles, the center of the broadcast band, throughout all of the tests. The gain and filament current were also kept at the same values to make the results obtained from day to day comparable. The loop antenna for the receiving set was placed approximately fifty-five inches from the test conductor and parallel to it so that very good coupling was obtained. Visual observations in a darkened room at night showed that the initial visible corona on the test conductor and audible radio interference from the receiving set were coincident.

Duddell Oscillograph.

The Duddell type of oscillograph used was a General Electric Type EM, Form C, three element oscillograph. It is so universally understood that no description will be given of the instrument. The output of the radio set was applied to one vibrator of the instrument through a specially constructed impedence matching transformer.

Corona Current Bridge Circuit.

A circuit was devised, and the necessary equipment constructed by the use of which it was possible to detect and measure the corona current from a test conductor. Two parallel conductors 22 feet long were supported 63 inches above the floor on transformer oil treated, maple wood strain insulators thirty-six inches long. The ends of these conductors were well shielded by grading rings to prevent corona at these points. The standard, or corona free conductor, was a well polished one-half inch galvanized iron pipe having an outside diameter of 0.835 inches after polishing. The test conductor varied in size from a No. 10 A.W.G. solid copper wire to a No. 0000 aluminum cable and were all highly polished. Ten sheet metal plates with shielded edges

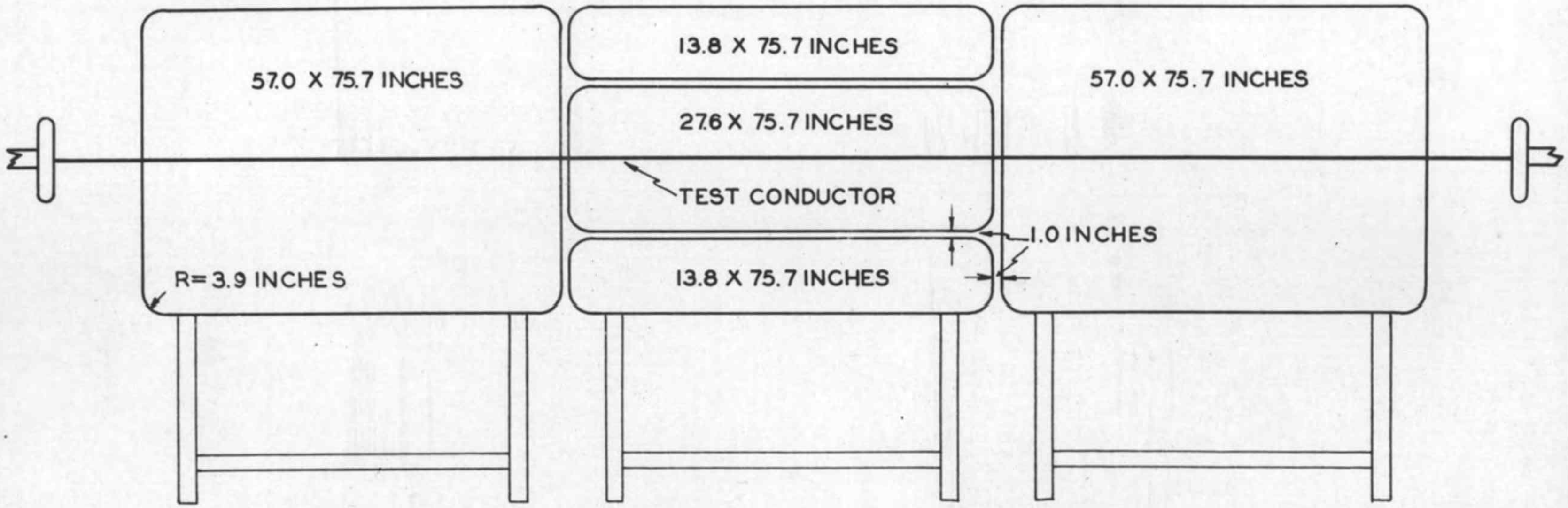


FIG. 2. DESIGN DIMENSIONS OF PLATES COMPRISING THE NEUTRAL PLANE.

were constructed for use as neutral planes. These plates are made of 24 gage galvanized iron sheets supported on three-eighths inch galvanized iron pipe frames which stiffen the plates and shield the edges. The four larger plates for the end shields also have pipe supports through their centers to further reinforce them. The sheet metal was rolled around the pipe and soldered in place, after which all excess solder and the sharp corners were filed off. These plates were screwed to treated maple strips which in turn were bolted to a lacquered Douglas fir framework. The frames were equipped with legs made of one inch ninety degree conduit elbows. A dimension drawing of the neutral plane plates for one conductor appears in Fig. 2. The complete neutral plane equipment consists of two sets of plates like those shown in Fig. 2. In the case of the frame carrying the three plates of the middle section, the center one of which must be well insulated from the other two, great care was used to obtain good creepage distances between the plates. In no case was this distance less than thirteen inches across treated maple strips three inches wide plus four inches across lacquered Douglas fir. There are a total of eight such paths in parallel between the two outside plates and the center plate.

It can be shown mathematically, from fundamental relationships, that the dielectric field between two identical conductors is undisturbed by the introduction of an infinite conducting plane half way between the two conductors if the plane potential is midway between that of the two conductors. In other words, the dielectric field between a conductor and an infinite plane S/2 centimeters from it is exactly the same as one-half the field between two conductors S centimeters apart when the voltage between these conductors is twice that between the conductor and the infinite neutral plane. With a neutral plane of practical dimensions the dielectric field is distorted because the total flux is decreased and the flux on the plane is increased in density because of the limited area. Most of the distortion is near the edges of the plates as is shown by the following data.

Neutral planes fifty-seven inches wide and 238 inches long with a central guarded section 23.8 inches wide and 78.8 inches long were used in this investigation. The arrangement of the plates constituting a plane is shown in Fig. 2. Experimental data show that for a 24 inch conductor to plane spacing the shielded plate in the plane intercepts 110 per cent of the theoretical flux for a segment of an infinite plane having the same dimensions or 36.6 per cent of the total flux per unit length of conductor to an infinite plane. At 36 inch conductor to plane spacing the flux intercepted is 111.7 per cent of the theoretical value or 23.8 per cent of the infinite plane flux. Therefore, the quantity and distribution of the flux on the shielded section of the experimental plane approximates very closely the corresponding values for the same area in a hypothetical infinite neutral plane midway between two parallel conductors. The fact that the calculated and experimental critical visual corona potentials for all conductors checked very accurately is further proof of the small reduction in total flux. Correction factors were applied to the corona current data taken from the cathode ray oscillograms and cyclograms to express them in terms of infinite plane conditions.

In the laboratory the two neutral planes were set up, back to back, between the two conductors. All of the plates except the one in the center of each group were connected together and grounded.

The charging current flowing between the conductor and its neutral plane is many times larger than the corona current near the critical corona voltage hence it is desirable to eliminate it when investigating the corona current. This was accomplished by the circuit shown in Fig. 3. The charging current from the corona free conductor to the neutral plane flows through the resistance R_1 to ground and the current from the test conductor through R_2. If these two charging currents are exactly equal and in phase, and if R_1 equals R_2 the two points A and B must be at equal potentials above ground; therefore, the potential difference between them is zero. If the two charging currents are not exactly equal but the product of one multiplied by the resistance through which it flows equals the IR product for the other there is no potential difference between A and B. It may be seen upon referring to Fig. 3 that the entire oscillator circuit and the anode circuit of the cathode ray oscillograph is at the potential I_1R_1 above ground, consequently a charging current will flow between the apparatus connected to this point and ground which will not be present in the other arm of the bridge unless the capacitance C_3 is connected in the circuit and adjusted to a value equal to that of the capacitance of the apparatus to ground.

The procedure in balancing the bridge circuit is as follows. R_2 is adjusted to some value to give a convenient scale and satisfactory sensitivity for the deflection on the cathode ray oscillograph. The

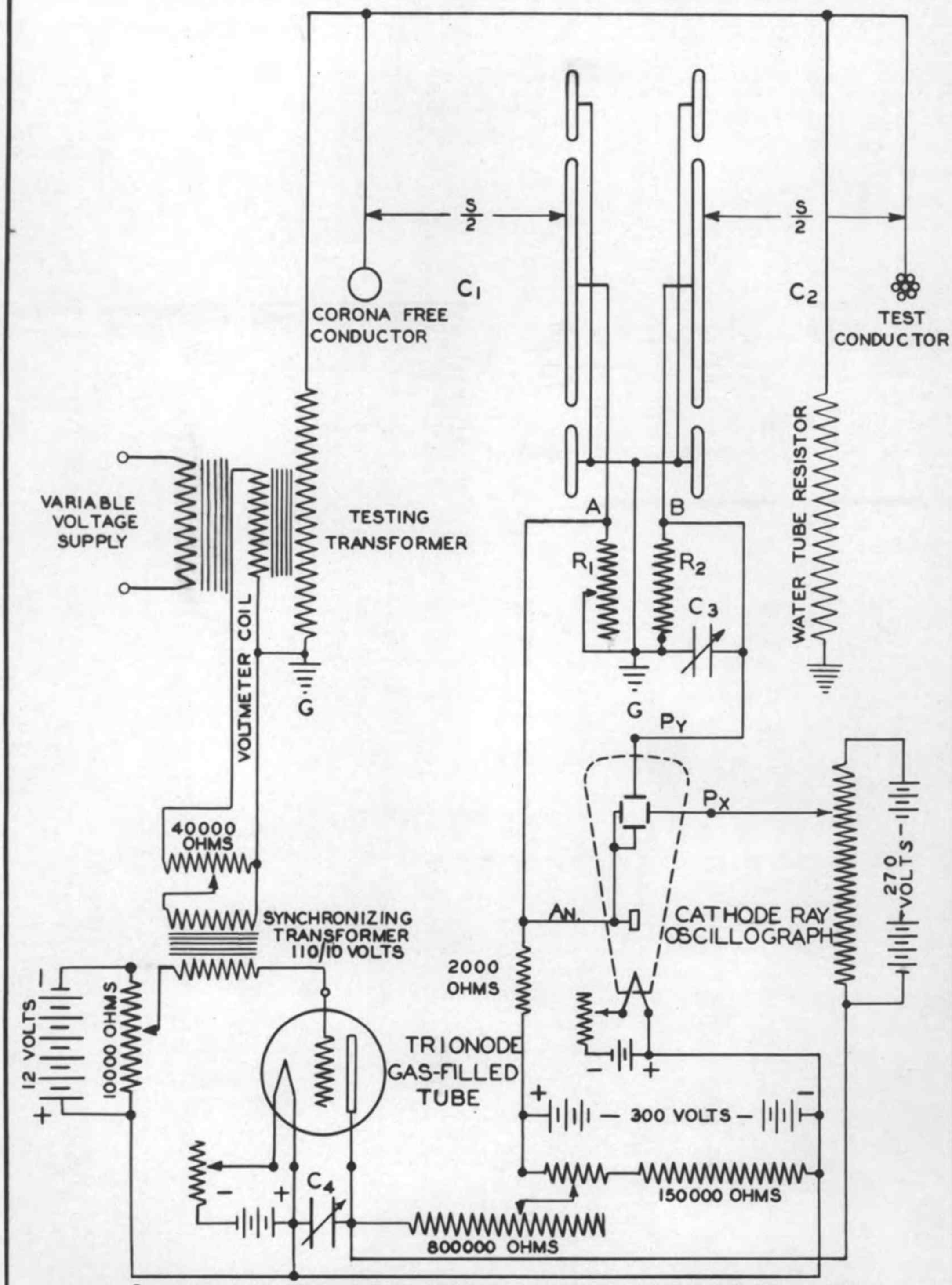


FIG. 3. CIRCUIT FOR DETECTING CORONA FORMATION AND MEASURING THE CORONA CURRENT ON A CONDUCTOR.

potential of the two conductors is then increased to some value slightly less than the critical visual voltage of the test conductor. R_1 is then adjusted until minimum deflection is obtained on the oscillograph fluorescent screen. C_3 is adjusted and R_1 readjusted until zero deflection is obtained on the oscillograph. This deflection will remain zero for all conductor voltages up to the critical corona potential, and above this value the deflection will be proportional to the corona current on the test conductor. If the voltage calibration of the cathode ray oscillograph tube and the value of the resistance R_2 are known the portion of the corona current corresponding to the flux terminating on the guarded plate can be readily calculated. This was the circuit employed in taking all cathode ray oscillograms in this paper.

In the case of the cyclograms a modification of the original circuit was used. The oscillator was disconnected from the horizontal deflector plate, and the output of a potential transformer with a ratio of five to one applied to the deflector plates. The high voltage winding of the potential transformer was connected to the voltmeter coil of the high voltage transformer. This arrangement makes the horizontal deflection proportional to the line voltage with a ratio of 5000 to 1 and the vertical deflection proportional to the conductor corona current as explained above.

The general arrangement of the equipment used in the investigation is shown in Fig. 4. The 3/4 inch hose shown at the right-hand ends of the ground planes carries the water forming the resistance load used to improve the voltage wave from the high voltage transformer. The cathode ray oscillograph, sweeping oscillator and auxiliary equipment in the

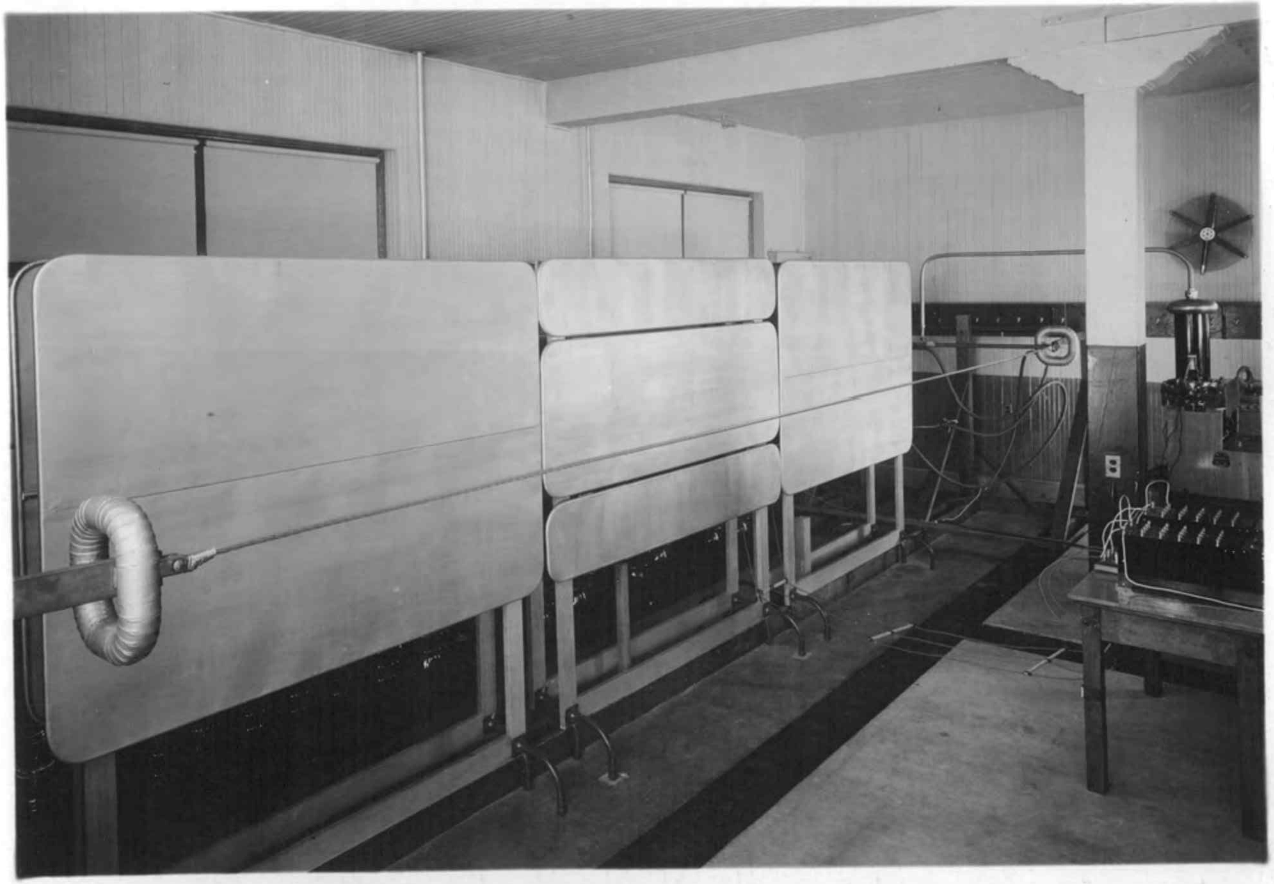


Fig. 4. General View of Laboratory Equipment

shielding cage are shown in Fig. 5.

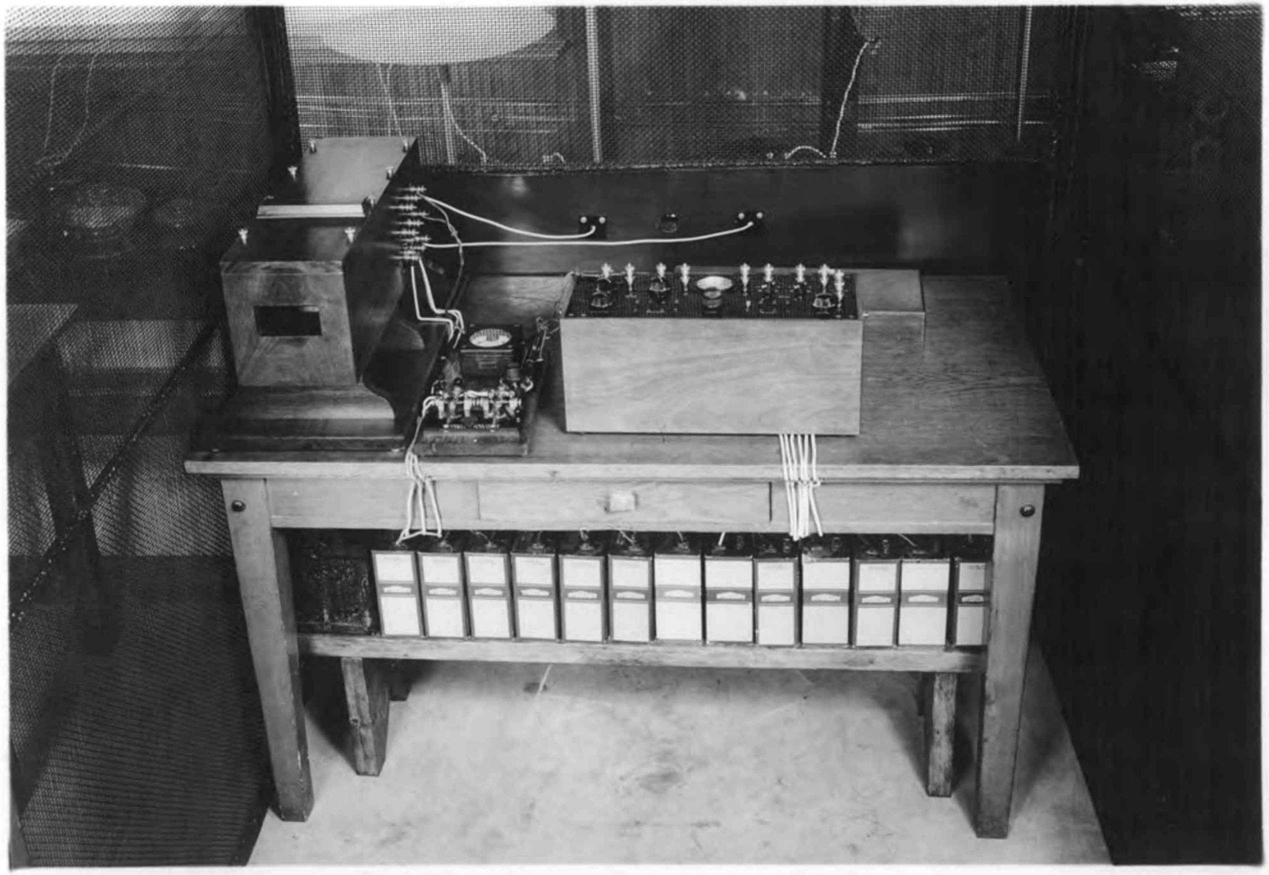


Fig. 5. Cathode Ray Oscillograph and Sweeping Oscillator

It can be easily demonstrated by experimental evidence that there are positively and negatively charged carriers of electricity or ions in the atmosphere at all times. These ions are known to be formed from atoms or molecules of gas by energy received from at least five different sources. Some of these sources are radioactivity, cosmic radiation, ultra-violet light, photoelectric effect, and Lenard effect.

The Bohr theory of atomic structure is universally accepted as the best physical conception of the atom in spite of the fact that it is not in agreement with the principles of wave mechanics. This theory assumes the atom to be made up of a central positive nucleus about which electrons are arranged in various shells and orbits. In the simplest element, hydrogen, this central nucleus is composed of a single proton and in the most complex element, uranium, it is composed of many protons and electrons with the protons exceeding the electrons by 92 which is the atomic number of the element. In neutral atoms the electrons in the outer orbits are equal in number to the excess protons in the nucleus.

The outer electrons can be removed from the atom by two methods, the absorption of radiated energy and ionization by collision phenomena described briefly in the introduction.

The phenomenon of corona formation may be explained as follows. The free electrons and negative ions in the air are accelerated by the dielectric field surrounding the conductor. When this voltage gradient reaches the critical value some of the electrons acquire enough energy while moving through their free paths to remove electrons from the atoms or molecules with which they collide, resulting in the formation of positive ions composed of the original atoms less the electrons lost by collision. These positive ions have practically all the mass of the original atoms and are, therefore, much less mobile than the electrons.

Consider now the first negative half cycle of a voltage wave with a crest value slightly in excess of that necessary to create corona. As the potential increases in the negative direction the dielectric field repels the chance negative ions in the vicinity of the conductor. As the potential approaches its maximum negative value the gradient becomes great enough to produce ionization by collision. This liberates free electrons which behave as the negative ions just described. The heavy sluggish positive ions resulting from the ionization by collision are attracted and move slowly toward the conductor. Many of these positive ions are lost by falling on the conductor and by recombination but a great number remain in the space adjacent to the conductor. Thus a positive space charge is formed about the negative conductor which is in turn surrounded by a negative space charge created by the electrons which have been repelled by the conductor field. This process continues until the potential wave reaches its maximum value. At this instant ionization ceases, because the critical ionizing gradient has been extended to its maximum distance by the flux from the conductor minus the positive space charge flux. As the potential decreases to zero no further ions are added to the negative space charge since practically all negative ions have been swept out of the ionized region; therefore, the negative space charge decreases in intensity due to recombination and diffusion of the ions.

The recombination for this condition is very rapid because a part of the remaining outer negative space charge falls into the inner positive space charge as the repelling action of the conductor field decreases. A part of the positive space charge is also lost by neutralization when the positive ions fall on the conductor under the influence of its field. Notwithstanding the large numbers of positive ions neutralized by these various means positive space charges of considerable magnitude remain around the conductor when the voltage reaches zero.

As the conductor increases in potential in a positive direction the second half cycle after corona is initiated, the phenomena are much altered. The residual positive space charge field adds to the flux of the positive conductor and the corona starts at a lower instantaneous potential than during the preceding negative half cycle. At the same instantaneous conductor potential the ionization is extended to a greater distance when the conductor is positive than when it is negative.

All of the free electrons formed by ionization are swept rapidly out of the field and fall into the conductor where they are conducted away. This leaves only a larger positive space charge surrounding the positive conductor much less of which is lost by recombination than during the previous half cycle because of the absence of free electrons. The maximum voltage gradient is produced by the sum of the fluxes from the conductor and the positive space charge; therefore, the corona will again cease at the crest of the voltage wave because the gradient at the outer boundary of ionization begins to decrease. Now as the conductor potential decreases a field is established between the persistent positive space charge and the conductor and the space charge moves in toward the conductor still further increasing the gradient. If the maximum value of conductor potential has been sufficiently great to create a space charge of high density and large size, corona may be reestablished before the potential actually reverses. With a maximum conductor potential slightly in excess of twice the value necessary to create the critical ionizing gradient the corona will start as the potential just crosses the zero axis. With very intense space charges corona may start even before the conductor potential reverses in polarity.

As the voltage increases on the second negative half cycle a high potential gradient is established between the conductor and the positive space charge that is very near the conductor. Small regions of intense ionization are formed between the negative conductor and the positive space charge which neutralize it abruptly with a sudden burst of corona current. These abrupt negative discharges cause electromagnetic radiations of radio frequency and these in turn cause audible radio interference.

The laboratory procedure followed was to put the test conductor to be studied in place and adjust it together with the corona free conductor to the desired distance from their neutral planes. The conductor was then highly polished. In the case of the solid conductors metal polish followed by clean cloths and chamois skin was found to give a good surface. The three sizes of cable used required considerably more work than solid wire. All burrs, dents, and other major imperfections were first removed with 7/0 sandpaper. The conductor was then well polished with metal polish which was allowed to dry on the conductor. The residue from the polish was then removed with a brush, followed by cloths, tissue paper and a chamois skin. After the completion of the polishing the conductor was not touched with the hands until the completion of the test, or in case it was touched it was again polished with tissue paper and the chamois. It was found necessary to use the chamois to remove the lint left by the tissue paper.

This appears to be an excessive amount of work and obviously does not represent a practical condition but it was found necessary in order to obtain consistent results. It was observed that the surface conditions of the polished conductors changed sufficiently in a few hours time under laboratory conditions to materially alter the corona characteristics and repolishing was necessary to restore the original condition.

After the polishing process was completed the critical visual corona voltage was determined. This potential was checked several times to insure its accuracy. The voltage was then decreased to slightly below the critical potential and the resistances and capacitance of the bridge circuit adjusted until the charging current was balanced out. Cathode ray oscillograms and cyclograms were then taken of the corona current through the range of voltage. The radio receiving set was then tuned to 1000 Kilocycles and the gain control and filament current adjusted to definite values so that all amplitudes obtained during different tests would be comparable. The output of the radio receiver was connected to one vibrator of the Duddell oscillograph through an impedence matching transformer. A set of Duddell oscillograms was then taken at the same voltages used for the cathode ray oscillograms and cyclograms.

The test and standard conductor spacings were then changed and a complete record taken for the new spacing. Spacings of 24 and 36 inches to the neutral plane were used with each conductor. The dimensions of the conductors used in the investigation are given in the following table:

Conductor Dimensions

Conductor Material	A.W.G. No.	Outside Diameter Inches	Number of Strands	Strand Diameter Inches
Copper	10	0.099	1	0.099
Copper	6	0.191	7	0.065
Copper	00	0.422	7	0.140
Aluminum	0000	0.569	7	0.188

Duddell oscillograms of the conductor to plane voltage and the audio frequency output of the radio receiver and cathode ray oscillograms of the corona current were taken for each test condition. In addition to the above records cyclograms were taken for five tests. Oscillograms were taken at the nearest potential which was a multiple of five kilovolts below and above the critical disruption potential and at every ten kilovolts thereafter. All of the oscillograms that were taken during the investigation do not appear in this thesis. Only a sufficient number to make the data conclusive were included.

The experimental data which were obtained were found to bear out every point of the corona theory presented. The oscillograms and cyclograms of Fig. 6 are particularly interesting since they show the conditions for a greater range of potentials above the critical disruption value. Both sets of records show the increase in the corona current as the potential is raised above the critical disruption value. The oscillograms show definitely the very rapid rate of rise of the negative corona current. In all instances the speed of the electron beam across the tube was so rapid that practically no record was obtained until the current was well up toward the maximum value. The increase of positive corona current while rapid is not as abrupt as the negative rise.

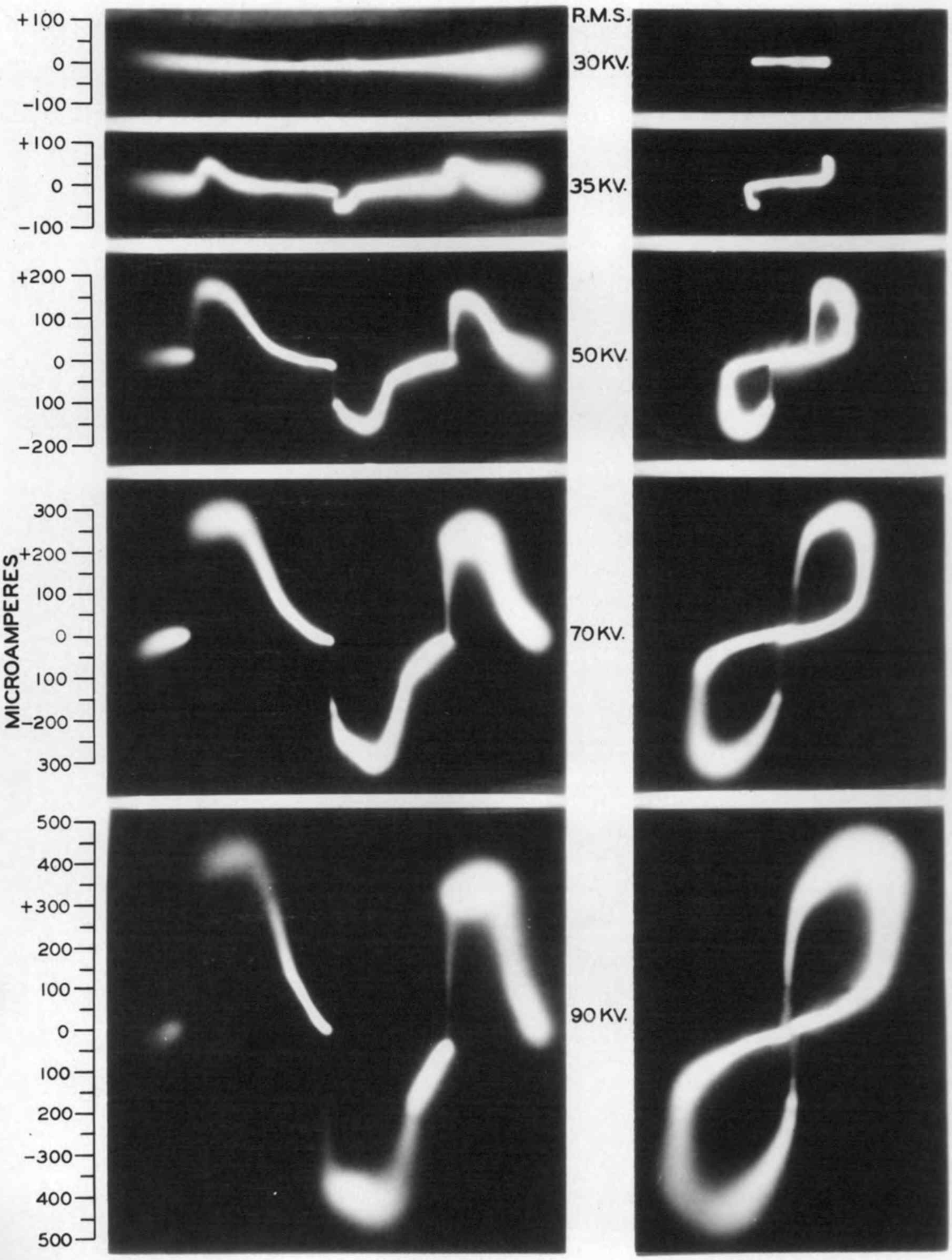
In the cyclograms on the right of Fig. 6, horizontal deflections are proportional to line voltage and vertical deflections to corona current. These cyclograms show conclusively that as the maximum potential increases the corona starts at lower instantaneous conductor potentials. The 50 kv. cyclogram shows that the corona currents do not start until the potential has increased to approximately one-third of its maximum value. At 70 kv. the corona starting point is at not more than one-tenth the maximum potential, and at 90 kv. corona is actually in existance before the potential reverses in polarity on both halves of the voltage wave. This is very definite proof of the existance of large space charges surrounding the conductor.

When the phenomena were viewed directly on the fluorescent screen of the oscillograph tube much better definition was obtained than shown in the oscillograms because of the fact that the film was not in intimate contact with the screen throughout the entire area. With better definition of visual observation another interesting phenomenon was apparent. The negative corona current was changing magnitude constantly, giving quite an irregular, rapidly changing line on the screen, showing the presence of oscillations of much higher frequencies and of appreciable magnitudes. The positive deflections were very stable and smooth, each cycle behaving just as the previous one and showing no indication of oscillations. The difference in the initial rate of increase of positive and negative corona currents was also very pronounced.

The oscillograms of Fig. 7 show the conductor to neutral plane voltage and radio interference produced by the conductor corona for the same conditions as obtained for cathode ray oscillograms of Fig. 6. The 30 kv. oscillogram was taken just below the critical disruptive potential. At 35 kv. it will be noted that the radio interference starts a very small electrical angle ahead of the maximum voltage and only on the half portion of the cycle when the conductor is negative. Again, as the potential increases the corona and radio interference start at lower and lower instantaneous potentials as the maximum voltage is increased.

These records were extended to 110 kv. which is 3.52 times the critical disruptive potential and at no time was interference caused by corona occurring during the positive half cycle of the voltage wave. It will also be noted upon inspection of Figs. 9, 11, 13, 15, 17, 19, and 21, which represent every test condition, that at no time was radio interference obtained during the positive half of the voltage cycle. The rough, oscillating character of the corona occurring during the negative half cycle becomes more pronounced as the conductor size is increased. Even the photographic records show this fact in the case of the large conductors. When the image is viewed directly on the fluorescent screen it appears very jagged and contains many sharp breaks, indicating sudden changes in the corona current. These changes are perhaps as great as 10% of the maximum corona current at the higher potentials. The small spots that appear during the rise of the negative current in the oscillograms of Fig. 12 and Fig. 20 are the result of these pronounced oscillations.

It will be remembered that all of the previous oscillograms apply only to highly polished conductors. To investigate the effect of a somewhat poorer surface condition an oscillogram was taken of the No. 6 cable in a semi-polished state. In this condition it was possible to obtain radio interference when the conductor was positive.

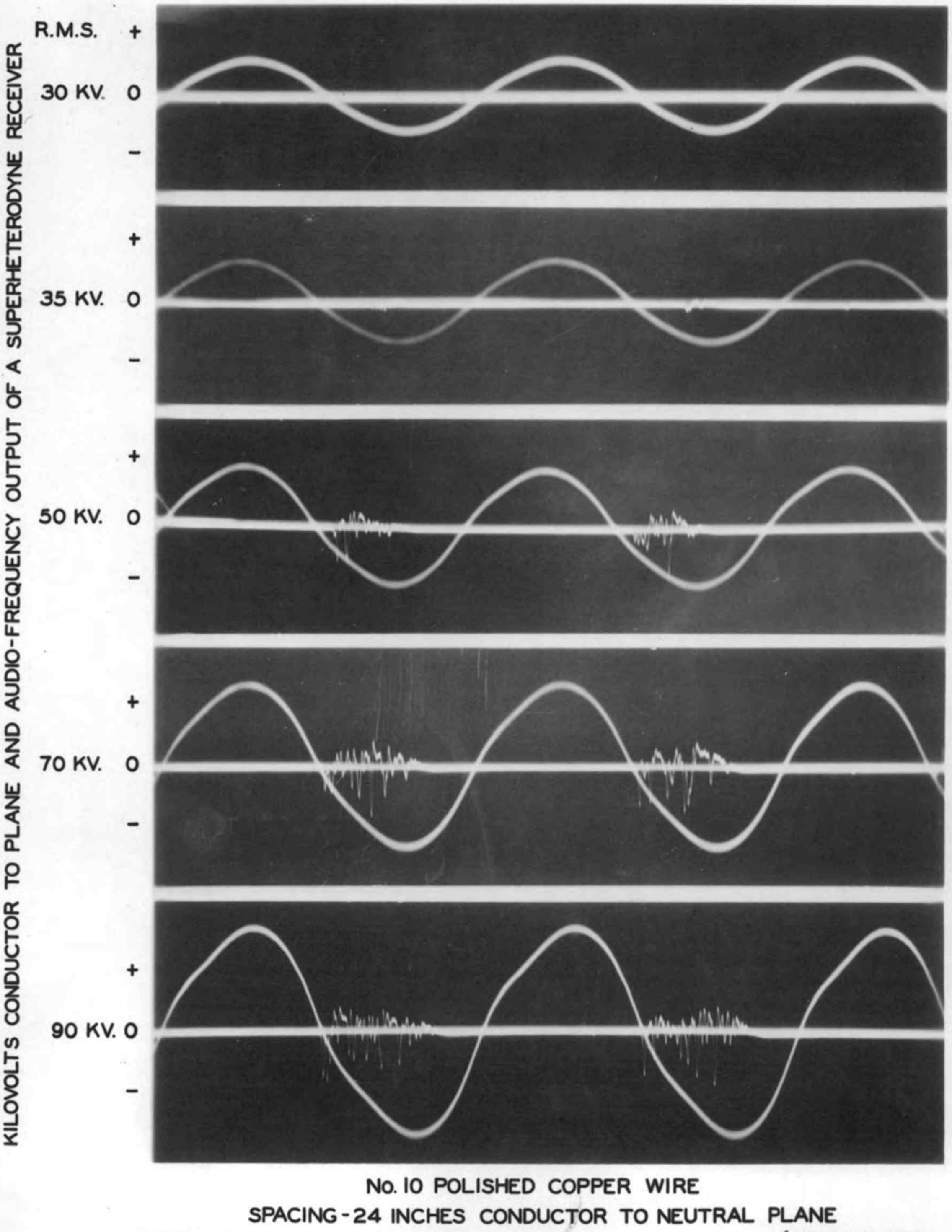


SPACING-24 INCHES CONDUCTOR TO NEUTRAL PLANE

BAROMETRIC PRESSURE 751.8 MM. OF HG. TEMPERATURE DEGREES C {DRY BULB 21.7, WET BULB 15.5}

HUMIDITY- RELATIVE 52.0 PER CENT. ABSOLUTE 10.25 GRAMS PER CUBIC METER

FIG. 6 . CATHODE RAY OSCILLOGRAMS AND CYCLOGRAMS OF THE CORONA CURRENT FOR A NO. 10 POLISHED COPPER WIRE



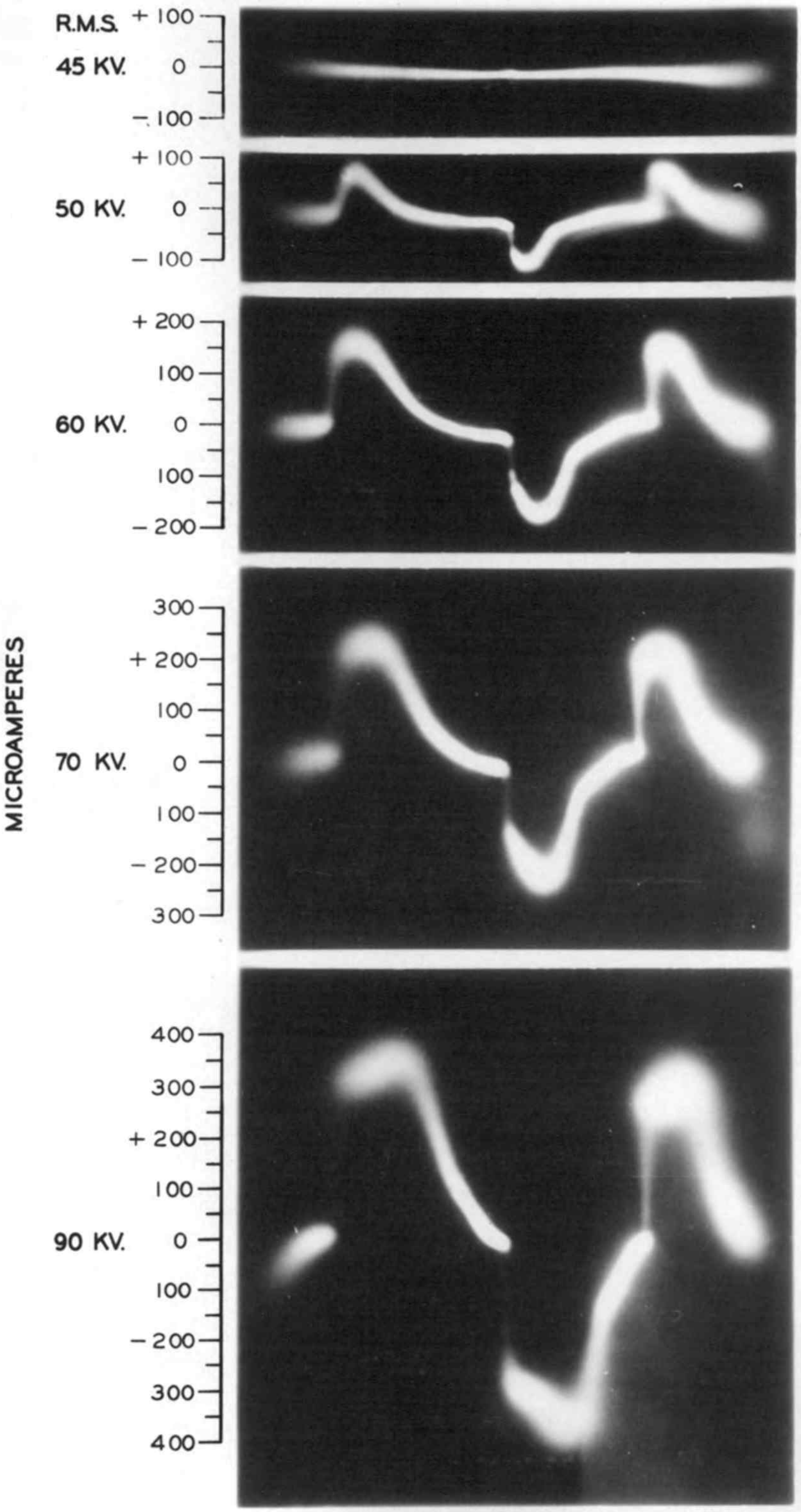
NO. 10 POLISHED COPPER WIRE

SPACING - 24 INCHES CONDUCTOR TO NEUTRAL PLANE

BAROMETRIC PRESSURE 750.8 MM. OF Hg. TEMPERATURE DEGREES C { DRY BULB 22.2, WET BULB 15.5 }

HUMIDITY - RELATIVE 49.0 PER CENT, ABSOLUTE 9.55 GRAMS PER CUBIC METER

FIG. 7 OSCILLOGRAMS OF CONDUCTOR TO PLANE VOLTAGE AND THE RADIO INTERFERENCE PRODUCED BY THE CONDUCTOR CORONA

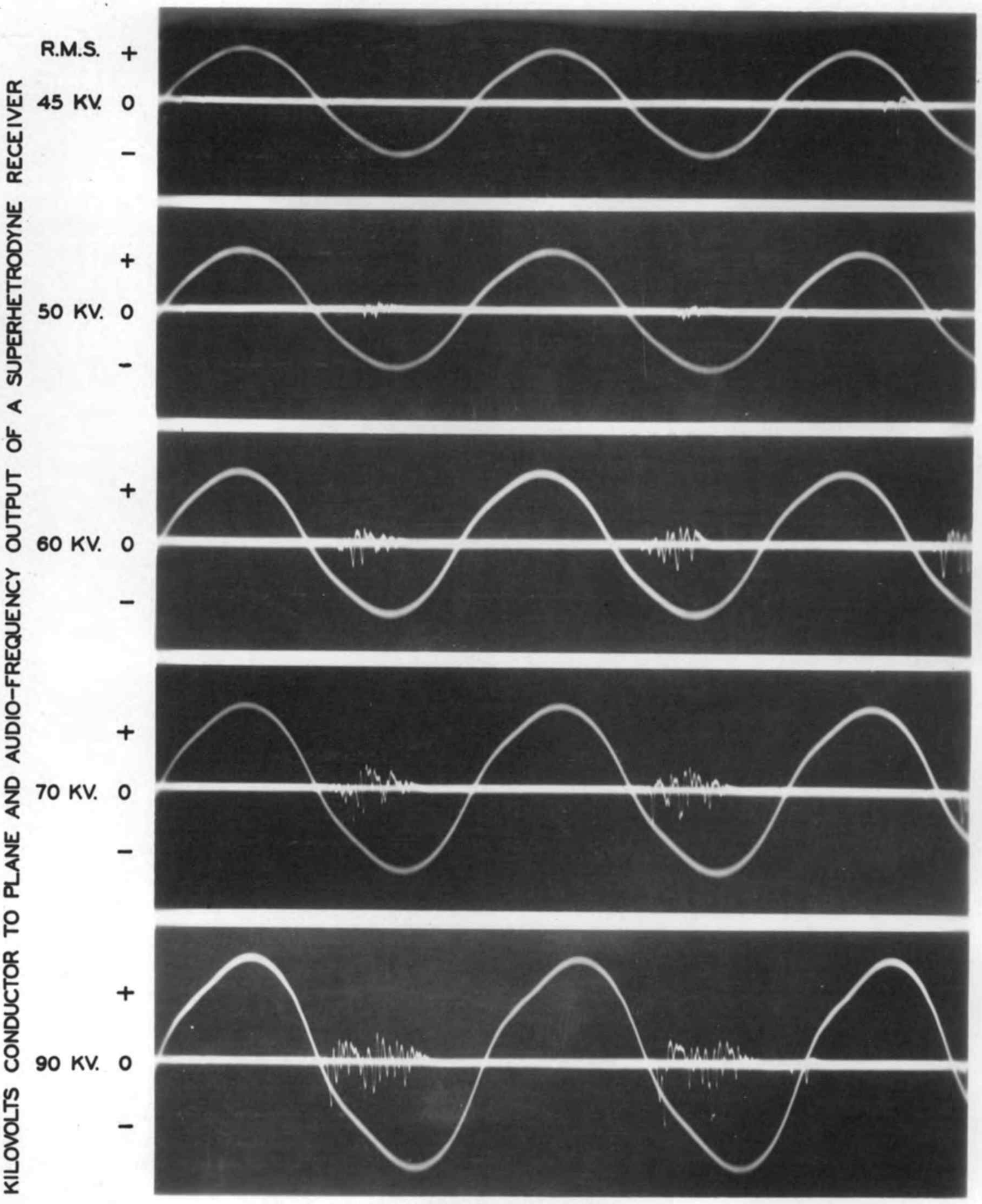


SPACING—24 INCHES CONDUCTOR TO NEUTRAL PLANE

BAROMETRIC PRESSURE 758.1 MM. HG. TEMPERATURE DEGREES C {DRY BULB 21.9, WET BULB 14.6}

HUMIDITY—RELATIVE 45.0 PER CENT. ABSOLUTE 8.6 GRAMS PER CUBIC METER

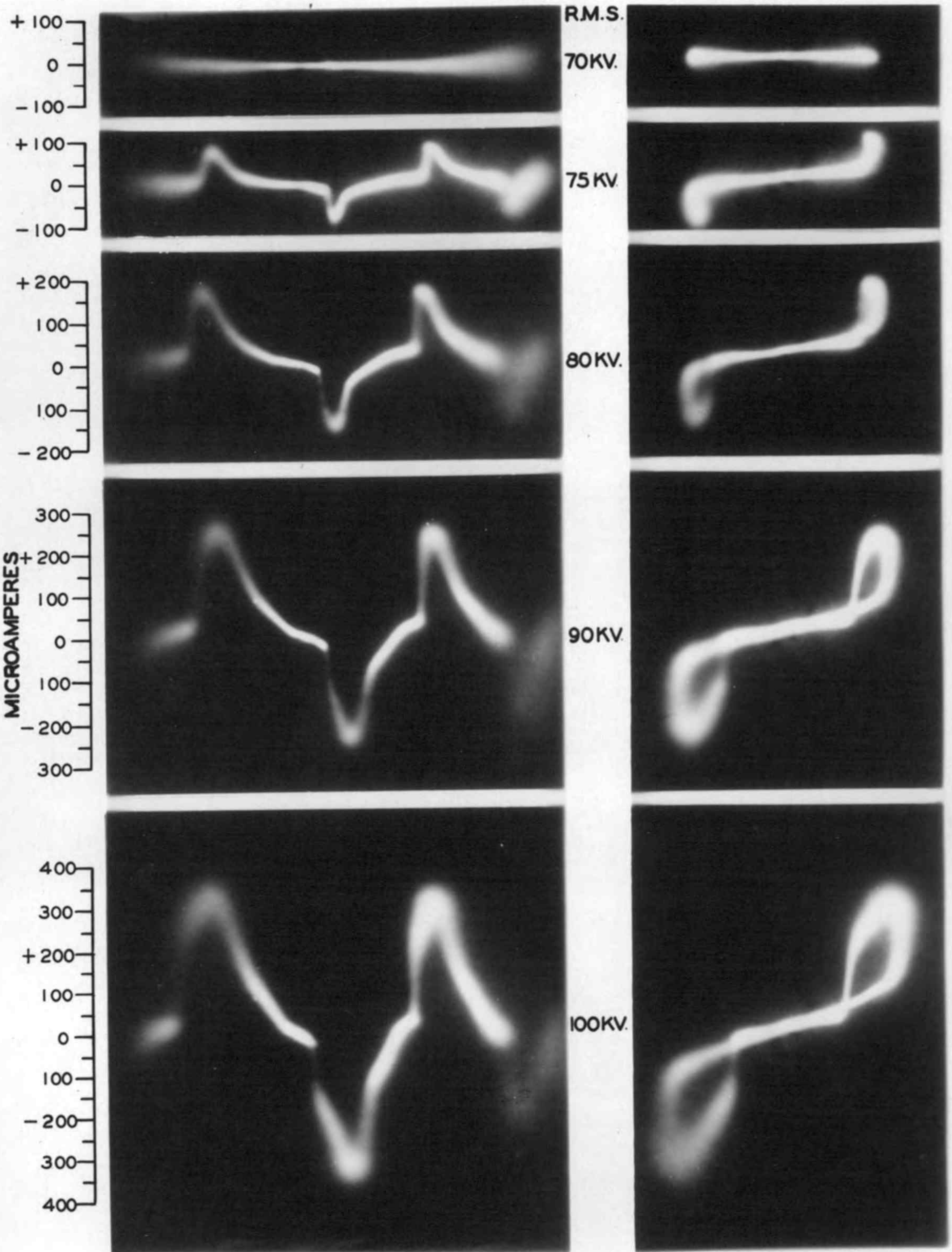
FIG. 8. CATHODE RAY OSCILLOGRAMS OF THE CORONA CURRENT FOR A NO.6 SEVEN STRAND POLISHED COPPER CABLE



NO. 6 SEVEN STRAND POLISHED COPPER CABLE
SPACING—24 INCHES CONDUCTOR TO NEUTRAL PLANE

BAROMETRIC PRESSURE 760.8 MM. OF HG. TEMPERATURE DEGREES C {DRY BULB 21.7, WET BULB 15.0}
HUMIDITY—RELATIVE 48.0 PER CENT. ABSOLUTE 8.97 GRAMS PER CUBIC METER

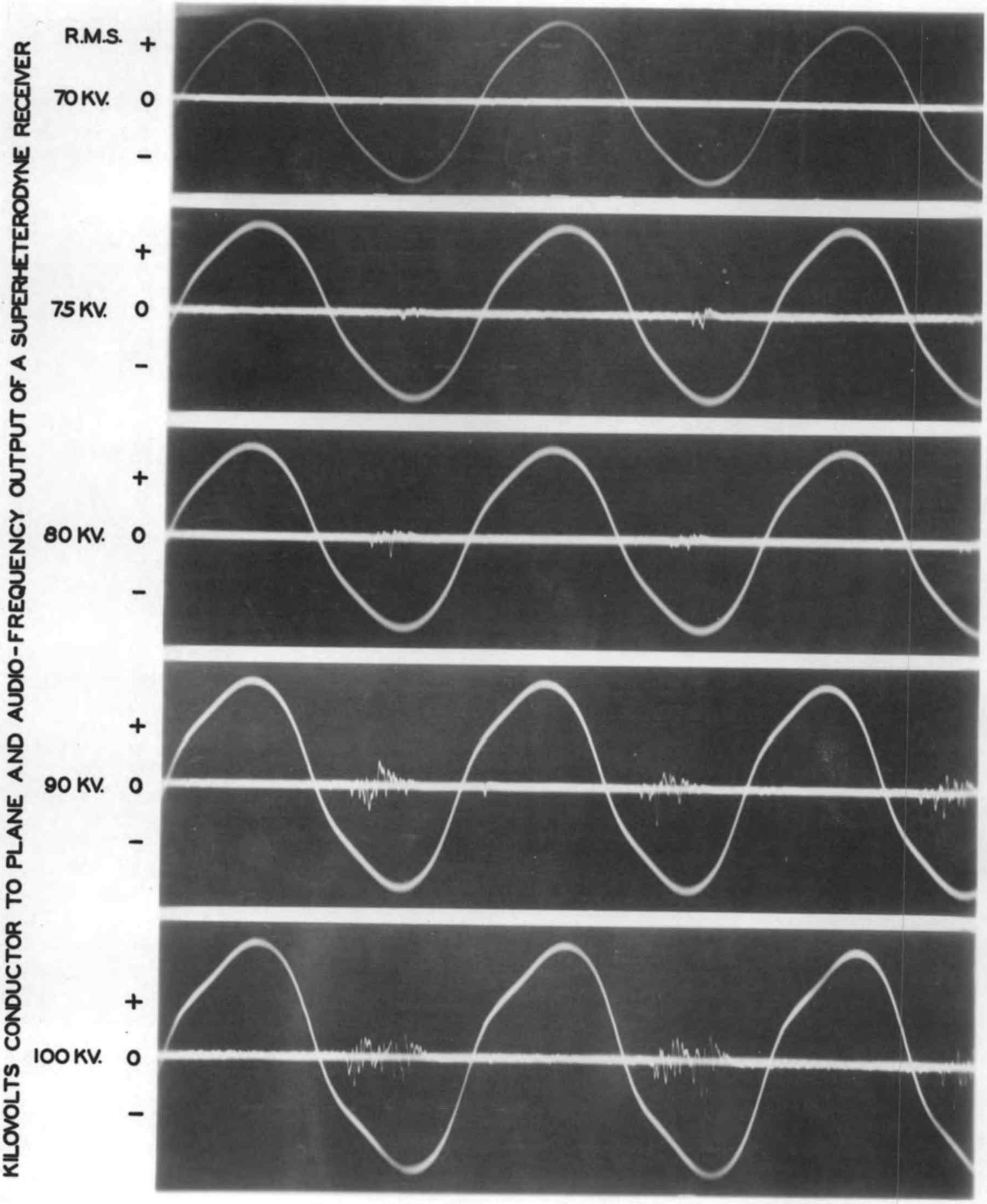
FIG. 9. OSCILLOGRAMS OF CONDUCTOR TO PLANE VOLTAGE AND THE RADIO INTERFERENCE PRODUCED BY THE CONDUCTOR CORONA



SPACING-24 INCHES CONDUCTOR TO THE NEUTRAL PLANE

BARTOMETRIC PRESSURE 754.5 MM. HG. TEMPERATURE DEGREES C {DRY BULB 23.3; WET BULB 15.3}
HUMIDITY-RELATIVE 41.0 PER CENT. ABSOLUTE 8.49 GRAMS PER CUBIC METER

FIG. 10. CATHODE RAY OSCILLOGRAMS AND CYCLOGRAMS OF THE CORONA CURRENT FOR A NO. 00 SEVEN STRAND POLISHED COPPER CABLE

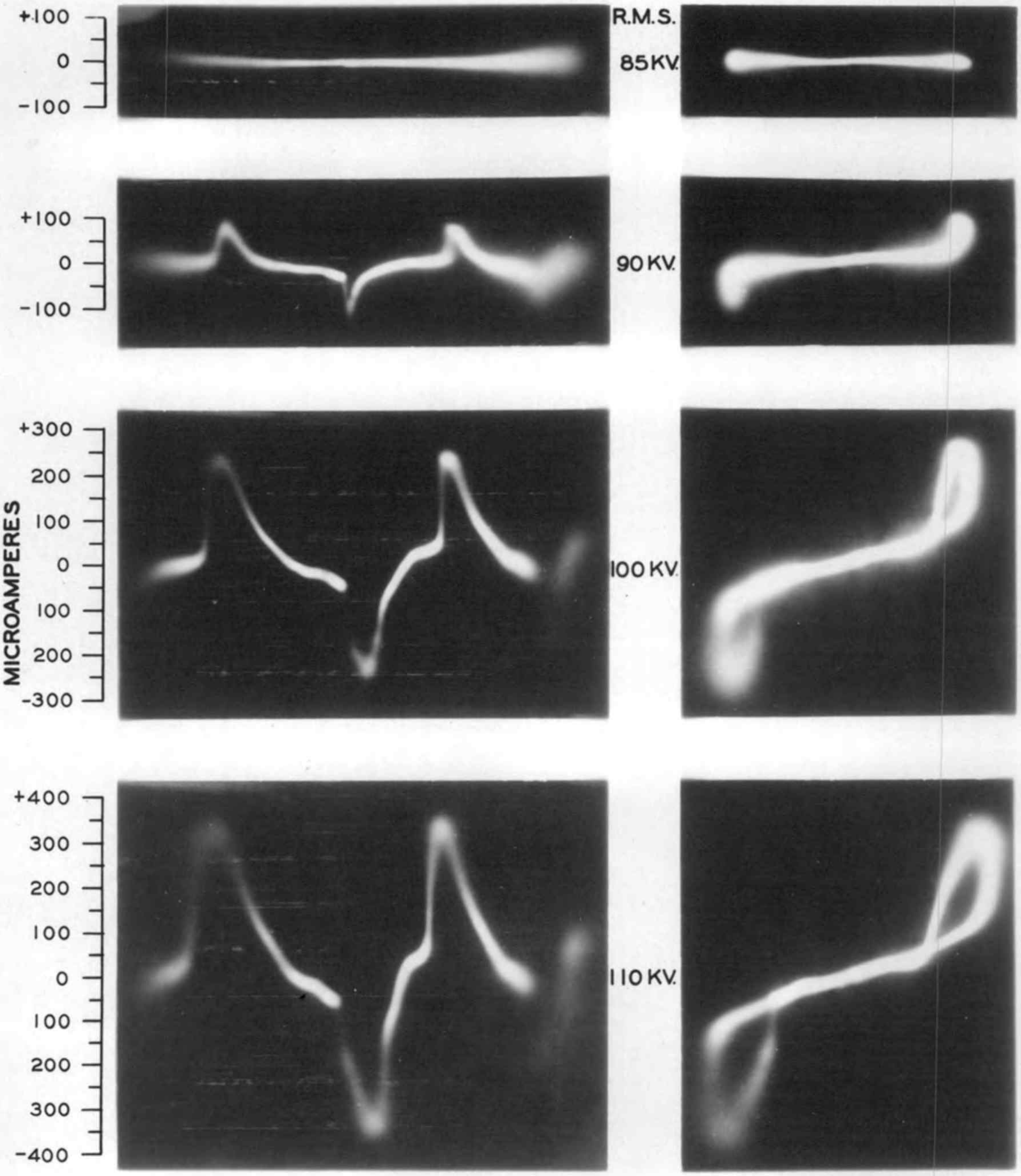


No.00 SEVEN STRAND POLISHED COPPER CABLE
SPACING-24 INCHES CONDUCTOR TO NEUTRAL PLANE

BAROMETRIC PRESSURE 756.6 MM. OF HG. TEMPERATURE DEGREES C. {DRY BULB 20.8 / WET BULB 13.6}

HUMIDITY-RELATIVE 43.0 PER CENT. ABSOLUTE 7.74 GRAMS PER CUBIC METER

FIG. 11. OSCILLOGRAMS OF CONDUCTOR TO PLANE VOLTAGE AND THE RADIO INTERFERENCE PRODUCED BY THE CONDUCTOR CORONA

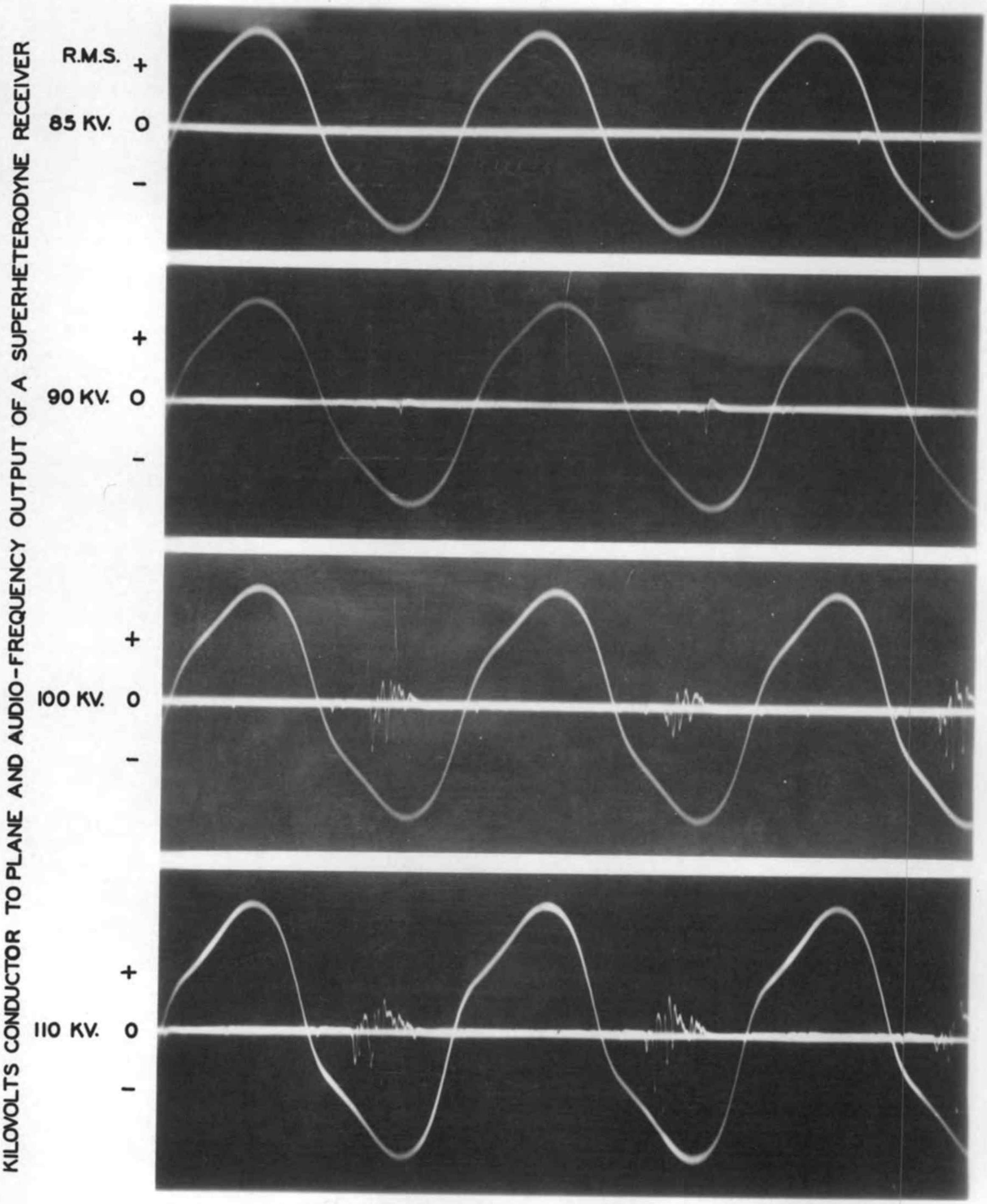


SPACING - 24 INCHES CONDUCTOR TO NEUTRAL PLANE

BAROMETRIC PRESSURE 756.6 MM. OF HG. TEMPERATURE DEGREES C { DRY BULB 22.2, WET BULB 14.3 }

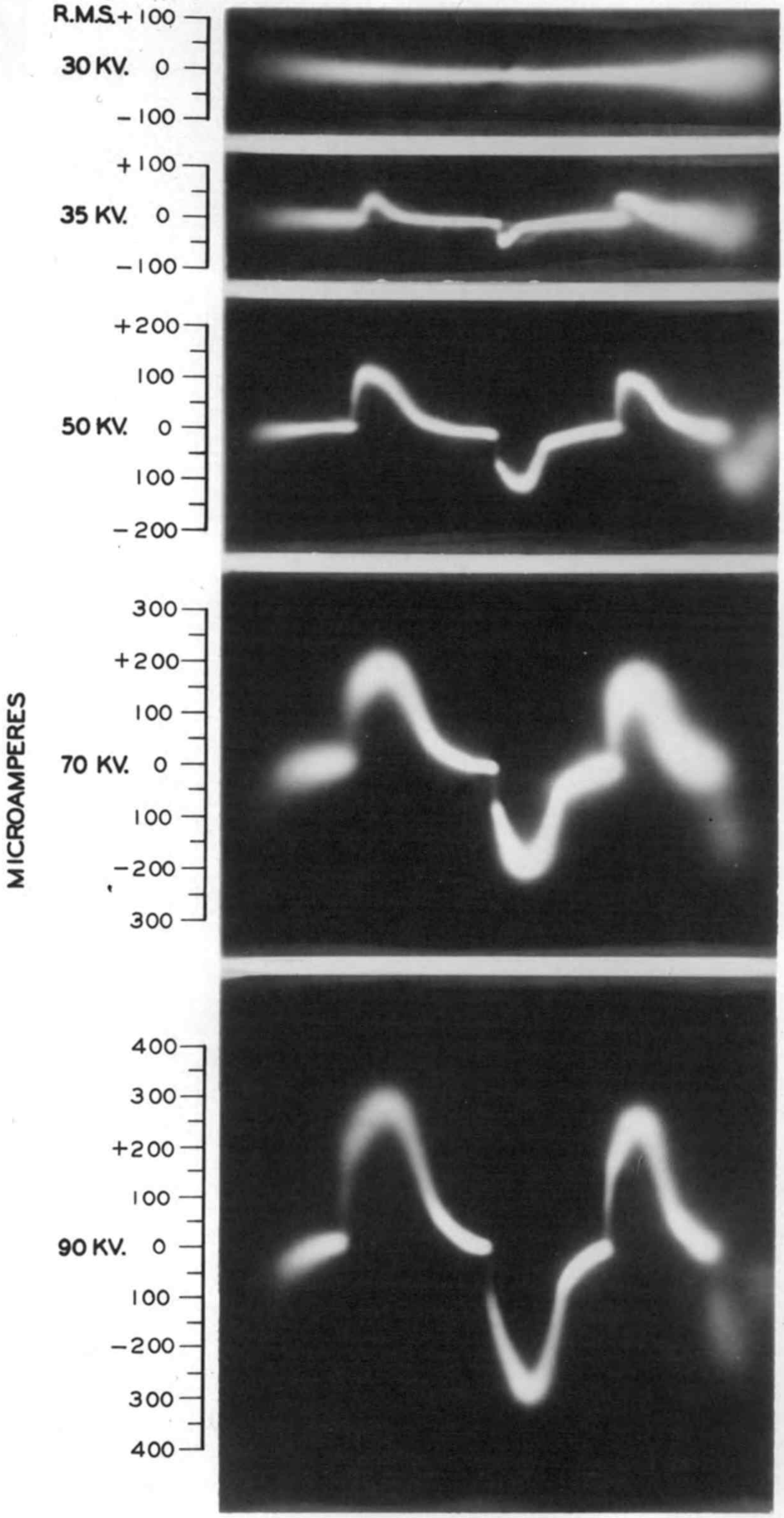
HUMIDITY - RELATIVE 42.0 PER CENT. ABSOLUTE 8.14 GRAMS PER CUBIC METER

FIG. 12. CATHODE RAY OSCILLOGRAMS AND CYCLOGRAMS OF THE CORONA CURRENT FOR A NO. 0000 SEVEN STRAND POLISHED ALUMINUM CABLE.



NO. 0000 SEVEN STRAND POLISHED ALUMINUM CABLE
SPACING - 24 INCHES CONDUCTOR TO NEUTRAL PLANE
BAROMETRIC PRESSURE 756.5 MM. OF HG. TEMPERTURE DEGREES C. {DRY BULB 21.7, WET BULB 13.8}
HUMIDITY - RELATIVE 41.0 PER CENT. ABSOLUTE 7.66 GRAMS PER CUBIC METER

FIG. 13. OSCILLOGRAMS OF CONDUCTOR TO PLANE VOLTAGE AND THE RADIO INTERFERENCE PRODUCED BY THE CONDUCTOR CORONA

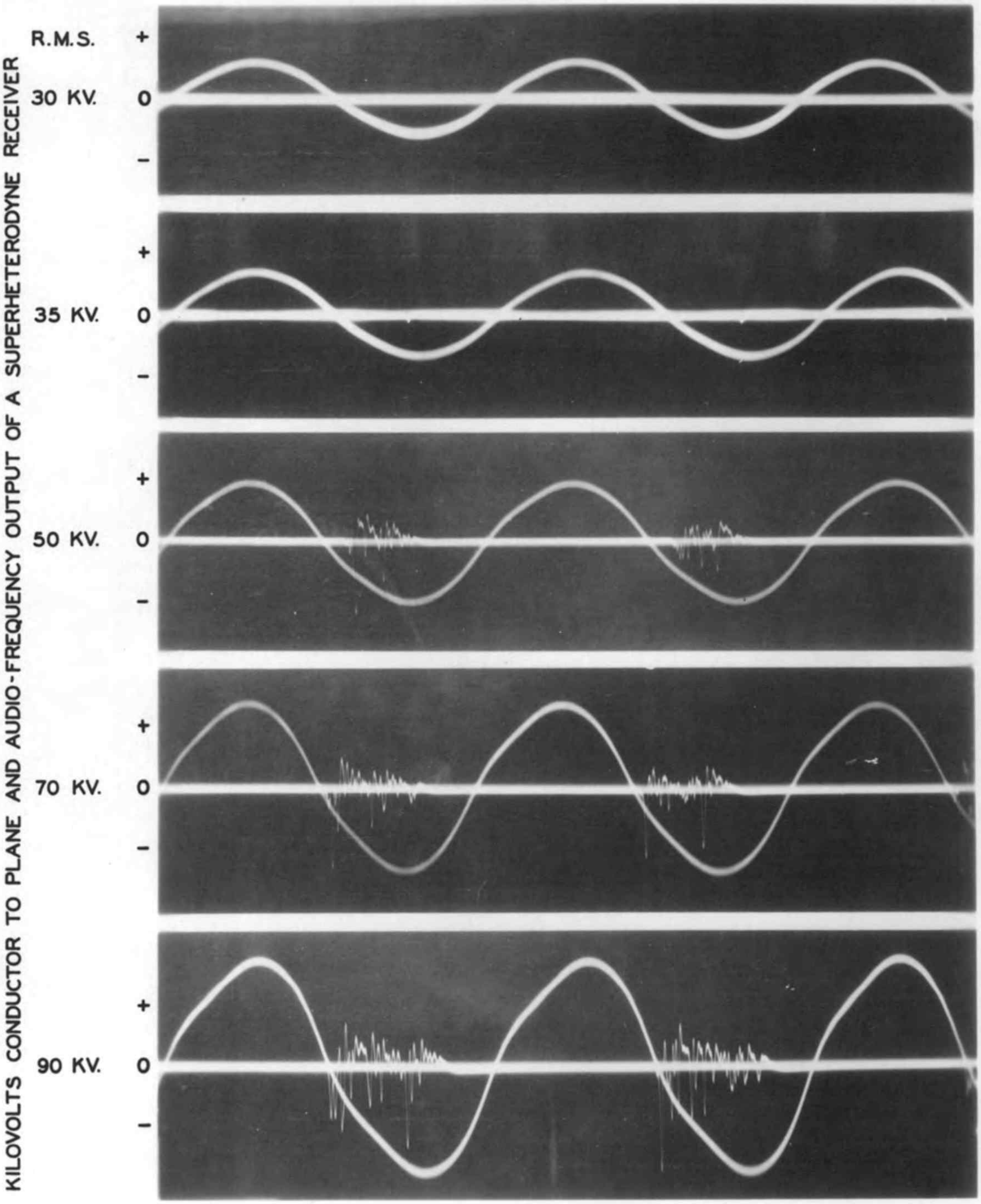


SPACING – 36 INCHES CONDUCTOR TO NEUTRAL PLANE

BAROMETRIC PRESSURE 749.5 MM. HG. TEMPERATURE DEGREES C {DRY BULB 20.5, WET BULB 14.4}

HUMIDITY – RELATIVE 51 PER CENT. ABSOLUTE 8.92 GRAMS PER CUBIC METER

FIG. 14. CATHODE RAY OSCILLOGRAMS OF THE CORONA CURRENT FOR A NO. 10 POLISHED COPPER WIRE



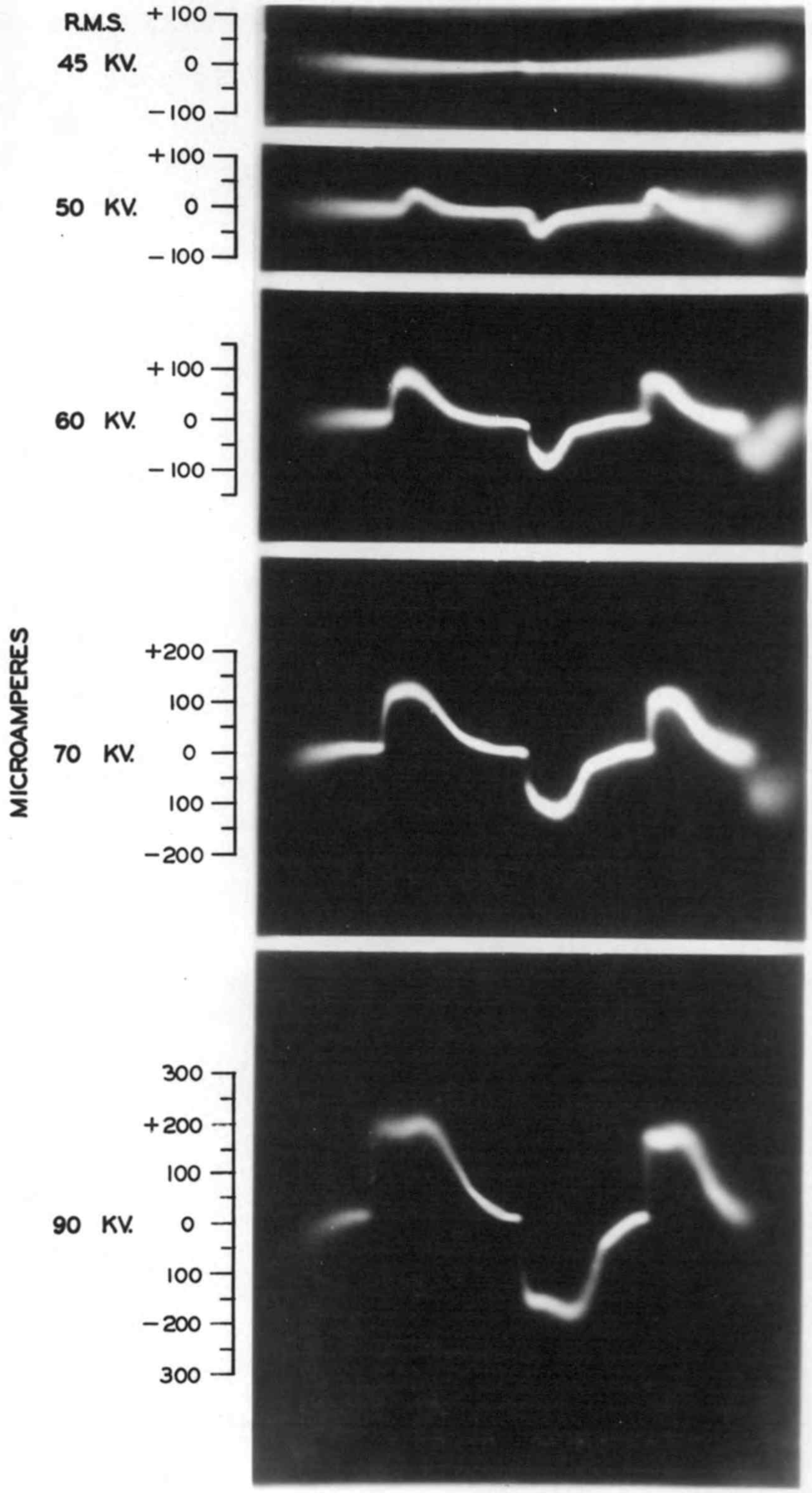
No. 10 POLISHED COPPER WIRE

SPACING - 36 INCHES CONDUCTOR TO NEUTRAL PLANE

BARAMETRIC PRESSURE 755.7 MM. OF Hg. TEMPERATURE DEGREES C { DRY BULB 20.8, WET BULB 14.2 }

HUMIDITY - RELATIVE 47.0 PER CENT, ABSOLUTE 8.46 GRAMS PER CUBIC METER

FIG. 15. OSCILLOGRAMS OF CONDUCTOR TO PLANE VOLTAGE AND THE RADIO INTERFERENCE PRODUCED BY THE CONDUCTOR CORONA

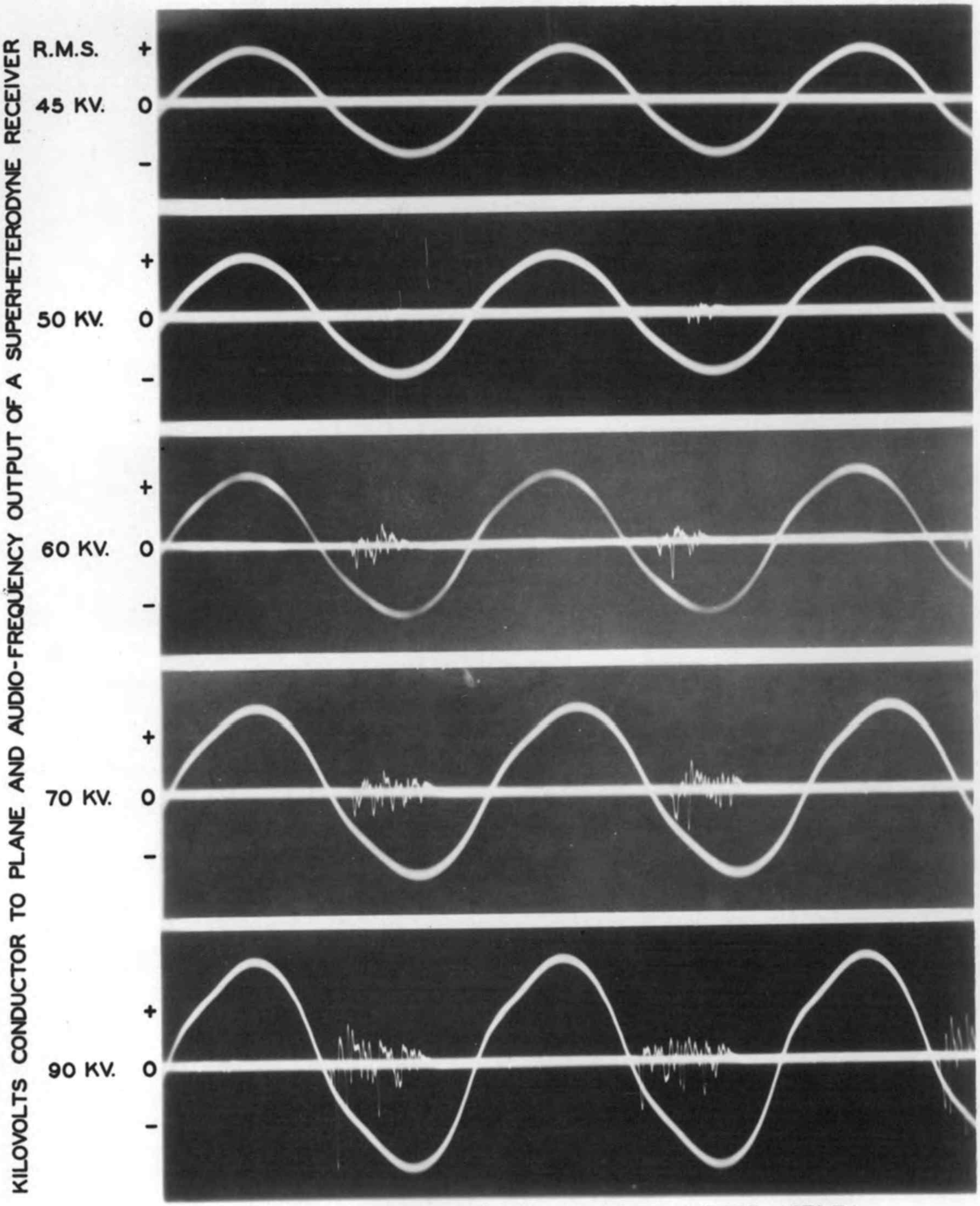


SPACING-36 INCHES CONDUCTOR TO NEUTRAL PLANE

BAROMETRIC PRESSURE 759.6 MM. HG. TEMPERATURE DEGREES C {DRY BULB 21.1, WET BULB 14.4}

HUMIDITY-RELATIVE 48.0 PER CENT. ABSOLUTE 8.73 GRAMS PER CUBIC METER

FIG. 16. CATHODE RAY OSCILLOGRAM OF THE CORONA CURRENT FOR A NO. 6 SEVEN STRAND POLISHED COPPER CABLE

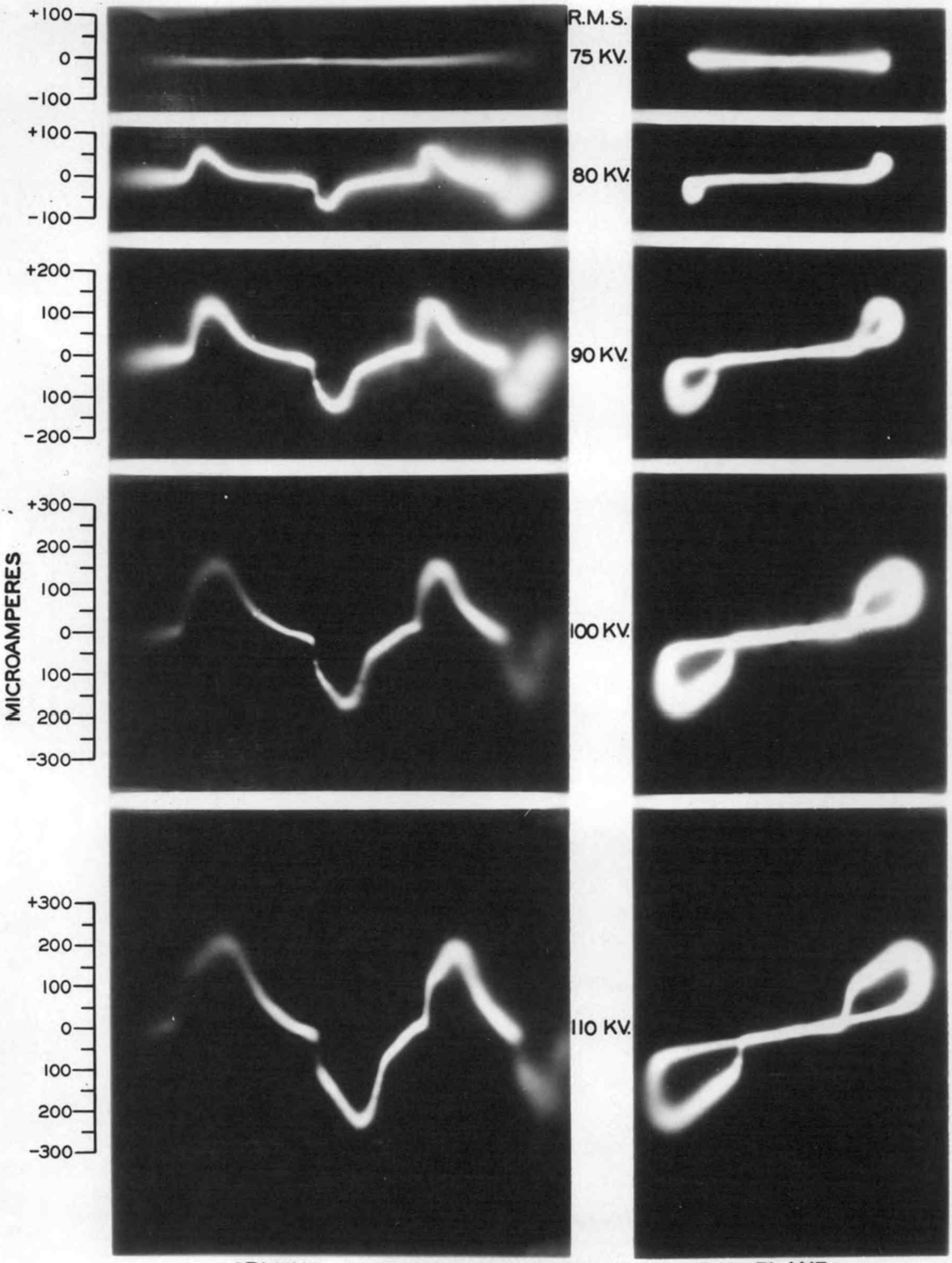


No. 6 SEVEN STRAND POLISHED COPPER CABLE
SPACING - 36 INCHES CONDUCTOR TO NEUTRAL PLANE

BAROMETRIC PRESSURE 756.4 MM. OF HG. TEMPERATURE DEGREES C {DRY BULB 21.1, WET BULB 15.2}

HUMIDITY - RELATIVE 49.0 PER CENT. ABSOLUTE 8.92 GRAMS PER CUBIC METER

FIG. 17. OSCILLOGRAMS OF CONDUCTOR TO PLANE VOLTAGE AND THE RADIO INTERFERENCE PRODUCED BY THE CONDUCTOR CORONA

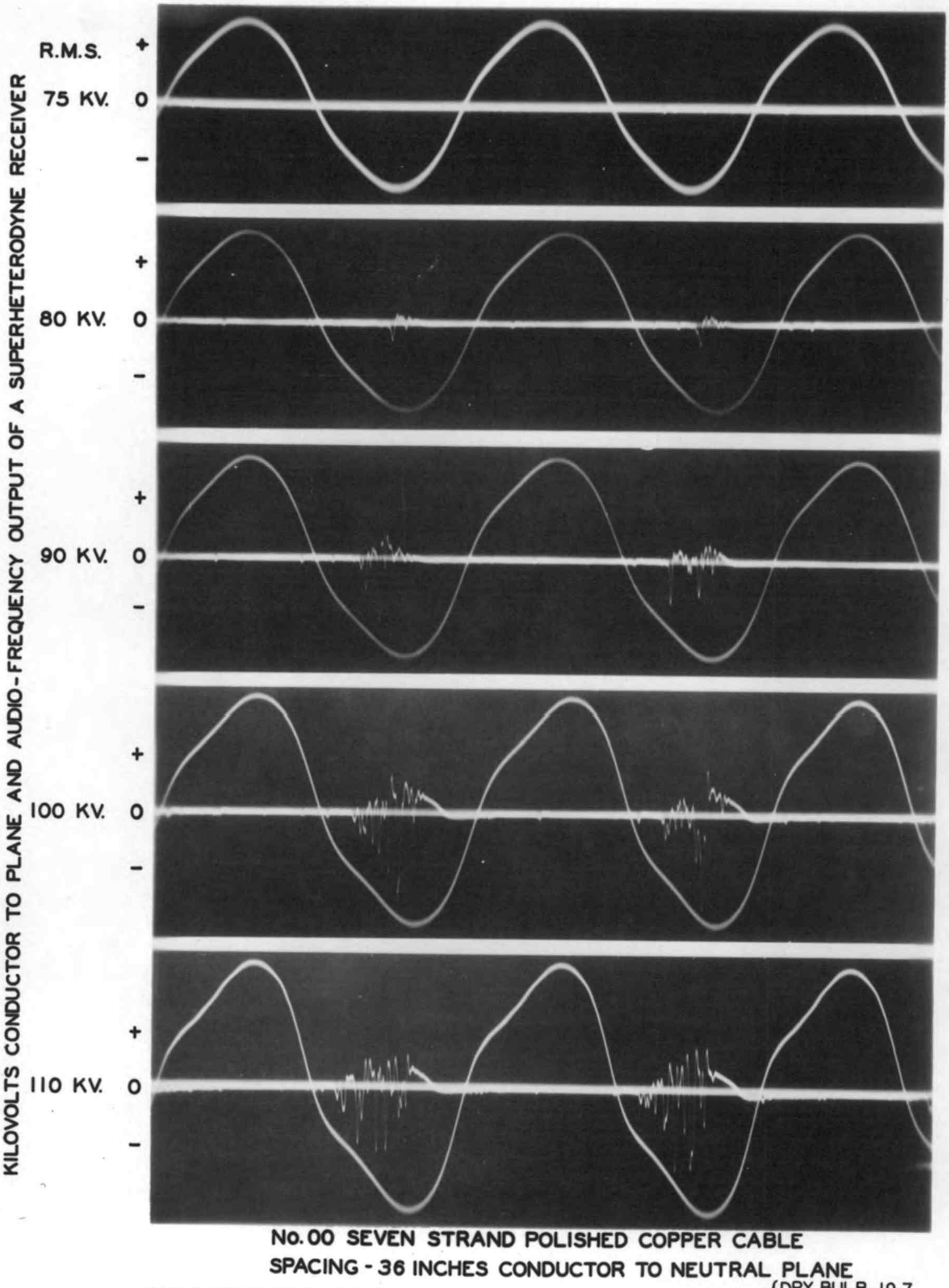


SPACING - 36 INCHES CONDUCTOR TO NEUTRAL PLANE

BAROMETERIC PRESSURE 757.5 MM. OF HG. TEMPERATURE DEGREES C {DRY BULB 21.1, WET BULB 13.9}

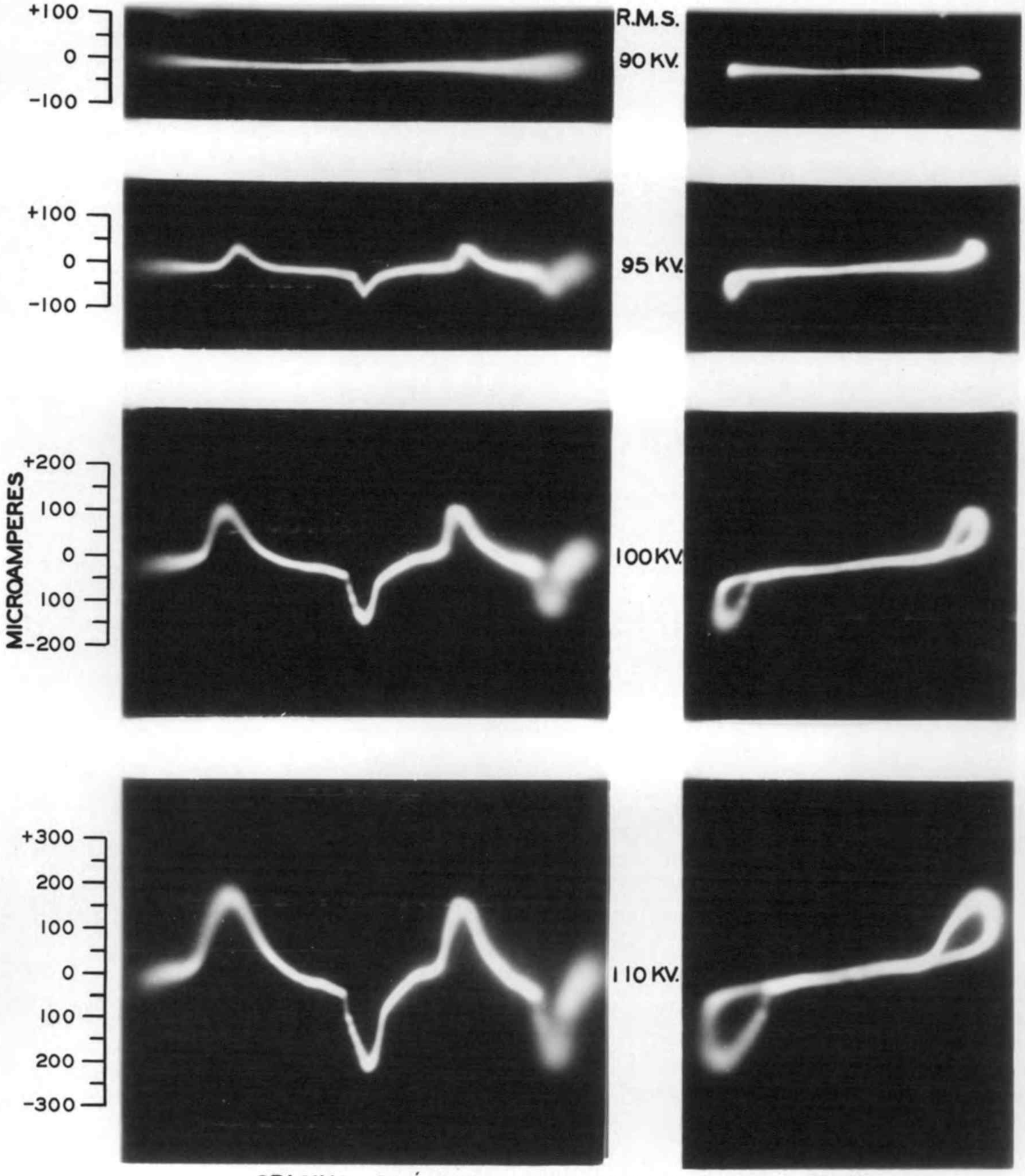
HUMIDITY - RELATIVE 44.0 PER CENT, ABSOLUTE 8.01 GRAMS PER CUBIC METER

FIG.18. CATHODE RAY OSCILLOGRAMS AND CYCLOGRAMS OF THE CORONA CURRENT FOR A NO. 00 SEVEN STRAND POLISHED COPPER CABLE



NO. 00 SEVEN STRAND POLISHED COPPER CABLE
SPACING - 36 INCHES CONDUCTOR TO NEUTRAL PLANE
BAROMETRIC PRESSURE 759.6 MM. OF HG. TEMPERATURE DEGREES C { DRY BULB 19.7, WET BULB 12.8 }
HUMIDITY - RELATIVE 43.0 PER CENT, ABSOLUTE 7.22 GRAMS PER CUBIC METER

FIG. 19. OSCILLOGRAMS OF CONDUCTOR TO PLANE VOLTAGE AND THE RADIO INTERFERENCE PRODUCED BY THE CONDUCTOR CORONA.

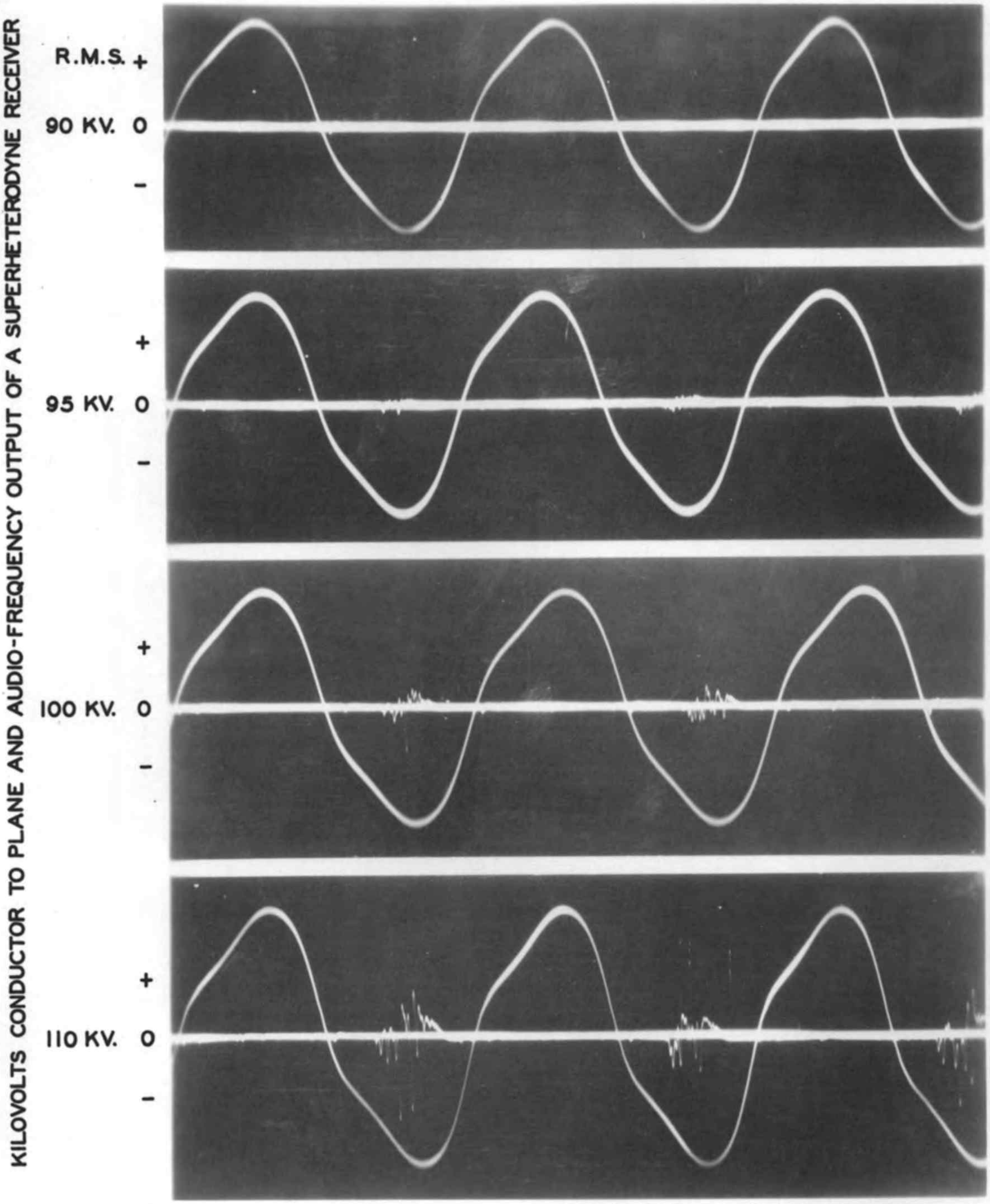


SPACING - 36 INCHES CONDUCTOR TO NEUTRAL PLANE

BARAMETRIC PRESSURE 756.2 MM. OF HG. TEMPERATURE DEGREES C { DRY BULB 22.2 / WET BULB 15.2 }

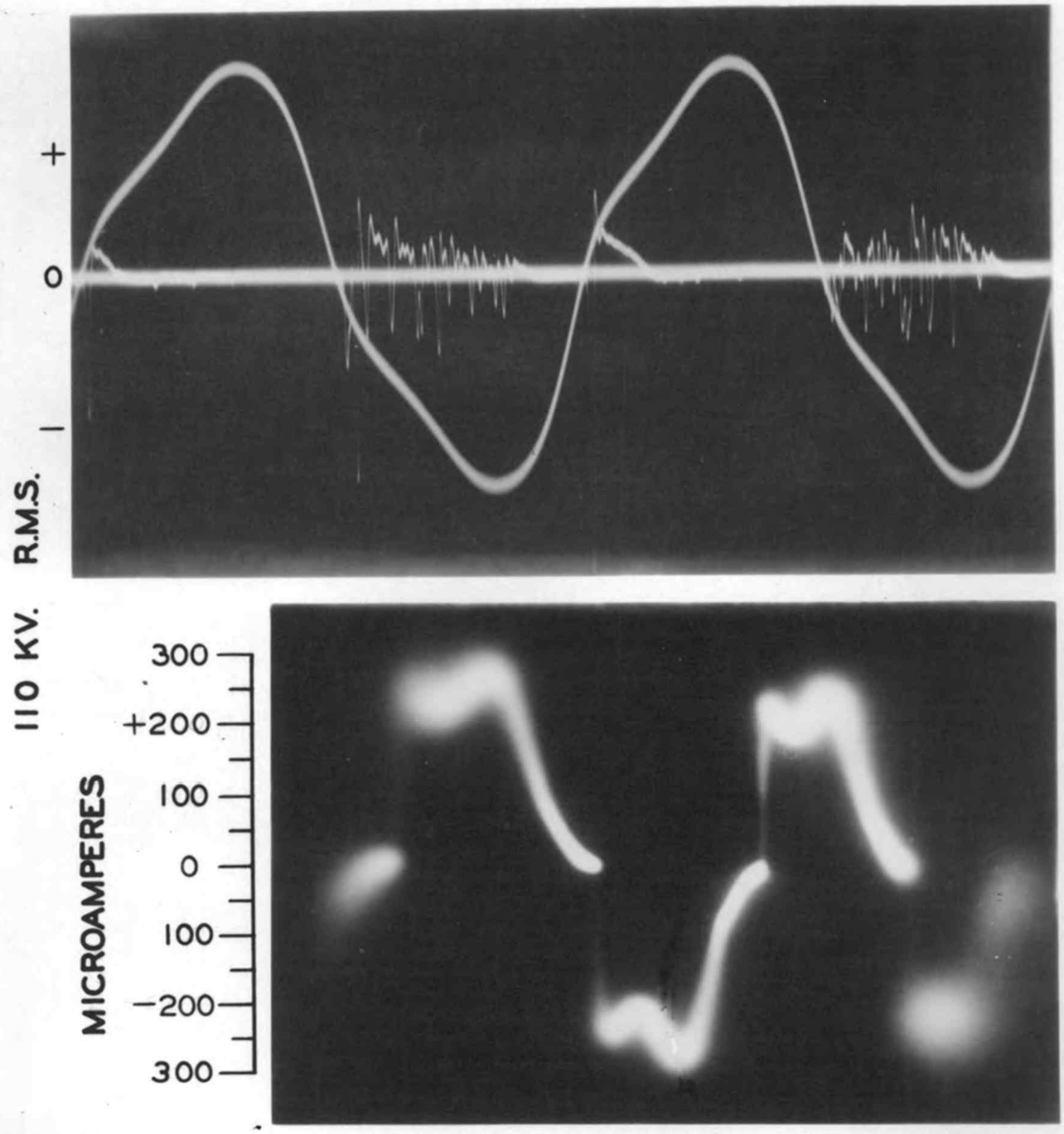
HUMIDITY - RELATIVE 47.0 PER CENT. ABSOLUTE 9.16 GRAMS PER CUBIC METER

FIG. 20. CATHODE RAY OSCILLOGRAMS AND CYCLOGRAMS OF THE CORONA CURRENT FOR A NO. 0000 SEVEN STRAND POLISHED ALUMINUM CABLE



No. 0000 SEVEN STRAND POLISHED ALUMINUM CABLE
SPACING - 36 INCHES CONDUCTOR TO NEUTRAL PLANE
BAROMETER PRESSURE 758.0 MM. HG. TEMPERATURE DEGREES C {DRY BULB 21.1, WET BULB 15.0}
HUMIDITY - RELATIVE 51.0 PER CENT, ABSOLUTE 9.28 GRAMS PER CUBIC METER

FIG. 21. OSCILLOGRAMS OF CONDUCTOR TO PLANE VOLTAGE AND THE RADIO INTERFERENCE PRODUCED BY THE CONDUCTOR CORONA.



NO.6 SEVEN STRAND PARTIALLY POLISHED COPPER CABLE
SPACING–36 INCHES CONDUCTOR TO NEUTRAL PLANE
BAROMETRIC PRESSURE 756.4 MM. OF HG. TEMPERATURE DEGREES C {DRY BULB 21.1, WET BULB 15.2}
HUMIDITY-RELATIVE 49.0 PER CENT. ABSOLUTE 8.92 GRAMS PER CUBIC METER

FIG.22 OSCILLOGRAMS OF CONDUCTOR TO PLANE VOLTAGE, AUDIO INTERFERENCE AND THE CORONA CURRENT WHICH CAUSED INTERFERENCE DURING BOTH POSITIVE AND NEGATIVE CONDUCTOR POLARITIES.

Duddell and cathode ray oscillograms of this condition at 110 kv. are shown in Fig. 22. An investigation of the phenomena were made in a darkened room and it was found that the radio interference appearing on the positive half of the voltage cycle appeared simultaneously with the formation of typical "positive corona plumes." These plumes are localized intermittent corona discharges that produce an audible snapping noise and appear on the positive half of the voltage wave only. They project themselves out relatively large distances from the conductor surface. Under the conditions of this test they were often observed to be as much as three or four inches in length. These positive discharges last only a very short interval of time as is shown by the Duddell oscillogram. The sudden change of current caused by these positive corona plumes causes oscillations in the circuit and produce serious radio interference. It will be noted from the Duddell oscillogram of Fig. 22 that the positive radio interference, although of very short duration, is extremely intense. On the second positive half cycle of the oscillogram the radio interference record extends completely to the bottom of the oscillogram.

Two groups of corona current curves were plotted from data obtained from the cathode ray oscillograms. The maximum values of the two positive corona current half cycles and the maximum value of the negative corona current were accurately measured from the oscillogram negatives. The average of these three values multiplied by the current calibration of the oscillograph tube which was explained under the heading Laboratory Equipment was taken as the maximum corona current to the test plate. It is that scale which appears on all cathode ray oscillograms and cyclograms.

This current converted to microamperes per foot of conductor was multiplied by, the ratio of the capacitance per foot of conductor to an infinite neutral plane, to the capacitance per foot of conductor to the shielded plate of the experimental neutral plane. This correction converts the experimental values of corona current to the total corona current per foot of conductor. This correction neglects the flux distortion caused by unsymmetrical corona formation on the conductor, however, this is believed to be negligible for the conditions of this investigation. The derivation of the equation and the calculation of the capacitance values used in determining the corona current correction factors are shown in Appendix I.

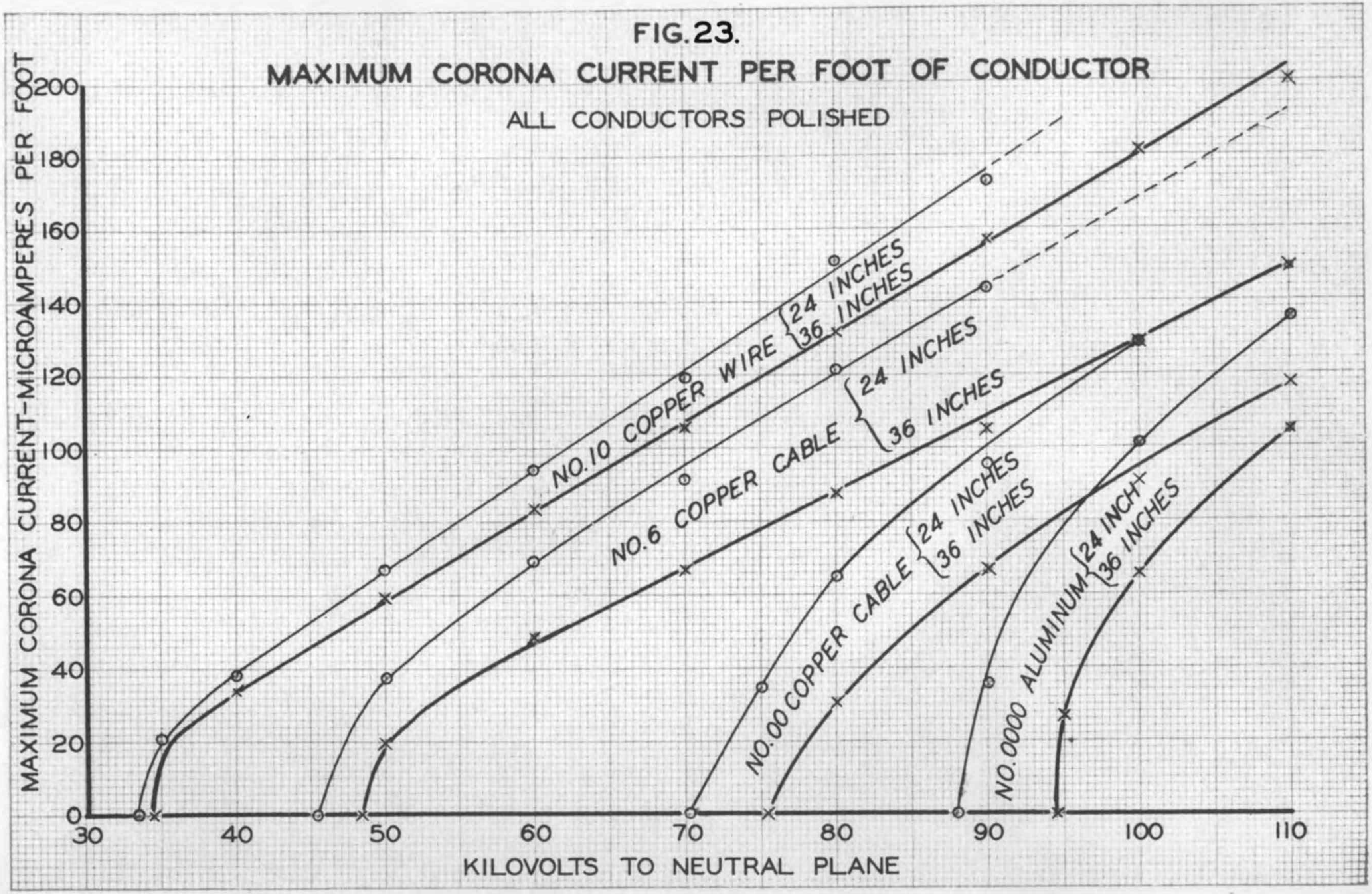
The corrected maximum corona current values per foot of conductor for all conductors and spacings investigated are shown graphically in Fig. 23. From these curves it will be seen that at the larger values of S/r the corona current increases quite rapidly as the voltage is raised above the critical value through a small range. Above this range the current is practically a straight line function of the potential. Although the data are not conclusive due to an insufficient potential range they indicate that the same phenomena would be observed at smaller values of S/r to a more pronounced degree.

The curves as plotted show very nicely the effect of S/r on the visual corona voltage of conductors. The initial abrupt rise of the negative corona current as a function of the potential to the neutral plane is shown graphically in Fig. 24 for all conductors and spacings

FIG. 23.

MAXIMUM CORONA CURRENT PER FOOT OF CONDUCTOR

ALL CONDUCTORS POLISHED



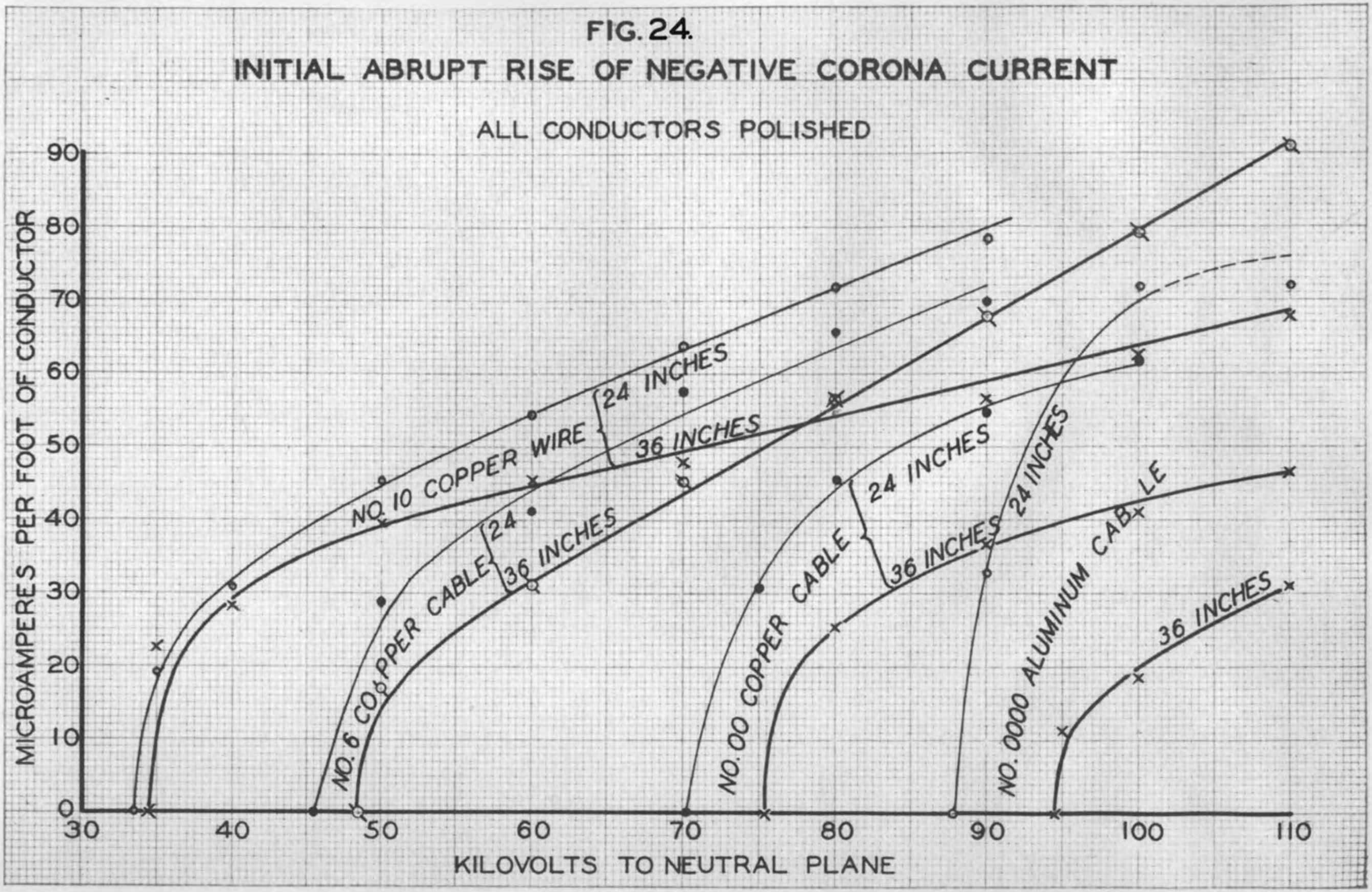


FIG. 24.
INITIAL ABRUPT RISE OF NEGATIVE CORONA CURRENT
ALL CONDUCTORS POLISHED
MICROAMPERES PER FOOT OF CONDUCTOR
KILOVOLTS TO NEUTRAL PLANE
0
10
20
30
40
50
60
70
80
90
30
40
50
60
70
80
90
100
110
NO. 10 COPPER WIRE
24 INCHES
36 INCHES
NO. 6 COPPER CABLE
24
36 INCHES
NO. 00 COPPER CABLE
24 INCHES
36 INCHES
NO. 0000 ALUMINUM CABLE
24 INCHES
36 INCHES

investigated. These curves show that as the value of S/r becomes smaller, the initial current rise becomes larger and larger. Since this initial current undoubtedly sets the line in oscillation with the attendant radio interference, therefore, close spacings should be avoided in the construction of transmission lines. Close spacings also decrease the critical visual voltage.

There are a number of problems which the work connected with the preparation of this thesis has suggested.

It would be particularly interesting and valuable to know all of the various factors that influence the sudden rise of negative corona current.

The effect of frequency on the radio interference produced by corona would be a very important and interesting subject for investigation. In the light of present knowledge it is apparent that the time interval between successive half cycles will have a marked influence on the magnitude of the residual space charges around a conductor and the radio interference from corona.

The present knowledge of direct current corona is very meager but is assuming increasing importance as the possibility for high voltage direct current transmission of power increases. Therefore, an investigation of the radio interference characteristics of direct current corona would be of interest and value.

The conductor surface conditions have been found to play a very important part in the formation of positive corona plumes. An investigation of the relative weathering characteristics of copper and aluminum from the standpoint of the radio interference produced as a result of changes in surface condition would be worth while and would yield very valuable practical information.

CONCLUSIONS

1 Radio interference from corona on well polished conductors occurs only when the conductor is negative.

2 Surface contamination causes the radio interference to occur for both positive and negative conductor polarities.

3 The initial increase in negative corona current is a sudden rush of very steep wave front which is much more abrupt than the normal positive corona current rise.

4 The magnitude of the initial rush of negative corona current is a function of the conductor spacing and radius.

5 Pronounced oscillations occur in the negative conductor corona current. The magnitude of these oscillations is dependent on the circuit constants.

6 The low voltage cathode ray oscillograph used in conjunction with a bridge type of circuit for balancing out the conductor charging current has proved to be a very reliable and practical device for studying conductor corona currents.

ACKNOWLEDGMENT

I wish to express my appreciation for the splendid cooperation of Professor F. O. McMillan in suggesting the subject of this thesis and the help given in its preparation.

I also with to thank Professor E. C. Starr for the suggestions which he has offered from time to time.

Also, to Mr. Glen Barnett I owe my sincere appreciation of his continued assistance in performing the experimental work.

APPENDIX I

DERIVATION OF EQUATIONS FOR CALCULATING CAPACITANCE BETWEEN CONDUCTOR AND NEUTRAL PLANE

SYMBOLS:

C = capacitance

ψ = dielectric flux

D = dielectric flux density

A = area

v = velocity of light = 3×10^{10} centimeters per second

g = potential gradient

k = relative permittivity

x = distance, along neutral plane at right angles to a perpendicular from the conductor to the neutral plane

a = distance from conductor to point in dielectric field

S = spacing from conductor to image of conductor such that the neutral plane is $\frac{S}{2}$ from conductor

r = conductor radius

e = voltage (maximum)

e_n = voltage to neutral (maximum)

EQUATIONS:

The capacitance in any circuit:

$$C = \frac{\varphi}{e} \qquad (1)$$

For any equipotential surface

$$\varphi = DA \qquad (2)$$

$$= g \frac{10^9 k}{4 \pi v^2} A \qquad (2a)$$

For 1 centimeter of line the flux through an area of elemental width, dx

$$d\varphi = g \frac{10^9 k\, dx\, (1)}{4 \pi v^2} \qquad (3)$$

It can be shown that, when S is large compared to r,* in the neutral plane

$$g = \frac{1}{a^2}\left[\frac{(S) e_n}{\log_\epsilon\left(\frac{S}{r}\right)}\right] \qquad (4)$$

when

$$a^2 = \sqrt{\left(\frac{S}{2}\right)^2 + x^2} \qquad (5)$$

Then from equations (4) and (5)

$$g = \left[\frac{S e_n}{\log_\epsilon \frac{S}{r}}\right] \frac{1}{\left(\frac{S}{2}\right)^2 + x^2} \qquad (6)$$

And from equations (3) and (6)

$$d\varphi = \left(\frac{10^9 k}{4 \pi v^2}\right) \frac{S e_n}{\log_\epsilon \frac{S}{r}} \frac{dx}{\left(\frac{S}{2}\right)^2 + x^2} \qquad (7)$$

* F. W. Peek, "Dielectric Phenomena in High-Voltage Engineering" pp. 339.

Integrating

$$\psi\Big]_{x_1}^{x_2} = \frac{10^9 k S e_n}{4\pi v^2 \log_\epsilon \frac{S}{r}} \int_{x_1}^{x_2} \frac{dx}{\left(\frac{S}{2}\right)^2 + x^2}$$

$$= \frac{10^9 k e_n}{4\pi v^2 \log_\epsilon \frac{S}{r}} \left[\tan^{-1}\frac{2x_2}{S} - \tan^{-1}\frac{2x_1}{S}\right] \quad (8)$$

From equations (1) and (8) the capacitance to the neutral plane, between x_1 and x_2

$$C = \frac{10^9 k}{2\pi v^2 \log_\epsilon \frac{S}{r}} \left[\tan^{-1}\frac{2x_2}{S} - \tan^{-1}\frac{2x_1}{S}\right] \quad (9)$$

The capacitance between an infinite neutral plane and conductor of radius, r, $\frac{S}{2}$ from the neutral plane, $x_1 = 0$ and $x_2 = \infty$

$$C = \frac{(2)10^9 k}{2\pi v^2 \log_\epsilon \frac{S}{r}} \left(\frac{\pi}{2} - 0\right) = \frac{10^9 k}{2 v^2 \log \frac{S}{r}}$$

farads per centimeter of conductor (10)

Substituting dimensions of test circuit and conversion factors in equation (10) for infinite neutral plane ($k = 1.0$)

$$C = \frac{(2.54)(12)(10^9)(1)}{(2)(9\times10^{20})(2.303)\log_{10}\frac{S}{r}}$$

$$= \frac{7.35\times10^{-12}}{\log_{10}\frac{S}{r}} \text{ farads per foot of line} \quad (11)$$

For test plate 71.8 centimeters wide, 24 inches, (60.95 centimeters) from conductor, $x_1 = 0$, and $x_2 = 35.9$ centimeters, from equation (9)

$$C = \frac{(2)(10^9)k}{2\pi v^2 \log_\epsilon \frac{S}{r}} \left[\tan^{-1} \frac{71.8}{121.9} - \tan^{-1} 0 \right]$$

$$= \frac{(2)(10^9)k}{2\pi v^2 \log_\epsilon \frac{S}{r}} (0.167\pi)$$

$$= \frac{(0.167)(10^9)k}{v^2 \log_\epsilon \frac{S}{r}} \text{ farads per centimeter} \qquad (12)$$

In air, from equation (12)

$$C = \frac{(0.167)(10^9)(12)(2.54)}{9(10^{20})(2.303)\log_{10} \frac{S}{r}}$$

$$= \frac{2.45 \times 10^{-12}}{\log_{10} \frac{S}{r}} \text{ farads per foot of plate} \qquad (13)$$

For test plate 71.8 centimeters wide, 36 inches (91.4 centimeters) from conductor, $x_1 = 0$, and $x_2 = 35.9$ centimeters, from equation (9)

$$C = \frac{(2)(10^9)k}{2\pi v^2 \log_\epsilon \frac{S}{r}} \left[\tan^{-1} \frac{71.8}{182.8} - \tan^{-1} 0 \right]$$

$$= \frac{(0.1192)\pi(10^9)k}{\pi v^2 \log_\epsilon \frac{S}{r}} \text{ farads per centimeter of plate} \qquad (14)$$

In air, from equation (14)

$$C = \frac{(0.1192)(12)(2.54)(10^9)}{(9)(10^{20})(2.303)\log_{10} \frac{S}{r}}$$

$$= \frac{1.752 \times 10^{-12}}{\log_{10} \frac{S}{r}} \text{ farads per foot of plate} \qquad (15)$$

SAMPLE CALCULATION FOR NO. 10 COPPER WIRE

Radius $r = 0.0495$ inches

Spacing $S = 48$ inches

$$\log_{10} \frac{S}{r} = \log_{10} 970 = 2.9868$$

Substituting in equation

$$C = \frac{2.45 \times 10^{-12}}{2.9868}$$

$$= 0.820 \times 10^{-12} \text{ farads per foot}$$

$$= 0.820 \text{ micromicrofarads per foot of plate}$$

DERIVATION OF EQUATION FOR CALCULATING CAPACITANCE FROM CONDUCTOR TO TEST PLATE FROM EXPERIMENTAL DATA

SYMBOLS:

C = capacitance

E = voltage, volts maximum

E_n = voltage, volts to neutral, maximum

E_n' = voltage, volts to neutral, effective

I_c = charging current, amperes maximum

x_c = capacitive reactance

f = frequency, cycles per second

Test plate length = 202.5 centimeters = 6.64 feet

EQUATIONS:

In any circuit the capacitive reactance

$$x_c = \frac{E}{I_c} = \frac{1}{2\pi f C} \qquad (16)$$

Then the capacitance from the conductor to the test plate is

$$C = \frac{I_c}{2\pi f E_n} \qquad (17)$$

Substituting constant values in equation (17)

$$C = \frac{I_c}{(6.28)(59.5)(6.64)(1.414)E'_n}$$

$$= \frac{2.85\ I_c}{E'_n} \times 10^{-4} \text{ farads per foot of plate} \qquad (18)$$

SAMPLE CALCULATIONS FOR NO. 10 COPPER WIRE SPACED 24 INCHES FROM NEUTRAL PLANE

$I_c = 77.5 \times 10^{-6}$ amperes (= 77.5 microamperes)

$E'_n = 2.5 \times 10^{4}$ volts (= 25 kilovolts)

Substituting in equation (18)

$$C = \frac{(2.85)(77.5)(10^{-6})}{(2.5)(10^{4})} = 0.884$$

micromicrofarads per foot of plate

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