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Title A STUDY OF DIRECT-CURRENT CORONA ON PARALLEL WIRES IN AIR

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In this paper are presented the results of a study of d-c corona phenomena in air. Two conductor arrangements were employed, a conductor opposite a paralleling plane and two parallel conductors. Considerable emphasis has been placed on the method of measuring the high, continuous voltage and resulting corona current. The study includes a brief summary of past investigations.

Three conductor arrangements have been commonly used in corona investigations, namely; concentric cylinders, a wire opposite a conducting plane and parallel wires. Due to certain inherent advantages the first of these has received far the greatest amount of attention, however, the parallel wire arrangement may become of great practical importance. Recent investigations have indicated that the results of d-c tests previously obtained with the concentric cylinder method are not directly applicable to the

case of parallel conductors in air. A fundamentally different condition exists in the case of concentric cylinders (as is also true of the conductor-to-plane arrangement) the d-c corona discharge current results from ionization at one conductor only. The d-c corona discharge current from parallel conductors on the other hand is due to the ionization from two sources of opposite polarity, hence the ionic carriers of both signs take part. The presence of charged carriers of both signs in the space between the conductors partially neutralize the space charge and results in a greatly increased current.

Corona current characteristics were obtained for wire sizes No. 12 AWG and No. 10 AWG by means of the conductor-to-plane and parallel wire arrangements. A limited amount of data was obtained with a No. 8 AWG conductor weathered and polished.

A maximum continuous voltage of approximately 90 kilovolts between lines or 45 kilovolts to ground was available from two diode rectifiers or kenotrons in conjunction smoothing capacitors. The resulting ripple voltage was inappreciable, remaining always less than 0.15 per cent.

Continuous voltage indications were afforded by a high voltage inverted vacuum tube voltmeter. The actuating voltage was obtained from a suitable tap in the water-tube leak resistor provided across the smoothing capacitors from line to ground. The voltmeter was calibrated against a standard 6.25 centimeter sphere gap placed between lines and also from line to ground.

The d-c corona current from line to ground plane was measured by means of an indicating microammeter placed in the ground lead of the active section of plane. The parallel wires were maintained at equal but opposite potential with respect to ground, thus necessitating the use of a microammeter shield suitably lighted to permit observation of the microammeter through a telescope. An electrical damping circuit was employed to indicate the average value of the rapidly fluctuating corona current. Special precautions were taken to prevent the insulator leakage current passing through the microammeter.

The results obtained were found to be in apparent agreement with those of previous investigators. Peek's expression for critical voltage determined for the case of a-c corona on parallel conductors yields results which are roughly one to two per cent lower than those observed with the positive d-c conductor to plane tests. The positive critical voltage for the polished conductors was consistently lower than the negative which Whitehead has pointed out as in accord with the theory of ionization, assuming that electrons are the chief source of ionization.

The d-c critical voltage for parallel wires was lower than the lower wire-to-plane value by an appreciable amount. Stockmeyer's curves seem to indicate the same trend.

In the range of voltage tested the d-c volt-ampere characteristic curves for parallel wires are very similar in appearance to those obtained with a single wire opposite a plane. In either case each characteristic curve may be divided into two branches. The first or lower branch is the more difficult to determine. It is very sensitive to the surface conditions, and is not linear, simulating somewhat one leg of a parabola. As the voltage is further increased the current characteristic enters the second branch which is a linear function of the voltage.

While the characteristic curves for the two arrangements evidenced considerable similarity it was found that the magnitude of the corona current from the parallel wire arrangement was many times that from the conductor-to-plane arrangement.

A STUDY OF DIRECT-CURRENT CORONA ON PARALLEL WIRES IN AIR

by

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and
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I. INTRODUCTION

Although a direct-current (Thury) system of high-voltage transmission has been employed in Europe for some time, the use of direct-current in the long-distance transmission of large blocks of electric power has only recently received very serious consideration in this country. Progress in the development of reliable, high capacity equipment capable of converting alternating current to direct-current at high voltages and vice versa has stimulated considerable interest in the possibility of securing the advantages inherent with the use of high continuous, transmission voltages. Indeed, the use of high-voltage direct-current system for transmitting a part of the power from Bonneville dam has been seriously proposed. While the Bonneville line would be admittedly a trial installation, it would, if successful, undoubtedly provide the impetus necessary for a wider adoption of high-voltage d-c power transmission in the future.

Progress in this field will bring with it a demand for information relative to the behavior of transmission line conductors subjected to high, continuous potentials. In particular data will be required concerning (1) the relation between the voltage and spacing at which the electric discharge known as corona takes place from various conductors, and (2) the magnitude of the power loss resulting from the corona discharge.

The general lack of interest in high-voltage d-c transmission previously cited has resulted in but little work on the subject of direct-current corona being reported in the literature in this country, especially in recent years. Some work has been done abroad, notably by DeFassi[2] in Italy, Stockmeyer[11], Strigel[12] and Marx and Goeschel[5] in Germany. Consequently, one may reasonably expect that the next few years will see a good deal of work done on this important subject.

Much of the previous work has been carried out by the concentric cylinder method of investigation in which case the field surrounding the conductor in corona contains charged carriers largely of one sign. On the other hand the d-c corona current from the important parallel wire arrangement is due to the charged carriers of both signs. A direct comparison of the d-c corona current characteristics resulting from a single source of ionization with that resulting from two sources of opposite polarity thus becomes of practical as well as fundamental importance. Although the data are limited in scope the results reported herein demonstrate that there is a very wide difference in the magnitude of the d-c corona discharge current from a single wire opposite a plane as compared with the discharge from parallel wires, the normal electric field in the absence of space charge being identical.

Since the procedure and methods of measuring the high d-c potentials and resulting corona current are not yet standardized, a good deal of emphasis is placed on that phase of the work in the present paper.

II. REVIEW OF STUDIES MADE BY OTHER INVESTIGATORS

A brief summary of a representative part of the work done by other investigators on d-c corona phenomena in air is given. In preference to following a chronological order four subdivisions are employed, namely: Methods of Study, Conductor Surface Gradient, D-C Corona Current from Concentric Cylinders and D-C Corona Current from Parallel Wires.

Methods of Study

There are three main conductor arrangements that have been employed in the investigation of corona phenomena: a wire in a coaxial, conducting cylinder; a wire opposite a parallel, conducting plane; and two parallel wires. The first of these has received far the greatest amount of attention due to its several inherent advantages. 1. The dielectric flux between a conductor not in corona and a concentric cylinder are easily and exactly determined. 2. The conditions within the cylinder are readily controlled with regard to temperature, pressure, humidity and the type of gas surrounding the conductor. 3. High gradients may be established at the conductor surface with relatively low voltage.

The so-called concentric cylinder method is particularly well suited to the determination of the critical surface gradients of various wire sizes and the effect of temperature, pressure, humidity and type of gas.

The second arrangement is well adapted to simulating the conductor to neutral plane condition for parallel conductors under test conditions which are not influenced by ion migration from both conductors. The dielectric field between a conductor and an infinite conducting plane at a spacing S/2 from the conductor is identical to half the field between two parallel conductors at a spacing S, the potential difference between conductor and plane being one half that between the parallel conductors. It is pointed out in the paper "Some Characteristics of A-C Conductor Corona" by F. O. McMillan[6] that this condition may be approached closely with a conducting plane of practical dimensions. With the use of shielding plates an area near the center of the plane can be obtained in which the flux concentration closely approaches that of the infinite plane.

Until more recently little work has been done using parallel conductors. In order to minimize the effect of proximate grounds the conductors may be maintained at an equal but opposite potential above ground. This necessitates operating a current indicating instrument at a high potential with respect to ground. The practical value of the parallel conductor arrangement lies in its application to studies of direct current corona loss. This arrangement alone permits the unhampered flow of ions of each sign originating in the space between two conductors of opposite polarity in corona.

Conductor Surface Gradient

Much of the early work of Peek and Whitehead was directed toward the determination of the very important critical surface gradient. The classical expression for the surface gradient g of a wire in a coaxial cylinder is written

$$g = \frac{e}{r \log_\epsilon R/r} \qquad (1)$$

in which r is the wire radius, R the cylinder radius and e the applied voltage. Peek[8] demonstrated further that the surface gradient on the line of centers of parallel conductors is given by an expression of identical form provided that the conductor spacing S is large relative to the conductor radius r. That is:

$$g = \frac{e_n}{r \log_\epsilon S/r} \qquad (2)$$

in which e_n is the voltage to neutral.

The critical or corona forming gradient at the conductor surface is of course not a function of the spacing, provided the spacing is large relative to the wire radius. To Peek[7] is due the empirical relation giving the so-called visual critical gradient g_v in terms of the conductor radius r and the critical gradient for air g_o

$$g_v = g_o \left(1 + \frac{k}{\sqrt{r}} \right) \tag{3}$$

in which g_o and k are experimentally determined constants.

Including the experimentally determined effect of the air density factor δ equation (3) was written in the familiar form:

$$g_v = A\delta + B\sqrt{\frac{\delta}{d}} \tag{4}$$

Here

g_v = Critical potential gradient at the surface of the conductor in Kv/cm.

d = Diameter of wire in centimeters

δ = Air density factor $= \dfrac{3.92\ P}{273 + t}$

(1 at 76 cm hg and 25 degrees C.)

t = Temperature in degrees Centigrade

P = Absolute pressure in Centimeter of Hg

A & B = Experimentally determined constants

The constants A and B as determined from several investigations are listed in Table I.

TABLE I

LIST OF SOME EXPERIMENTALLY DETERMINED
VALUES OF THE CONSTANTS A AND B FOR THE DETERMINATION
OF CRITICAL SURFACE GRADIENTS

Investigator	Polarity of Conductor	Constants A	Constants B	Reference
*Peek	A. C.	29.8	12.7	8b
Peek	A. C.	31.0	13.5	8b
Whitehead	A. C.	32.0	13.4	18
*Farwell	Positive	31.6	8.47	18
	Negative	38.0	8.06	
Whitehead & Brown	Positive	33.7	11.5	18
	Negative	31.0	13.5	
	A. C.	33.7	12.6	
Whitehead & Lee	Positive	39.8	10.36	19
	Negative	40.3	11.91	

Asterisks indicate investigator employed parallel lines. Other data refers to concentric cylinders.

The relatively wide variation in the results indicated by Table I may be credited in part to the surface condition of the conductors tested. That the surface condition does greatly influence the critical voltage has been demonstrated by several. Whitehead[15] in an early paper reported a 33 per cent decrease in critical voltage due to dirt or surface impurities. At a later date he observed that rubbing the conductor for cleaning purposes introduced discrepancies in results unless the conductor was permitted to stand for several minutes[17]. Walter Stockmeyer[11] more recently reported a decrease of close to 30 per cent in the critical voltage from a roughned wire surface as compared to a smooth wire of 8 mm diameter. These results emphasize the importance of specifying closely the surface condition of the conductor under test.

D-C Corona Current from Concentric Cylinders

One of the early expressions relating the corona discharge current and voltage from a conductor in a coaxial cylinder was that of J. E. Almy[1].

$$i = \frac{C \; E\,(E - E_o)}{R^3} \qquad (5)$$

Here E represents the impressed voltage, E_o the critical voltage, R radius of the cylinder and C an experimentally determined constant.

More recently Walter Stockmeyer[11] reported that his results obtained with wire sizes ranging from 1 to 20 millimeters in diameter in an 80 centimeter cylinder and a maximum d-c potential of 170 kilovolts were in good agreement with Almy's formula. However, he found the relation of C as a function of R to be more nearly $C = 1/R^{1.82}$ so that his final results were expressed:

$$i = \frac{37 \quad E(E - E_o)}{R^{1.82}} \quad mA/Km \qquad (6)$$

Based on his theory of ionization Townsend[14] proposed the expression

$$i = \frac{2k \; E\,(E - E_o)}{R^2 \log_\epsilon (R/r_o)} \qquad (7)$$

in which k is a function of the ion mobility and R and r_o the outside cylinder and wire radius respectively.

Schaffers[10], basing his derivation on a solution of Poisson's equation, arrives at the relation

$$i = \frac{k}{2} \left[\frac{E - E_o}{R \log_\epsilon (R/r)} \right]^n \qquad (8)$$

in which the exponent $n = f\,(R/r)$ and r is the outer radius of the corona sheath. The value of n is equal to $\log_{10} (R/r)$ and increases progressively as the ratio R/r approaches 100 but never exceeds the value 2.

In 1934 DeFassi[2] conducted tests in Italy using both the concentric cylinder and parallel wire arrangements. From a solution of Poisson's equation DeFassi arrived at the following expression for the current i for concentric cylinders:

$$i = \frac{k}{2} \frac{(E - E_o)^2 \left[1 + \frac{1}{\log_\epsilon (R/r)}\right]^2}{R^2} \frac{10^{-5}}{9} \text{ A} \quad (9)$$

While equations 7, 8, and 9 are allegedly on a rational basis the nature of the assumptions involved should be kept in mind. For example the so-called "corona sheath" is not always continuous, hence r is by the nature of the phenomena a kind of average value difficult of determination. Likewise the mobility k is not a simple constant but a function of a number of factors including not only atmospheric conditions but the ion "age". An assumption of fundamental nature enters DeFassi's solution, namely:

$$\int_r^R dV = (E - E_o) \quad (10)$$

That is, the voltage drop V within the radius of the "corona sheath" is thus arbitrarily made equal to the critical voltage.

While many factors enter to render an exact solution for the corona current difficult the preceding formulas represent a summary of both the experimental and theoretical work involving the concentric cylinder arrangement. Stated briefly, the d-c corona current has been found to vary directly as the applied potential raised to a power approaching two and inversely as the radius of the outer cylinder raised to approximately the second power. It should be observed here that in order for Peek's well known quadratic law of corona power loss, expressed as a function of voltage, to hold; the corona current must be a linear function of voltage.

It is of interest that Marx and Goeschel[5] have found that within the range of voltage tested the d-c and a-c corona power loss from a wire in a coaxial cylinder are closely comparable when based on the crest values of a-c voltage.

D-C Corona Current from Parallel Wires

Very little work has been directed toward the formulation of an equation representing the d-c corona current from parallel wires. DeFassi has relied on his equation for the case of a wire in a concentric cylinder making certain modifications to fit the observed physical differences in the phenomena from parallel conductors. The critical voltage for parallel wires was assumed that of the negative wire (it being the lower value according to his results) and the corona current was assumed equal to the sum of the current due to the passage of negative ions in the one direction and positive ions in the opposite direction. The equation in its final form follows.

$$i = (k_n - k_p)\frac{(E - E_o)^{\log_{10}(E - E_o)}}{S^2}\left[1 + \frac{1}{\log_\epsilon(S/r)}\right]^2 \frac{10^{-5}}{9} \text{ A.} \qquad (11)$$

In which S represents the spacing between lines in centimeters and $(k_n - k_p)$ the difference in negative and positive ion mobility. The exponent log $(E - E_o)$ was found to give results in better agreement with the experimental results than the exponent 2. With the 3 mm wire at 66 cm spacing the predicted results are in acceptable agreement with the experimental, however at 33 cm spacing the predicted values are much higher than the calculated.

In 1932 Yoshio Satoh[9] completed considerable work on the experimental determination of the space potential between electrodes in corona. The application of his results presented in a later Japanese publication appears to be of particular interest. Quoting from the English synopsis: "The electric field around a conductor in d-c corona is theoretically considered in two regions, the region of ionization and that of ionic transportation, and by employing the condition of continuity at the boundary of these two regions, the solution of the field as a whole is obtained." His calculated and experimental values of corona current plotted as a function of the voltage indicate a good agreement.

In a recent paper Robert Strigel[12] of Germany presented a comprehensive study of a-c and d-c corona loss from parallel conductors. These comparative tests were conducted outdoors with stock wires ranging from 1 to 25 mm in diameter and an available potential difference of 280 Kilovolts a-c or d-c. Based on crest values of voltage the difference in the a-c and d-c corona current was relatively small. It is noteworthy that Strigel found both the a-c and d-c corona loss characteristic curves to be definitely discontinuous in nature, consisting of two branches. The lower branch represents the loss from surface irregularities and the second that due to intense general corona.

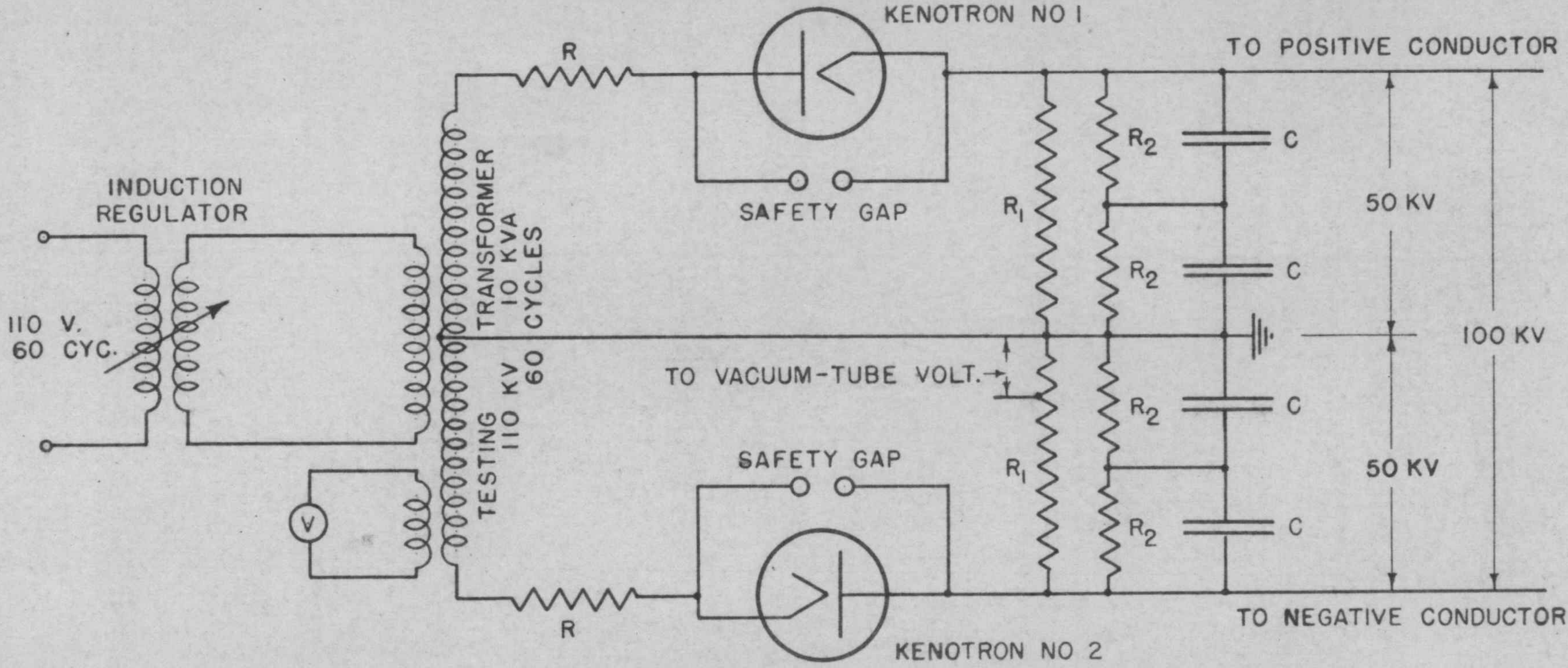
Walter Stockmeyer[11] reports the results of a preliminary test comparing the d-c corona current from the wire-to-plane arrangement with that from the parallel wire arrangement. These results will be discussed in a later section of this paper.

III. DIRECT-CURRENT POWER SUPPLY

The continuous potentials used in this investigation were obtained by employing the circuit schematically shown in Figure 1. As indicated in the figure, the conductors to be investigated were charged to equal, unidirectional potentials above and below ground potential respectively by rectifying the high-voltage output of a 110 kilovolt, 10 kilovolt-ampere, 60-cycle testing transformer. Smooth, easily adjusted control of the high-voltage output was afforded by exciting the testing transformer through a single-phase induction regulator connected to the 110-volt, 60-cycle, laboratory busses.

As further indicated in Figure 1, the half-wave rectification employed was obtained by using two high-vacuum, diode rectifiers or kenotrons having a peak inverse voltage rating of 100 kilovolts, and a maximum instantaneous current rating of one ampere. The very appreciable illumination supplied by the incandescent kenotron filaments was eliminated by enclosing the kenotrons in light shields or hoods constructed of bakelite impregnated paper tubes to withstand the necessary voltage and provided with sufficient ventilation for cooling.

With this type of rectification the potential impressed upon the conductors would consist of a series of unidirectional pulses if provision were not made for main-



R = 0.2 MEGOHM R_2 = 70 MEGOHMS
R_1 = 140 MEGOHMS C = 1 MICROFARADS
EQUIVALENT RESISTANCE ACROSS EACH CAPACITOR = 52 MEGOHMS

FIG. 1 - SCHEMATIC DIAGRAM OF CIRCUIT USED IN OBTAINING HIGH, CONTINUOUS POTENTIALS

taining the conductor potential during the alternate half-cycles of the alternating voltage in which the kenotrons are non-conducting. In the present case, the necessary smoothing of the rectified voltages applied to the conductors was obtained by connecting capacitance between each conductor and ground as shown in the figure. The capacitors available had a capacitance of one-half microfarad and a voltage rating of 25 kilovolts d-c. Since eight such units were available a series-parallel combination was used as shown in Figure 2, which gave an equivalent capacitance between each conductor and ground of one-half microfarad.

It has been found that capacitors in series subjected to high continuous potentials tend to divide the total voltage in proportion to their respective leakage resistances, so that there is a resultant tendency toward an increasingly unequal division of voltage between the capacitors involved[4]. This, if allowed to proceed, results in either a capacitor failure or spark-over of a suitable protective gap. The lesser of these two evils would disrupt the continuity of a set of data, and is therefore undesirable.

The difficulty described above was avoided in the present instance by connecting voltage equalizing resistances of suitable value across each capacitor. The resistances used consisted of glass tubing through which

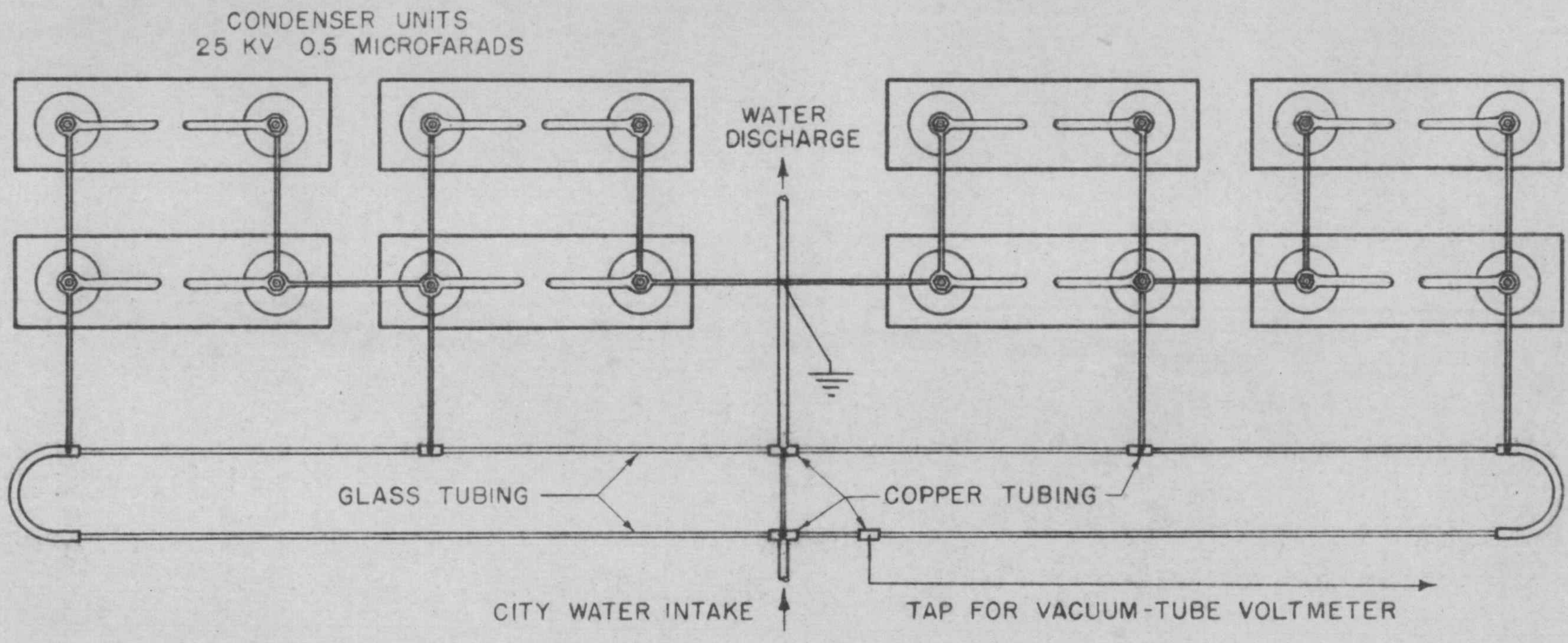


FIG. 2 - PHYSICAL PLAN OF SMOOTHING CAPACITORS AND VOLTAGE BALANCING RESISTOR CONNECTIONS

water was continually circulated at a velocity sufficient to prevent appreciable heating. The values of resistance selected were of such a magnitude that proper division of the voltage between capacitors was maintained without appreciably impairing the voltage-smoothing function of the capacitors. The water-tube resistors were also found useful in developing a voltage measuring device to be described in a later section of this report.

The source of continuous potential described in the preceding paragraphs was found to perform very satisfactorily throughout the investigation. The ripple voltage may be calculated from the expression:

$$\Delta E = \frac{i \, \Delta t}{C} \qquad (12)$$

Assuming a most unfavorable condition; for example the maximum possible time of discharge, one cycle (60-cycle source), a corona discharge current of one milliampere and a one milliampere drain through the voltage balancing resistors the ripple voltage with respect to ground is

$$E = \frac{2 \quad 10^{-3} \text{ milliamp.} \quad 1.66 \quad 10^{-2} \text{Sec}}{0.5 \quad 10^{-6} \quad \text{farads}} = 66.4 \text{ Volts} \qquad (13)$$

Thus expressed as a per cent of the applied potential to ground (45 kv in this case) the ripple voltage never exceeded 0.15 per cent and generally was much less.

IV. DIRECT-CURRENT VOLTAGE MEASUREMENT

In any investigation of the corona phenomena, it is, of course, of extreme importance that rapid, accurate determination of the voltages impressed upon the electrodes under observation be made readily. For this reason, a fairly extensive investigation of several available methods of measuring this important quantity was made. A brief summary of the results of this investigation is presented in the following paragraphs.

The high-voltage, testing transformer used was provided with an accurate voltmeter coil, and reasonably satisfactory voltage indications obviously could have been secured by simply using voltmeter-coil values in conjunction with the sphere gap. It was found, however, that a large change in the direct-current line voltage was represented by relatively a very small change in voltmeter-coil voltage over the useful voltage range. A few test runs served to demonstrate the disadvantage of the resultant low voltage sensitivity of this method. The test runs further demonstrated the desirability of a voltage-indicating device actuated directly by the voltage or a definite portion of the voltage to be measured. The investigation, therefore, was directed to the possibilities of the use of an electrostatic voltmeter which was available in the laboratory.

The electrostatic voltmeter available, which was of the oil filled type, had rated voltages ranges of 0-40, 0-80, and 0-120 kilovolts effective. Unfortunately, however, the voltmeter was designed for measuring a-c voltages and the two upper ranges were secured by the insertion of suitable built-in condensers in series with the active elements. This, of course, rendered the use of these two ranges out of the question, since the direct voltages used would have tended toward a distribution proportional to leakage resistances and not necessarily the capacities of the condensers.

Further investigation of the electrostatic voltmeter revealed it to be capable of indicating but slightly more than 25 kilovolts d-c with the voltage to be measured impressed directly upon the activating elements. A voltage divider was therefore required if the voltmeter was to be used in this manner, since the use of a maximum line to ground voltage of 50 kilovolts d-c was contemplated. Since the capacitor banks between each line and ground were shunted with bleeder resistances a maximum of 25 kilovolts could be obtained by connecting the electrostatic voltmeter to the half voltage junction point of either bank and the ground; assuming, of course, equal voltage division. There resulted a very uneven distribution of the total voltage between the capacitors due to the leakage and transient charging current required by the voltmeter. This was remedied to some extent by lowering the bleeder resistance. Even then satisfactory voltage indications could not be obtained. Wide line voltage fluctuations were indicated which could not possibly have occurred under the conditions existing at the time. This action was probably due to ionic migration through the oil within the voltmeter.

When the latter two devices were found unsatisfactory, a search was started for some other means of obtaining suitable voltage indications. It was suggested at this time that a vacuum-tube voltmeter of the slide-back type might prove suitable, a voltage proportional to conductor voltage being obtained by making suitable connection to the water-tube bleeder resistors connected across the capacitors. This would eliminate one of the causes which rendered the electrostatic voltmeter useless, namely: it would draw no current from the power source. However, this type of voltmeter was found very difficult to calibrate against the sphere gap, and was therefore unsuited for use in this investigation.

The experimental work with the slide-back type of vacuum-tube voltmeter suggested the possibility of using the three-electrode vacuum tube inverted, i.e., using the electrode nominally designated as the plate as a grid, and the nominal grid as a plate as previously described by Terman[13]. The several circuit constants and connections finally arrived at in applying the inverted triode as a voltage-measuring device are schematically shown in Figure 3. As indicated in this figure, a voltage proportional to the conductor voltage is obtained by making suitable connection to the water-tube, bleeder resistor, and the voltage thus obtained applied to the plate of the triode in such a manner as to make that electrode negative. As further indicated in the figure, a constant, positive, direct voltage (derived from storage cells) is applied to the nominal grid of the tube through a suitable resistance and a current-indicating device. Changes in conductor voltage thus result in proportional changes in the negative voltage applied to the plate of the triode which is acting as the grid. These voltages are reflected as changes in the current flowing in the grid which is acting as the plate and this current is indicated by a current-measuring device. Obviously, this arrangement is capable of being readily calibrated against the sphere gap to give continuous indication of the voltages impressed upon the conductors under observation.

The nature of the line to line and positive and negative line to ground voltage calibration curves obtained for the device are shown in Figure 4. However, the voltage values tabulated with the experimental data were not taken from the calibration curves, but were calculated from linear equations obtained by adjusting the calibra-

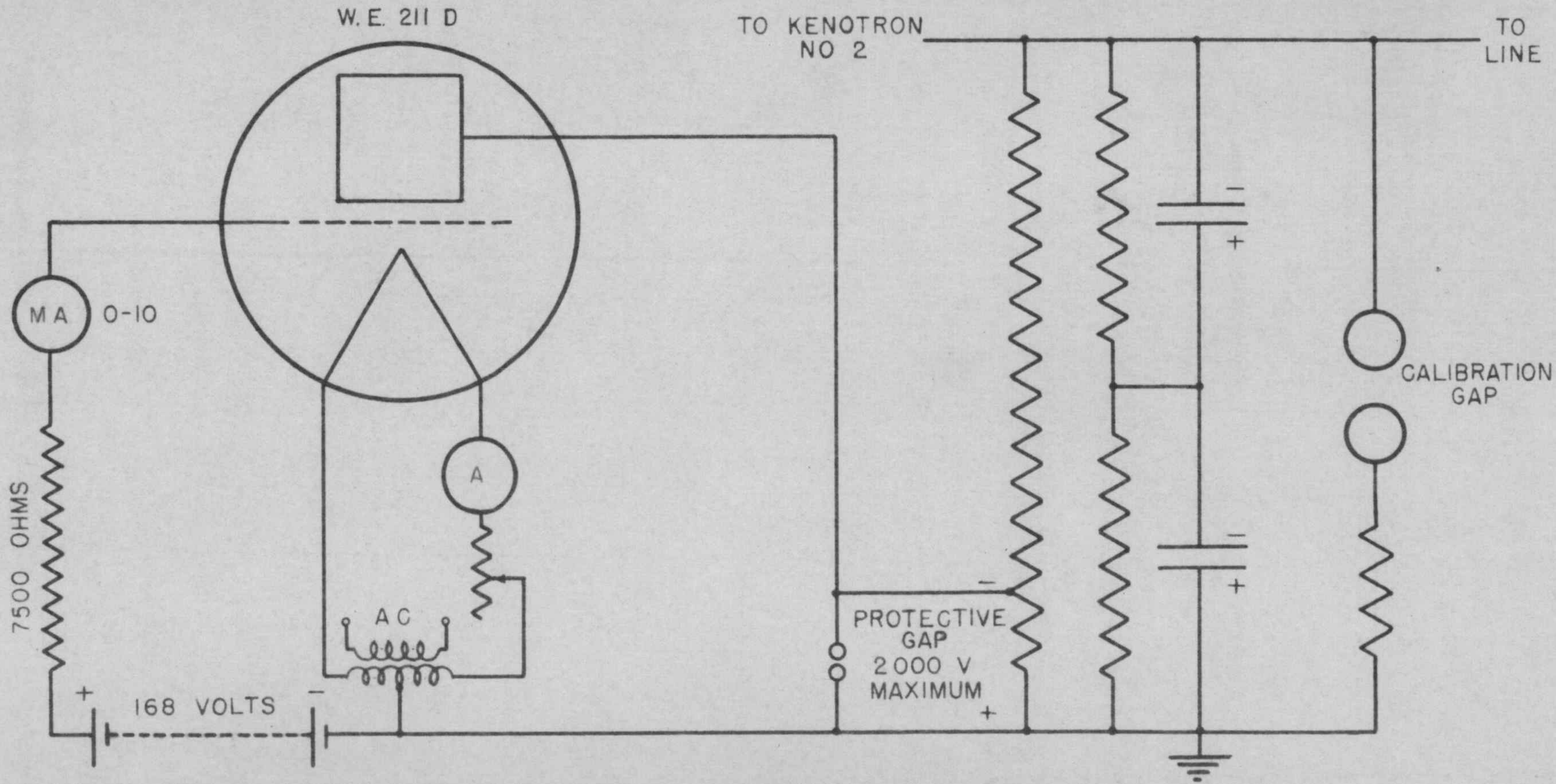
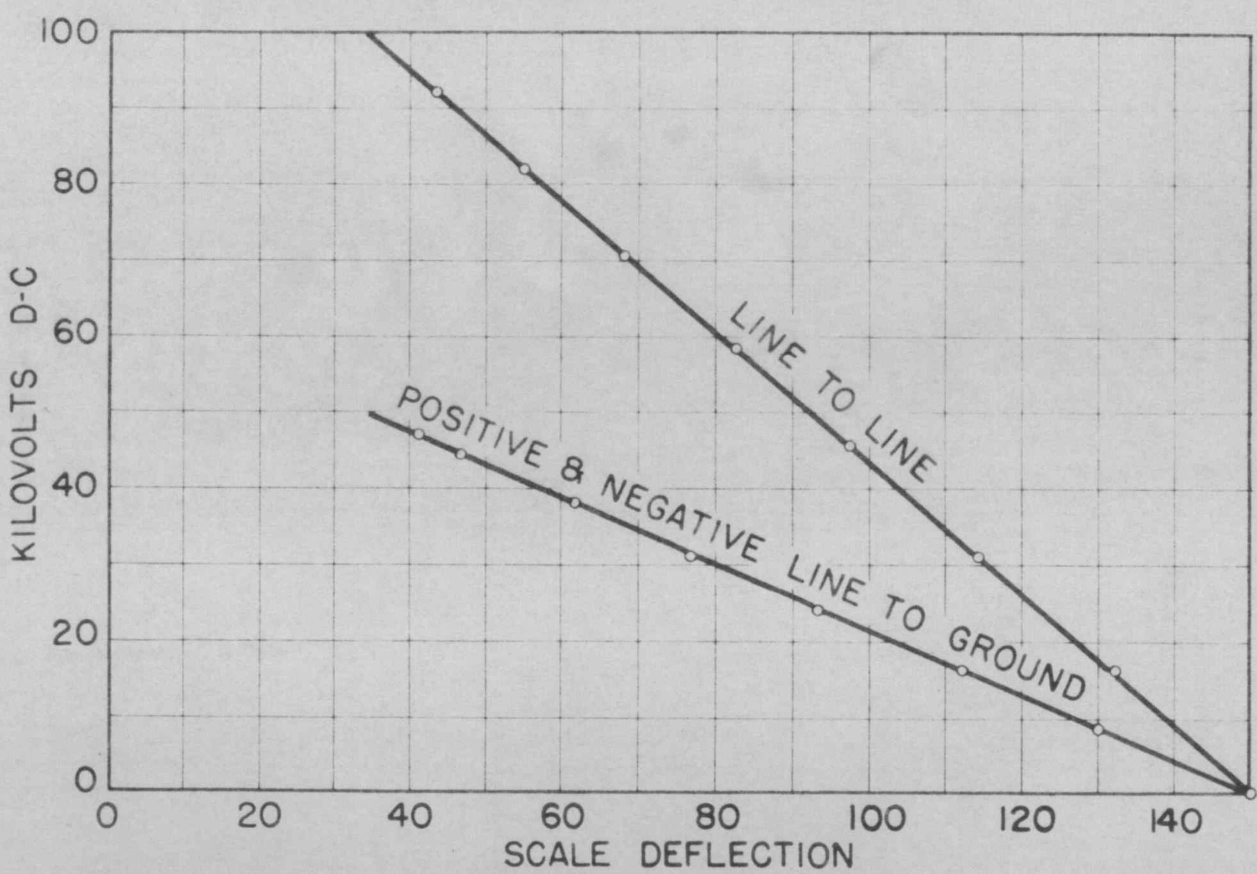


FIGURE 3
HIGH VOLTAGE, INVERTED VACUUM-TUBE VOLTMETER

FIGURE 4

CALIBRATION CURVES FOR HIGH VOLTAGE,
INVERTED VACUUM TUBE VOLTMETER



tion data by the method of least squares.

Two points which were found to be of importance in the application of the inverted triode as a voltage indicator should be discussed briefly here. First, as one would suspect, it is very important that the connection made to the water-tube, bleeder resistor be very positive and permanent in character. In the present instance, this end was attained by inserting a short length of copper tubing at an appropriate point along the water tube and utilizing a very rigid construction to prevent movement of the component parts. The second item of importance is the source of direct voltage used in the grid circuit which is functioning as the plate of the inverted tube. It was found essential that this voltage remain constant within very close limits. Storage cells in good condition proved satisfactory for this purpose. High capacity B batteries or a direct-current generator provided with an automatic regulating device probably would prove satisfactory. Recourse could be had to a continual adjustment of the voltage, but this would rob the device of much of its convenience. It may be possible, and would be preferable, to develop a bridge circuit utilizing two similar tubes in which slight changes in the nominal grid-circuit voltage would cancel out in their effect on the current-indicating device where the voltage source does not possess the necessary constancy.

V. DIRECT-CURRENT CORONA CURRENT MEASUREMENT

Measurement of the current flow resulting from direct-current corona discharges on two electrode configurations were made during the course of this investigation. The first series of measurements were made with two parallel wires as the electrodes, and the second series with a wire and a paralleling ground plane.

For the parallel wire arrangement, preliminary estimates based upon the results of previous investigators indicated that a direct-current microammeter having a range of 500 microamperes would be satisfactory. Later it was found desirable to extend the range of this instrument in order that the currents of nearly a milliampere encountered at the closer conductor spacings could be measured. This was easily accomplished by shunting the instrument with a non-inductive resistance of suitable value.

In the parallel wire arrangement, both positive and negative conductors were insulated from ground so that the microammeter when in use was at a high potential with respect to ground, and thus making it essential that the instrument be well shielded electrostatically. A spherical copper shield was obtained for the latter purpose. Facilities for moving the shield and instrument as occasion required and the necessary insulation from ground were provided for by suspending the shield from an overhead trolley with sticks of oil-treated maple. A suitable system for illuminating the microammeter scale was installed within the shield. The fact that the microammeter used was designed to perform in either a horizontal or vertical position eliminated any necessity for the use of mirrors in the shield. Of necessity instrument deflections were observed through a telescope.

Some difficulty was experienced in the first few attempts at securing the volt-ampere characteristics of the corona discharge due to the rather violent and rapid fluctuations of the microammeter needle. At first it was thought that this was due principally to too great a ripple component in the voltage being impressed upon the conductors, but an investigation showed that such was not the case. Then it was decided that since, apparently, the fluctuations in current observed were a characteristic of the phenomenon, some method of obtaining a representative average value of the current would have to be devised. As a first method, instantaneous observations of the microammeter deflections were recorded regularly over an interval of from one to two minutes and the results averaged. While this method gave reasonably satisfactory results, it was very unsatisfactory from the standpoint of the time consumed and the possibility of not obtaining a truly representative average value.

The following method of obtaining suitable averaging of the current values was considered, but was not used because it was felt that the use of an indicating instrument was to be preferred. In this method, it was proposed that suitable capacitors be connected in series with the conductors, and short-circuiting switches and spark gaps be connected across the capacitors. Then, by applying the desired potential to the conductors, opening the short-circuiting switches across the capacitors, and noting the time elapsing between opening of the switches and spark-over of the gaps, the average value of the current flow could be determined from the relation:

$$I_{avg} = (CE)/t \qquad (14)$$

In the above relation, I_{avg} is in microamperes when C is the capacitance of the capacitors used in microfarads, E is the sparking voltage of the gaps used in volts and t is the time interval in seconds between opening of the short-circuiting switches and spark-over of the gaps. A suitable voltmeter of the electrostatic type could be substituted for the spark gaps in the above arrangement.

It was proposed that reliable averaging of the corona current could be obtained by the use of suitable values of capacitance and resistance in conjunction with the 0-500 microammeter previously described. Accordingly, the behavior of the instrument when used with various values of capacitance and resistance connected as shown in

Figure 26 in the appendix was investigated. The combination chosen removed most of the violent fluctuations indicated by the instrument without impairing the response of the instrument too greatly. This method was employed throughout the investigation with very excellent results. A mathematical demonstration of the fact that the combination of resistance and capacitance described above will give average current values is to be found in one of the appendices.

It will be noted that the device described above does nothing more or less than to increase, in effect, the damping of the microammeter. Comparable results could probably be obtained more simply by employing an instrument having greater natural damping.

The conductors were first suspended from 1 x 3 x 28 inch oil impregnated maple insulators. However, the microammeter indicated an appreciable current before the appearance of corona. A Locke suspension type porcelain insulator No. 18090 added to each end of the line in addition to the maple insulation reduced the leakage appreciably but not completely. The high voltage lead was then tapped between the source of d-c potential and the microammeter and connected between the porcelain and maple insulation at each end of the line containing the microammeter as shown schematically in Figure 5. The voltage differential across the porcelain was thus practically zero and

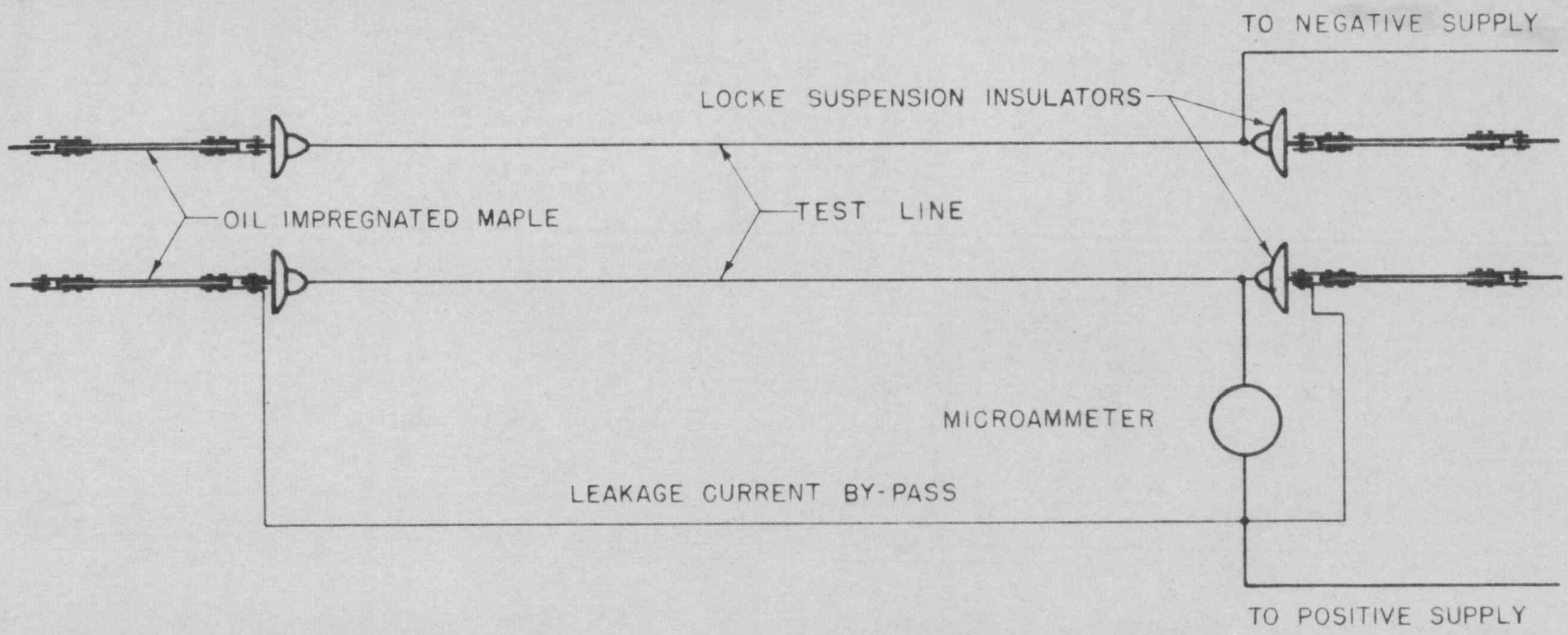


FIG. 5 - DIAGRAM OF CIRCUIT DESIGNED TO PREVENT THE INSULATOR LEAKAGE CURRENT FROM PASSING THROUGH MICROAMMETER

the leakage current was effectively shunted around the microammeter.

Measurement of the current flow to a ground-plane collector from a single wire in corona presented little difficulty. The active section of the ground-plane was simply grounded through a suitable current-indicating instrument, and the resulting current recorded. The violent fluctuations in current observed with the parallel wire arrangement were not present in the ground-plane case, thus eliminating any necessity for the use of a current-averaging device.

Figure 6 is a general view of the laboratory arrangement for the parallel wire investigation. The spherical microammeter shield with its micarta tube, light guard is prominently displayed in the background. Beneath the shield is visible the capacitor bank to the right of which the d-c power source may be seen.

Figure 7 is another view of the laboratory showing the d-c power source and control table with the voltage measuring circuit in the foreground.

In Figure 8 is shown the wire-to-plane electrode arrangement. The central section is the collector plane which is grounded through a current measuring instrument not shown. The sections of plane bounding on every side the "active" section are directly grounded.

FIG. 6. LABORATORY ARRANGEMENT FOR PARALLEL WIRE CORONA TESTS

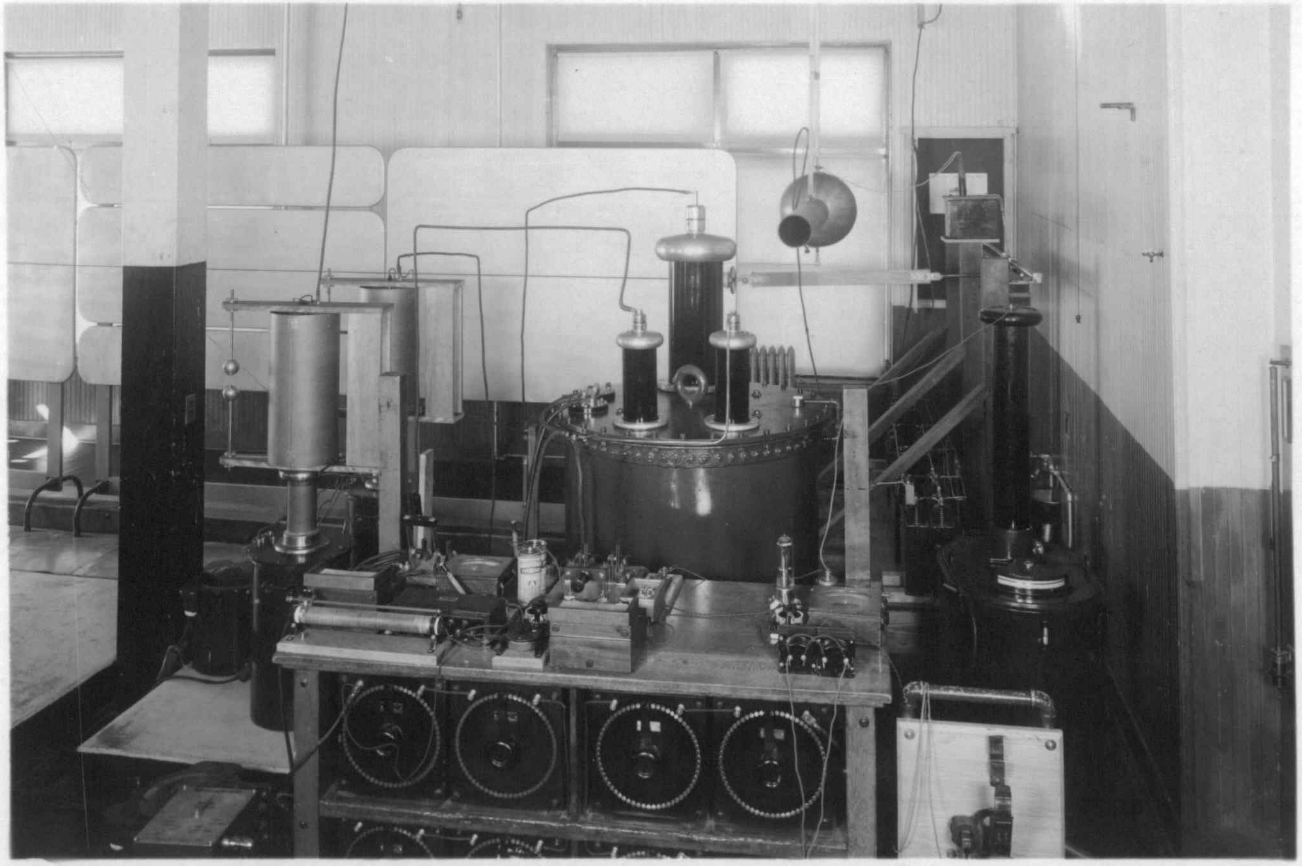


FIG. 7. LABORATORY HIGH VOLTAGE EQUIPMENT

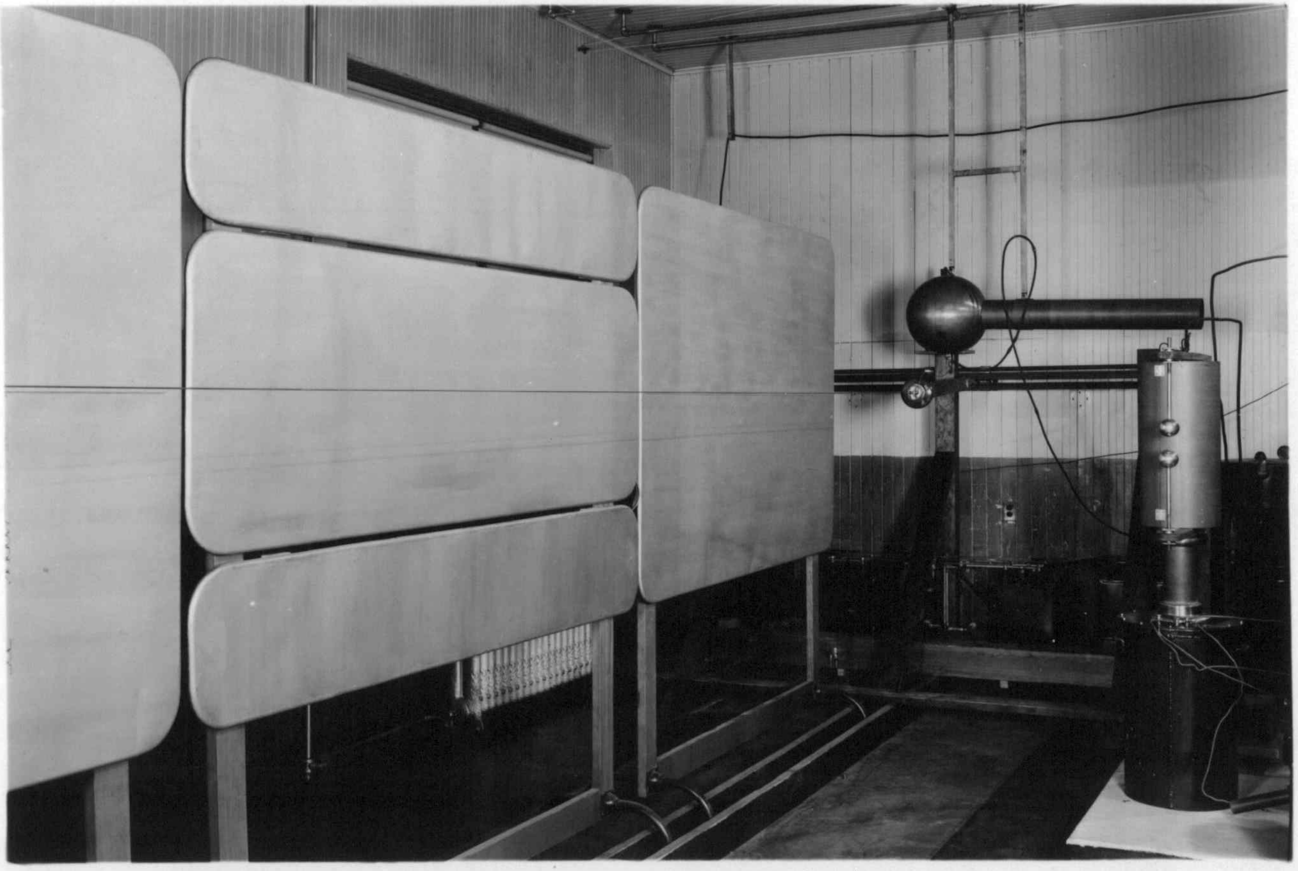


FIG. 8. ARRANGEMENT FOR CONDUCTOR-TO-PLANE TESTS

VI. PROCEDURE

The conductors were suspended from trucks which could be propelled in a horizontal direction along the back of the main supporting frame by means of a threaded shaft. This provided a means of adjusting the spacing while the conductors remained in mechanical tension.

After suspending a conductor preparatory to testing, the conductor was thoroughly cleaned with a metal polish, rubbed with a cloth dampened with denatured grain alcohol and then carefully polished with chamois skin. Preceding each succeeding change in spacing the conductor was simply cleaned with alcohol and polished with chamois skin.

A slowly increasing potential was applied between lines or from line to plane until the first definite current indication was observed and recorded with the corresponding voltage deflection. The voltage was increased further in uniform increments. At each increment the potential was maintained constant a few seconds to insure steady state conditions so far as the instruments were concerned and the resulting current and voltage deflections recorded. When a series of readings was interrupted for any reason it was found preferable to clean with alcohol, polish with chamois and repeat the entire series of observations.

It is noteworthy that a definite procedure must be specified and followed in this regard if the results are to be comparable. To illustrate, it was found that each succeeding series of readings following one polishing operation resulted in an increased current. The increased corona current may have been due to the accumulation on the wire surface of foreign particles electrically precipitated from the air. A careful scrutiny of the wire surface after exposure revealed the presence of foreign matter and a slight degree of tarnish. An attempt to reach a steady state condition by exposing the conductor to corona discharge for a period of time before recording results proved too time consuming and was in general unsatisfactory.

During the test barometric pressure as well as wet and dry bulb temperatures were recorded at approximately one hour intervals.

VII. DISCUSSION OF RESULTS

When a slowly increasing unidirectional potential difference was applied either between parallel conductors or a conductor and parallel conducting plane under observation in a dark room, the first evidence of ionization was the appearance of very small flashes along the conductor surface. These erratic flashes accompanied by a distinct hissing sound were observed at a potential appreciably below the so-called visual critical voltage. In the case of parallel conductors general corona apparently occurred simultaneously on both conductors.

The negative corona formed in the characteristic beads or tufts which evidenced considerable activity and appeared to be mutually repulsive. The positive corona was first evidenced by a pale bluish glow which on casual observation appeared to form a smooth sheath along the positive conductor. However, in the case of parallel wires a more careful examination revealed that the positive conductor was surrounded by ionized "bands", each band lying opposite a "bead" on the negative line. This phenomenon was more pronounced at close spacings. The general character of the direct current corona is shown by the photograph, Figure 9, which is in agreement with the observations of previous investigators.

It is noteworthy in this connection that a considerable portion of the corona radiation is of the ultra vio-

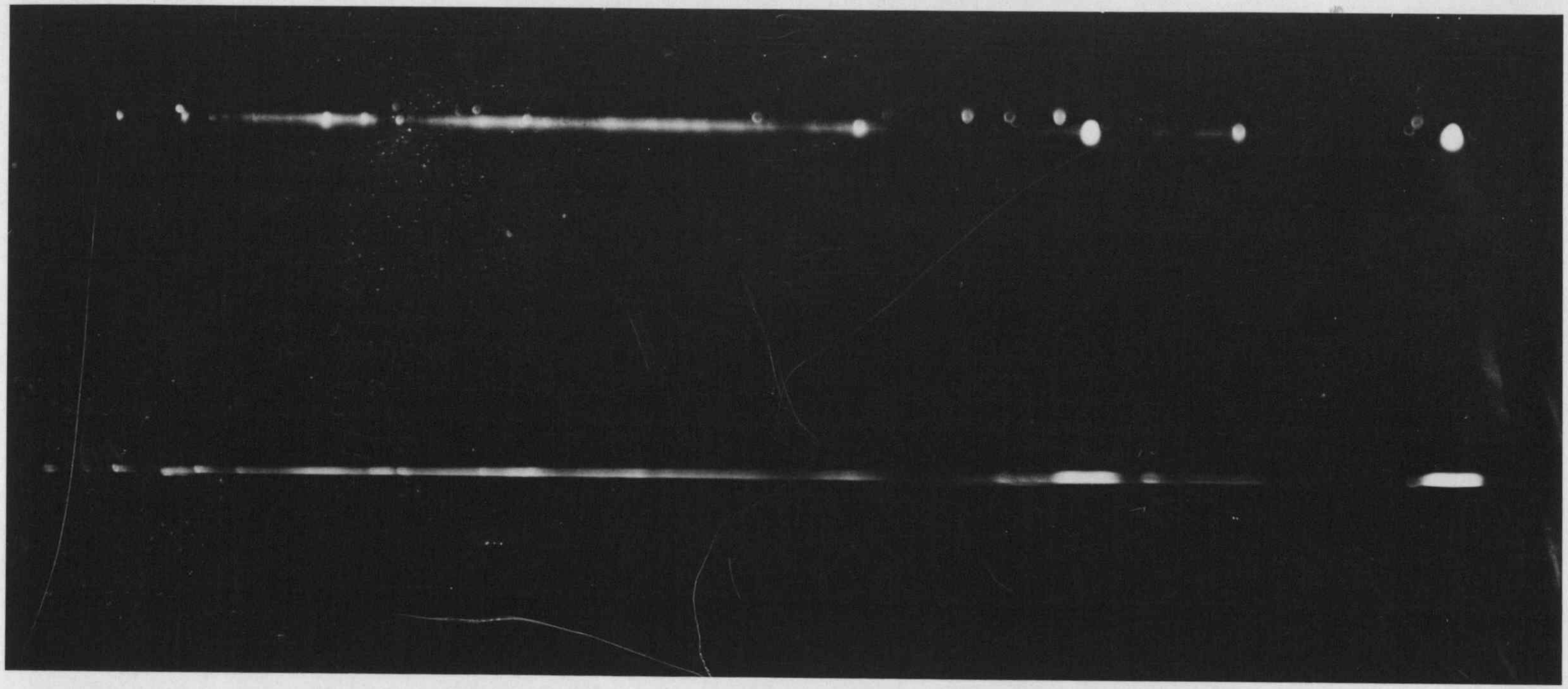


FIG. 9. CORONA ON PARALLEL CONDUCTORS
Polished Wires No. 10 AWG
Exposure Time Approx. 40 Sec.
4.5.f Glass Lense
Upper Wire Negative
Lower Wire Positive

let band not visible to the eye. Whitehead[16] compared the apparent corona diameter obtained from visual observations with those from photographs using both glass and quartz lens and found the ratio of diameters thus obtained to be 1 : 1.6 : 1.9 respectively. Misleading results might also be obtained by the difference in the required exposure time, the extended and less sharply defined boundary of the positive corona requiring a relatively greater exposure than the more intense negative beads.

Figures 10 - 13 represent the corona discharge current from a polished conductor to a ground plane. Two wire sizes were employed and the corona current characteristics indicated for both the positive and negative polarity. A distinct polarity effect will be noted from a casual observation of these curves. The positive volt-ampere characteristic curves, Figures 10 and 12, somewhat resemble one leg of a parabola, whereas the negative volt-ampere characteristics, Figures 11 and 13, are essentially straight lines. However, it will be observed that the non-linear portion of the positive corona current curves represent a starting phenomena, these curves also approaching a linear law as the voltage is increased.

The corona current curves were extrapolated where necessary to their intersection with the voltage axis and the critical voltages thus obtained recorded in Table II. While these values must be considered approximate, they

FIGURE 10

D-C CORONA DISCHARGE CURRENT
FROM WIRE TO GROUND PLANE
WIRE POSITIVE

POLISHED WIRE NO 12 AWG DIAMETER 2.03 MM

BAROMETRIC PRESSURE, MM HG	756.3
DRY BULB TEMPERATURE, DEG C	22.8
WET BULB TEMPERATURE, DEG C	16.8
RELATIVE HUMIDITY, PER CENT	53.8
WATER VAPOR PRESSURE, MM HG	11.4

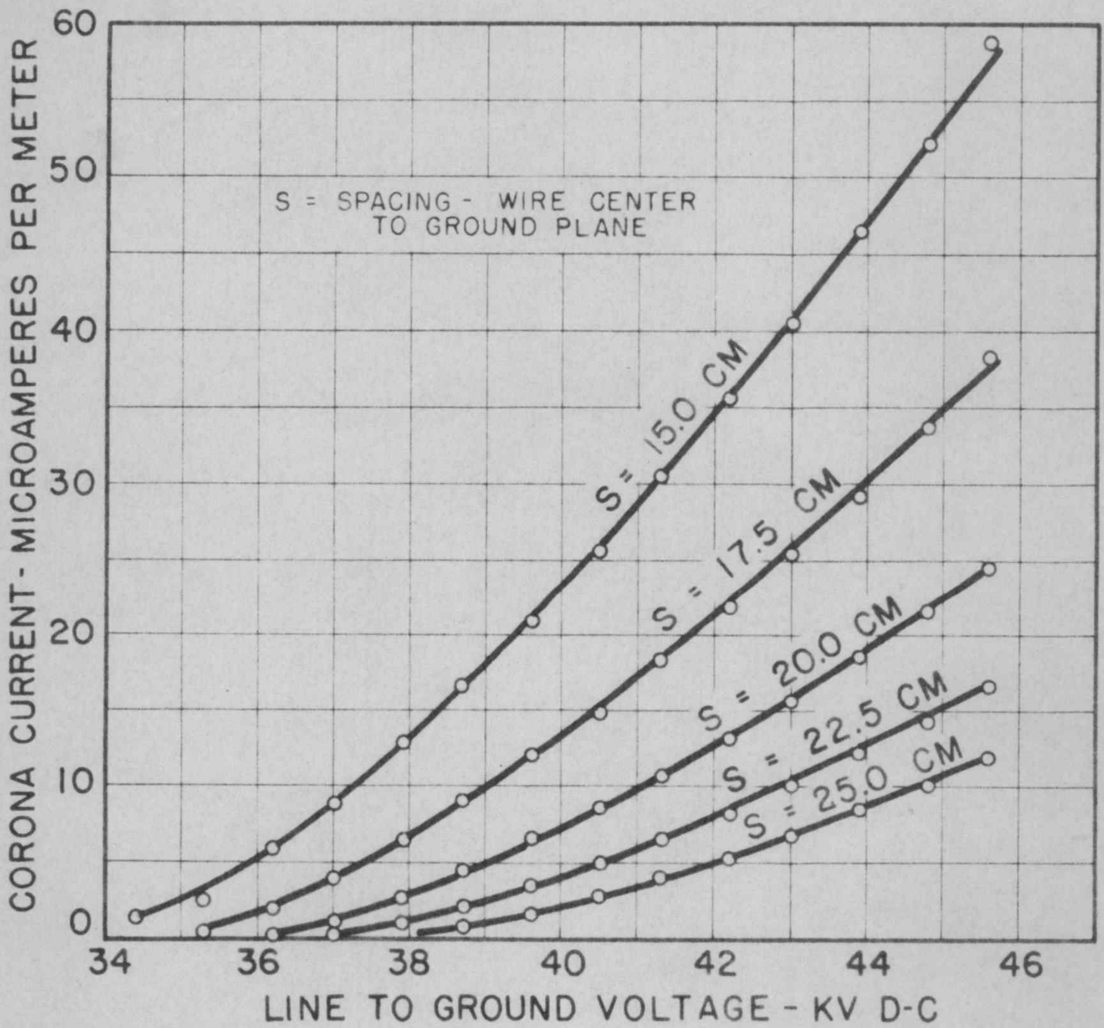


FIGURE 11

D-C CORONA DISCHARGE CURRENT
FROM WIRE TO GROUND PLANE
WIRE NEGATIVE

POLISHED WIRE NO 12 AWG DIAMETER 2.03 MM

BAROMETRIC PRESSURE, MM HG	756.3
DRY BULB TEMPERATURE, DEG C	22.8
WET BULB TEMPERATURE, DEG C	16.8
RELATIVE HUMIDITY, PER CENT	53.8
WATER VAPOR PRESSURE, MM HG	11.4

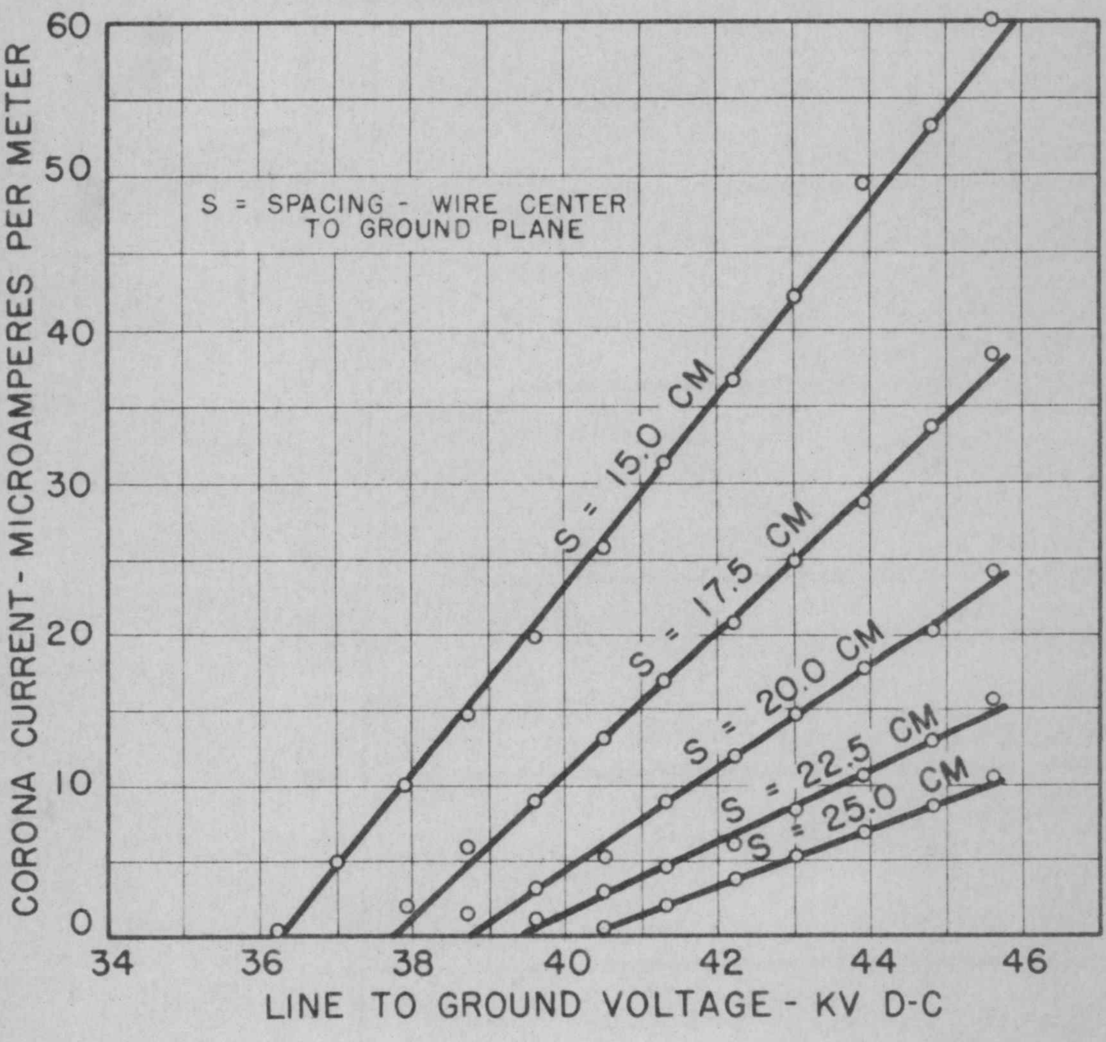


FIGURE 12

D-C CORONA DISCHARGE CURRENT
FROM WIRE TO GROUND PLANE
WIRE POSITIVE

POLISHED WIRE NO 10 AWG DIAMETER 2.55 MM

BAROMETRIC PRESSURE, MM HG	757.9
DRY BULB TEMPERATURE, DEG C	23.3
WET BULB TEMPERATURE, DEG C	16.9
RELATIVE HUMIDITY, PER CENT	51.6
WATER VAPOR PRESSURE, MM HG	11.2

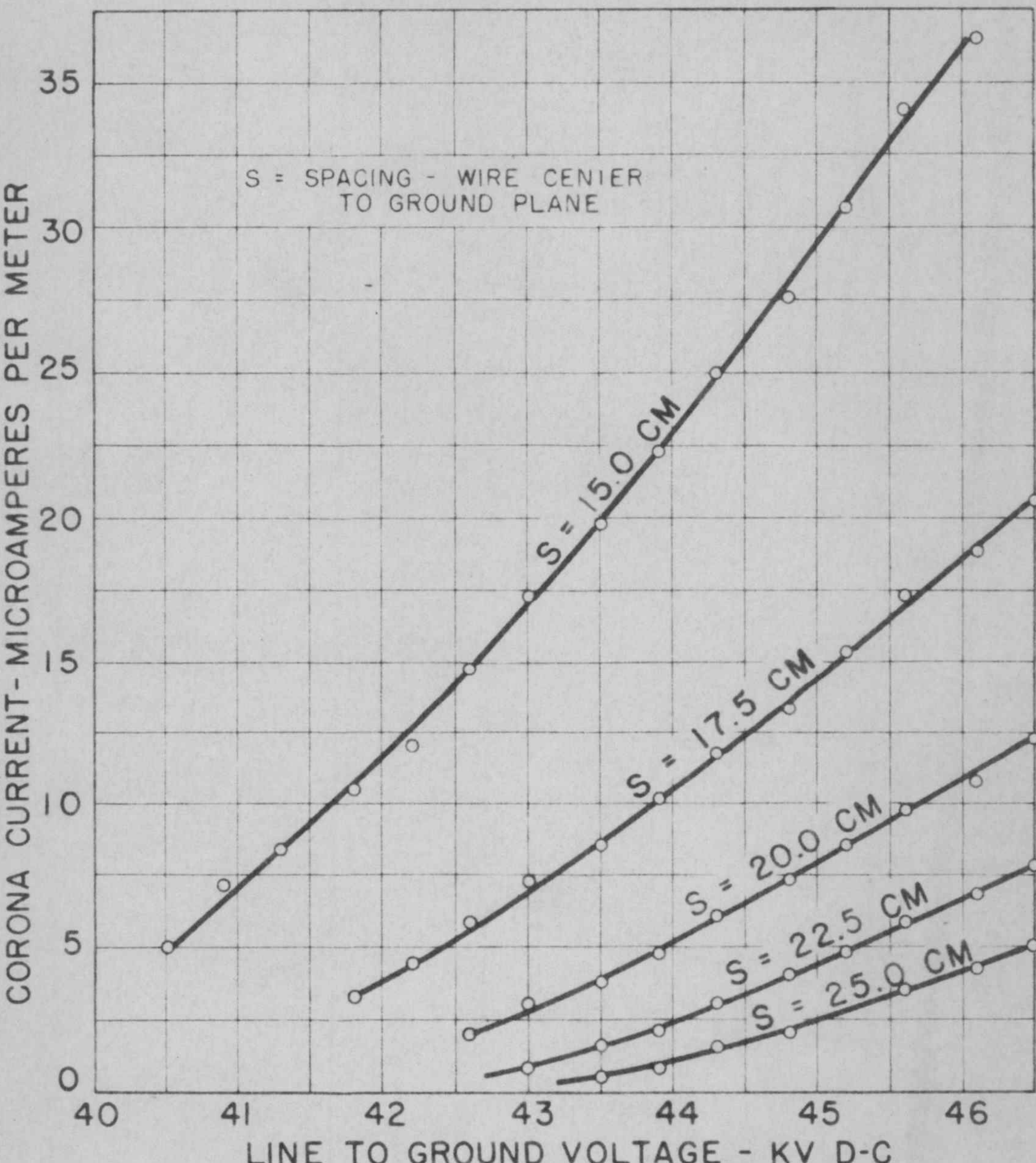


FIGURE 13

D-C CORONA DISCHARGE CURRENT
FROM WIRE TO GROUND PLANE
WIRE NEGATIVE

POLISHED WIRE NO 10 AWG DIAMETER 2.55 MM

BAROMETRIC PRESSURE, MM HG	757.9
DRY BULB TEMPERATURE, DEG C	23.3
WET BULB TEMPERATURE, DEG C	16.9
RELATIVE HUMIDITY, PER CENT	51.6
WATER VAPOR PRESSURE, MM HG	11.2

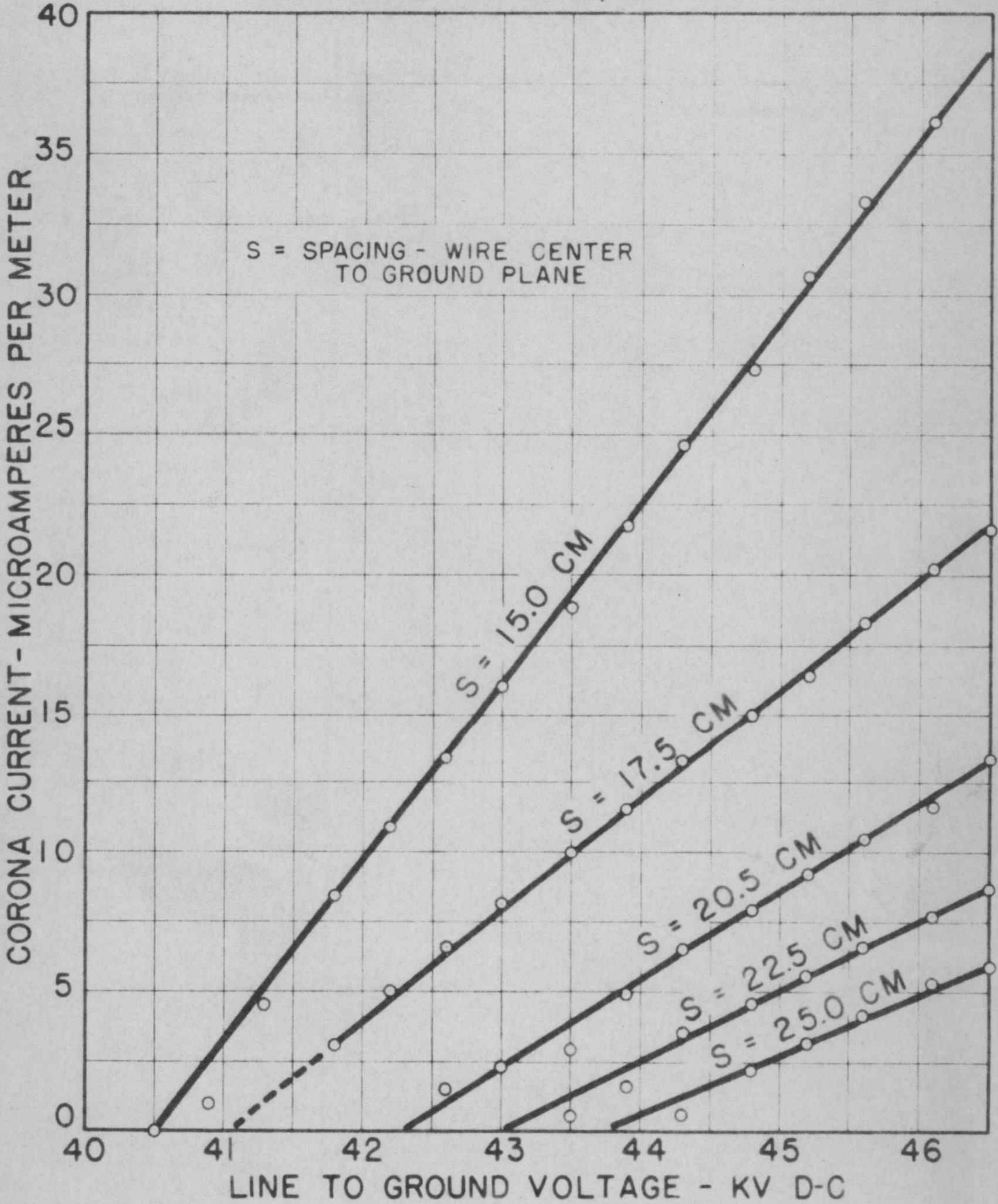


TABLE II

CRITICAL CORONA VOLTAGES AS DETERMINED FROM THE CONDUCTOR TO PLANE VOLT-AMPERE CHARACTERISTIC CURVES

Spacing Wire to Grnd.Pl. Cm.	Wire Size - No. 12 AWG			Wire Size - No. 10 AWG		
	Wire Polarity Pos. Kv.	Neg. Kv.	Diff. in % of Neg.	Wire Polarity Pos. Kv.	Neg. Kv.	Diff. in % of Neg.
15.0	33.5	36.1	7	39 -	40.5	4
17.5	35.1	37.0	5	40	41	2
20.0	36.2	37.5	5	41	42	2
22.5	37.0	38.0	3	42	43	2
25.0	38.0	39.8	4	43 -	43.5	1

serve to indicate a trend of importance, namely; that the positive critical voltage is consistently lower than the negative. The difference given in per cent of the negative critical voltage ranges roughly from 4 to 7 per cent for the No. 12 AWG wire and 1 to 4 per cent for the No. 10 AWG wire. The difference is more pronounced at the closer spacing and smaller wire size.

Whitehead[19] points out that the appearance of corona at a lower critical voltage when the conductor is positive is in full accord with the theory of ionization, assuming that electrons are the chief source of ionization. When the wire is positive, electrons are attracted into a field of increasing gradient. The electrons therefore experience the full energy of the field. When the wire is negative the electrons are repelled in the direction of diminishing field strength, hence only those electrons originating near the conductor surface can experience the maximum voltage gradient.

When comparing experimentally determined data, the wire size and surface conditions of the conductors tested must be taken into consideration. Discharges from points and very small wires are known to appear at a lower voltage with a negative electrode polarity. Schaffers[10], for example, found the point of cross-over to be 0.01 centimeters conductor radius which closely checks Farwell's[3] results. Marx and Goeschel[5] who more recently conducted corona loss tests in Germany using new untreated conductors from approximately 0.18 to 1 inch in diameter report an appreciably higher positive than negative corona forming voltage. Stockmeyer[11], on the other hand, testing carefully polished conductors from 1 to 20 millimeters in diameter reports a consistently lower positive critical voltage and comments that the apparent discrepancy between the results of Marx and Goeschel and his own may be due to the difference of the conductor surface conditions.

Stockmeyer's curves indicate that the positive and negative critical voltages approach each other at the larger wire sizes tested. Table II indicates the same trend. Here the per cent difference in positive and negative critical voltages are seen to be appreciably higher for the No. 12 AWG than for the No. 10 AWG wire. Since the curves representing the positive and negative critical voltages as a function of the conductor radii cross in the neighborhood of 0.01 centimeter radius and tend to coincide again at the larger wire sizes a point of maximum difference is indicated. The wire radius resulting in the maximum difference in positive and negative critical voltage from polished conductors has not been determined to the authors' knowledge.

By adopting Peek's experimentally determined constants given in Table I for the case of parallel wires on a-c potential and substituting these in equation 4, the critical gradient g_v is given by the expression

$$g_v = 29.8 + \frac{12.7}{\sqrt{d}} \qquad (15)$$

This may also be written in the following form generally given by Peek:

$$g_v = 29.8 \left(1 + \frac{0.301}{\sqrt{r}} \right) \qquad (16)$$

Substituting the above value of gradient in equation (2) and solving for the critical voltage there results

$$E_o = 29.8 \left(1 + \frac{0.301}{\sqrt{r}} \right) r \log_{\epsilon}(S/r) \qquad (17)$$

Equation 17 yields results which range within approximately one to two per cent lower than the positive critical voltages given in Table II, and close to seven per cent lower than the negative. The critical voltages determined from a-c tests would be expected to correspond to those from the d-c polarity resulting in the lower value of critical voltage, that is; the positive in the present test. The experimental results recorded in Table II may therefore be considered in quite good agreement with those of Peek. Referring again to Table I, it will be observed that Peek found the constants for the wire in a concentric cylinder to be somewhat higher, as are the results of the other investigators adopting that method.

After starting of corona the positive wire current curves, Figures 10 and 12, tend to approach a straight line relation which is characteristic of the negative.

With the exception of the curves for the 15 centimeter spacing, the positive discharge current from the No. 12 AWG wire remains above the negative in the range tested. However, it may be observed that the slopes of the linear portion of the negative curves are somewhat greater than the positive. That is; there is evidenced a tendency for the curves to cross. The positive and negative current curves for the No. 10 AWG wire cross in the range of voltage used. Thus, though the positive current begins at a lower voltage the negative loss is ultimately greater.

This observation corroborates both Farwell's[3] and Whitehead's results. Though the positive corona is more extended in nature than the negative, as Lichtenberg figures serve to demonstrate, the resulting current becomes space charge limited in either case. Hence, as Whitehead has suggested, the greater negative ion mobility is the factor responsible for the larger negative current.

Preliminary to recording the parallel wire data, tests were made to determine whether a polarity effect could be detected. It would seem reasonable to believe that, as in the case of a wire opposite a plane, the positive wire corona could appear at a lower voltage than the negative. There is this difference however; ion migration from the conductor first developing corona would immediately proceed in the direction of the opposite conductor, tending to increase its surface gradient. Actually there appeared to be no difference in the critical voltage of the positive and negative conductor.

A series of preliminary corona current tests were also conducted using the No. 10 AWG conductor at the minimum and maximum spacings employed during the test. A slight difference in current could be noted by shifting the microammeter from one line to the other. Later the instrument was maintained in one line and the polarity reversed a number of times. Typical of the results thus obtained are those recorded in Table III. Strictly speaking it would have been preferable to make observations of the current in both lines simultaneously. However, it was concluded that no appreciable polarity effect existed and the further tests were conducted with the microammeter in the positive line.

Turning to Figures 14, 15, and 16, it will be seen that the general character of the discharge current from parallel wires is similar to that observed from a positive wire to a plane. This is particularly evident in Figure 15 which has a more extended voltage scale, and Figure 16 which shows the discharge from a polished and from a weathered conductor. The similarity is worthy of note as it suggests that the law of corona loss from parallel wires is not fundamentally different in type from one applicable to the wire-to-plane arrangement.

TABLE III

RESULTS OF TESTS MADE TO SHOW
EQUALITY OF POSITIVE AND NEGATIVE CURRENT

Polished Wire No. 10 AWG Diameter 2.55 MM

	Positive Line	Negative Line
Barometric Pressure, MM HG	750.3	749.8
Dry Bulb Temperature, Deg F	77.2	77.5
Wet Bulb Temperature, Deg C	20.4	20.5

Line to Line Voltage D-C Kv.	Corona Current in Microamperes					
	Max.	Avg.	Min.	Max.	Avg.	Min.
73.5	Current Starts to Flow Here					
74.2	20	20	20	30	26	20
75.1	90	68	56	90	60	40
76.0	150	134	110	164	140	100
76.8	206	192	170	228	216	210
77.7	290	280	270	300	284	264
78.5	350	346	342	380	360	330
79.4	412	404	392	436	422	400
80.3	470	464	460	492	478	460
81.1	520	516	510	560	542	430
82.0	588	584	580	610	598	580
82.9	640	640	636	670	662	640
83.7	700	694	690	730	720	700
84.6	760	760	760	796	792	770
85.4	830	824	820	850	838	830
86.3	908	900	892	920	906	890
87.2	976	966	960	990	974	960

Length of conductor 5.28 meters.
Spacing 30 centimeters.

FIGURE 14

D-C CORONA DISCHARGE CURRENT
FROM PARALLEL WIRES IN AIR

POLISHED WIRES NO 12 AWG DIAMETER 2.03 MM

BAROMETRIC PRESSURE, MM HG	759.4
DRY BULB TEMPERATURE, DEG C	22.9
WET BULB TEMPERATURE, DEG C	16.6
RELATIVE HUMIDITY, PER CENT	52.5
WATER VAPOR PRESSURE, MM HG	11.0

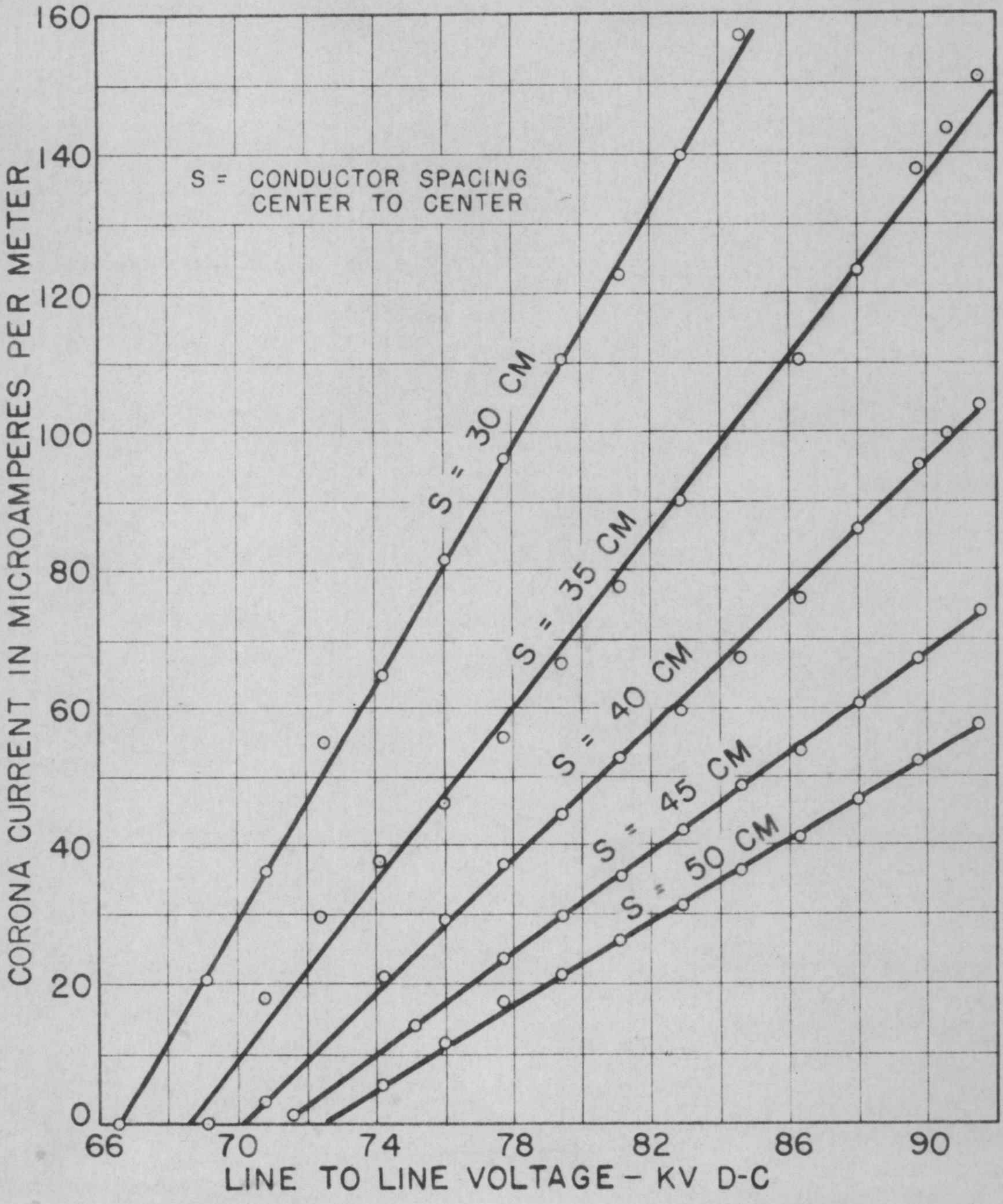


FIGURE 15

D-C CORONA DISCHARGE CURRENT FROM PARALLEL WIRES IN AIR

POLISHED WIRES NO 10 AWG DIAMETER 2.55 MM

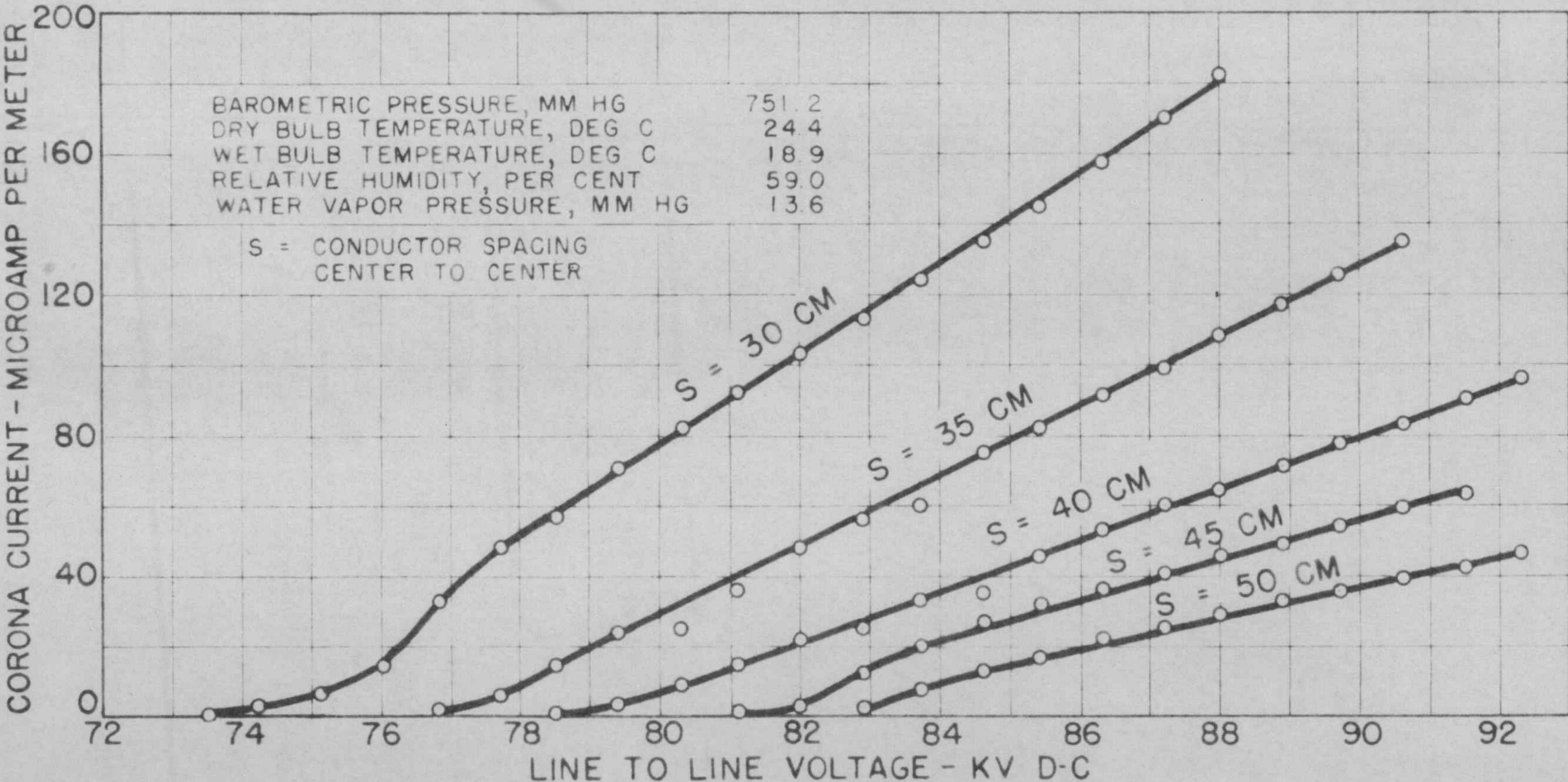


FIGURE 16

D-C CORONA DISCHARGE CURRENT
FROM PARALLEL WIRES IN AIR

WIRES NO 8 AWG DIAMETER 3.23 MM

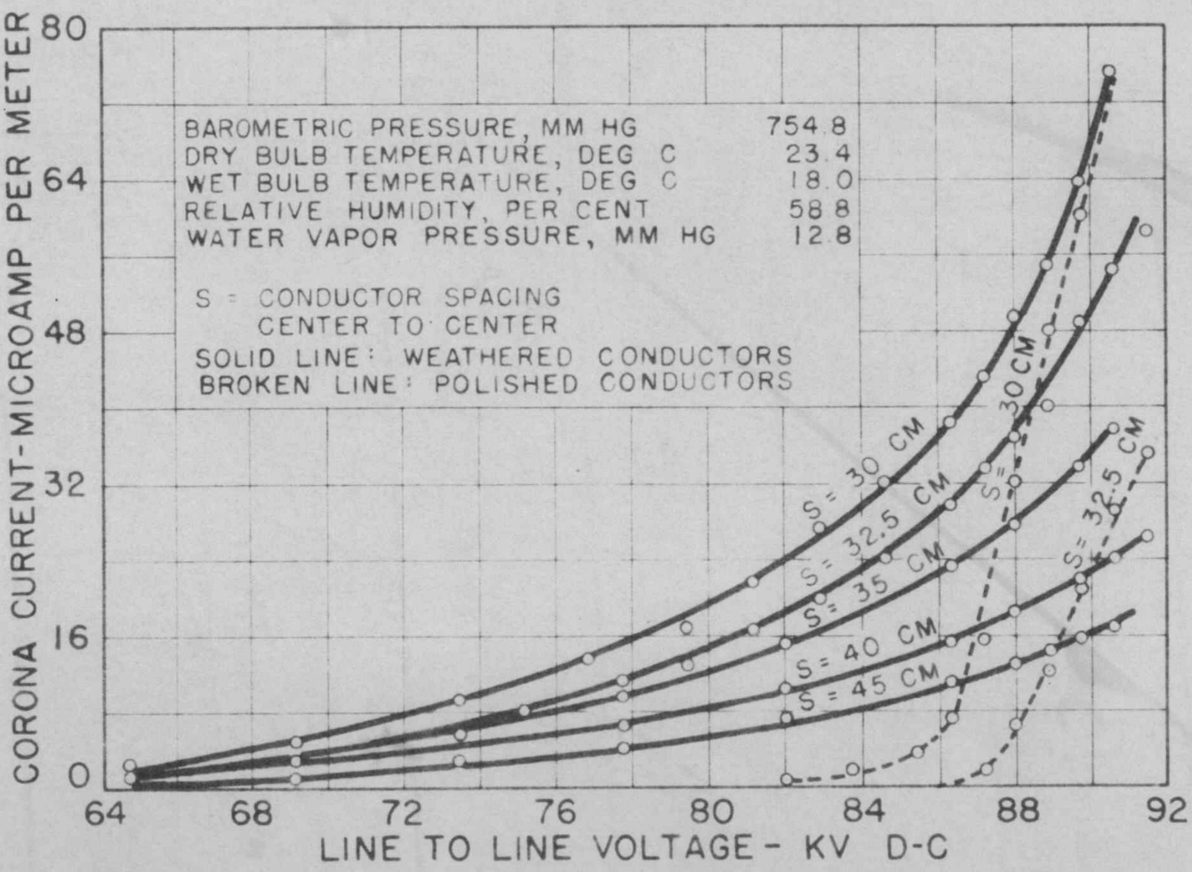


Figure 16 is of peculiar interest as it shows the very marked effect of the conductor surface condition on the critical voltage. The No. 8 AWG wire had been in actual service a number of years. Before conducting the weathered test the wire was lightly cleaned with a dry chamois skin to eliminate foreign particles adhering to the surface. On completion of the weathered test the same conductor was thoroughly cleaned and polished, using a commercial metal polish and the test repeated. The surface condition of the conductor before and after polishing is shown fairly well in Figure 17. It may be observed that the surface was not physically rough in the weathered condition. The surface had a dull mottled greenish appearance which with polishing took on a bright copper surface with minute pits. No attempt was made to eradicate these. Nevertheless it will be noted that polishing effected nearly a 30 per cent increase in critical voltage at the closest spacing used. It appears from the limited data that the weathered corona current curves approach and tend to coincide with the curves representing the linear portion of the polished conductor loss. This again points to the possible universal nature of the law of corona loss for the linear portion of the corona discharge current characteristic curves and also indicates that the surface condition is an important factor in determining the non-linear portion of the characteristic.

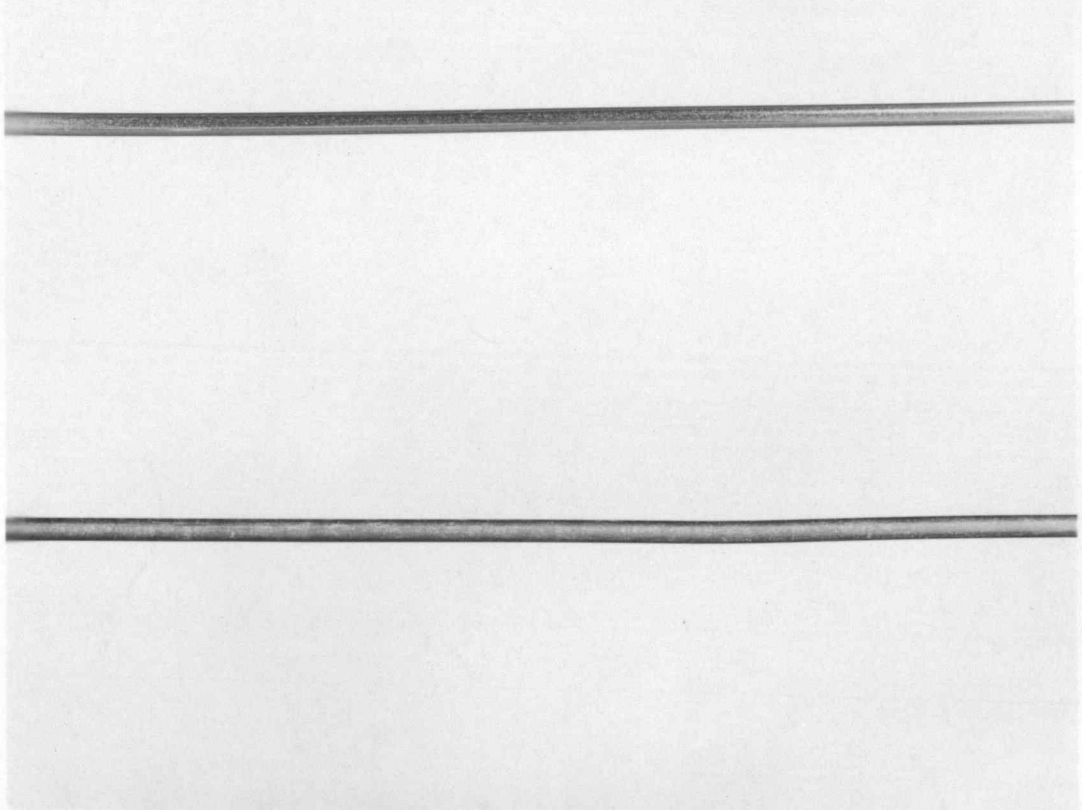


FIG. 17. PHOTOGRAPH SHOWING NO. 8 AWG CONDUCTOR IN WEATHERED AND POLISHED CONDITION

Upper Conductor Polished
Lower Conductor Weathered

Table III which was prepared to show the equality of the positive and negative current from parallel wires is of interest in another respect. It was observed that whereas the voltage corresponding to the first microammeter indication could be repeated quite consistently the current throughout the non-linear portion of the volt-ampere characteristic curve varied considerably with each run, sometimes fluctuating by relatively large amounts while a constant voltage was maintained. The maximum difference expressed as a per centage of the average reading amounted to as much as 35 and 40 per cent in the non-linear range, dropping rapidly as the data entered the linear range. This difficulty of checking the low values of corona current was experienced throughout the test. It is believed that the erratic nature of the current in the non-linear range is indicative of a probability phenomena. The current in the early stages of corona is undoubtedly very sensitive to any minute particles precipitated from the air. This phenomena is at least one of the factors that must be considered when formulating an expression for the corona current below the linear portion of the volt-ampere characteristics.

Figures 18 and 19 were prepared to give a more direct comparison of the parallel wire and the wire-to-plane data. For the purpose at hand only the results obtained with the maximum and minimum spacings are shown. The abscissa rep-

FIGURE 18

D-C CORONA DISCHARGE CURRENT
FROM POSITIVE WIRE TO GROUND PLANE
COMPARED WITH PARALLEL WIRES

POLISHED WIRES NO 12 AWG DIAMETER 2.03 MM

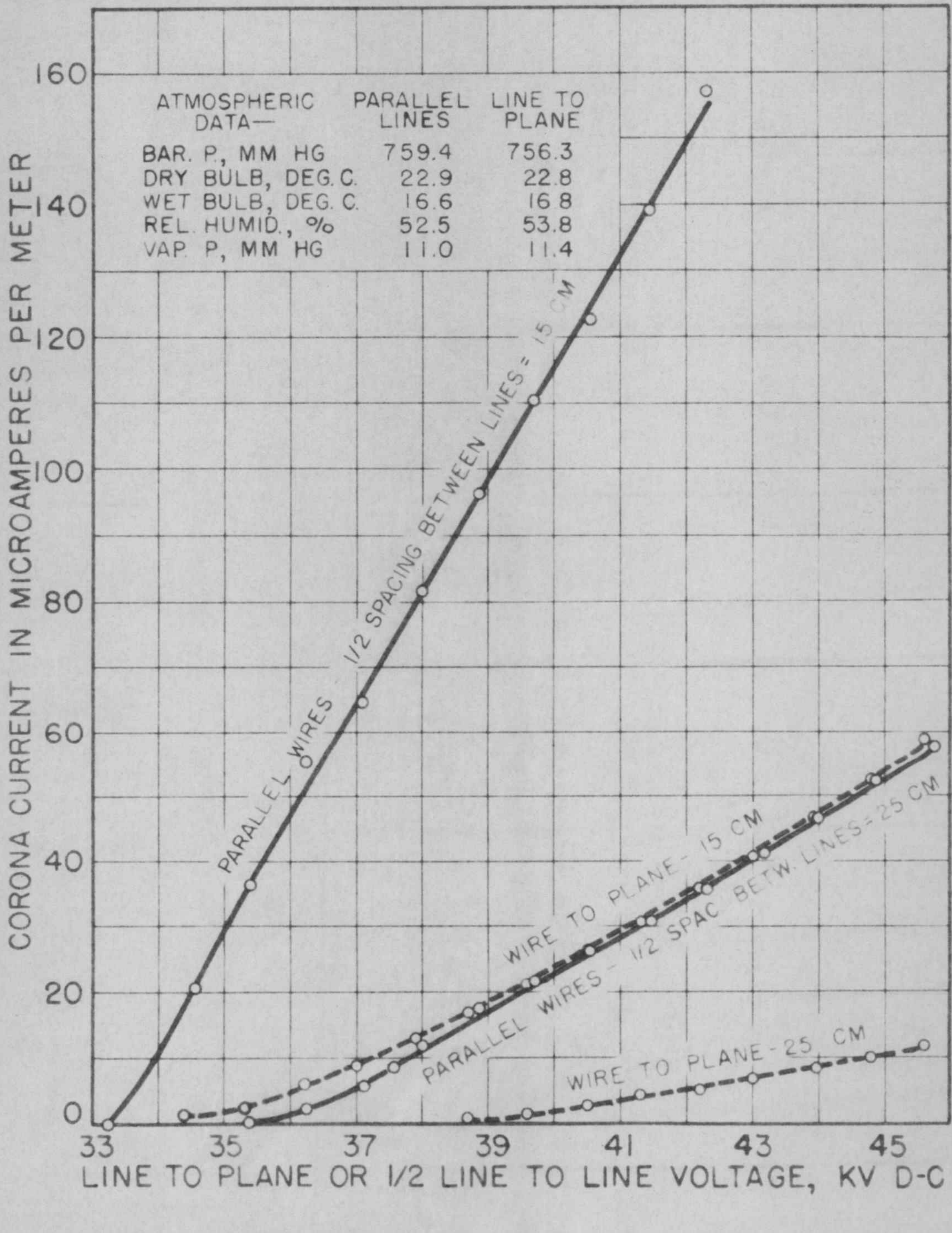
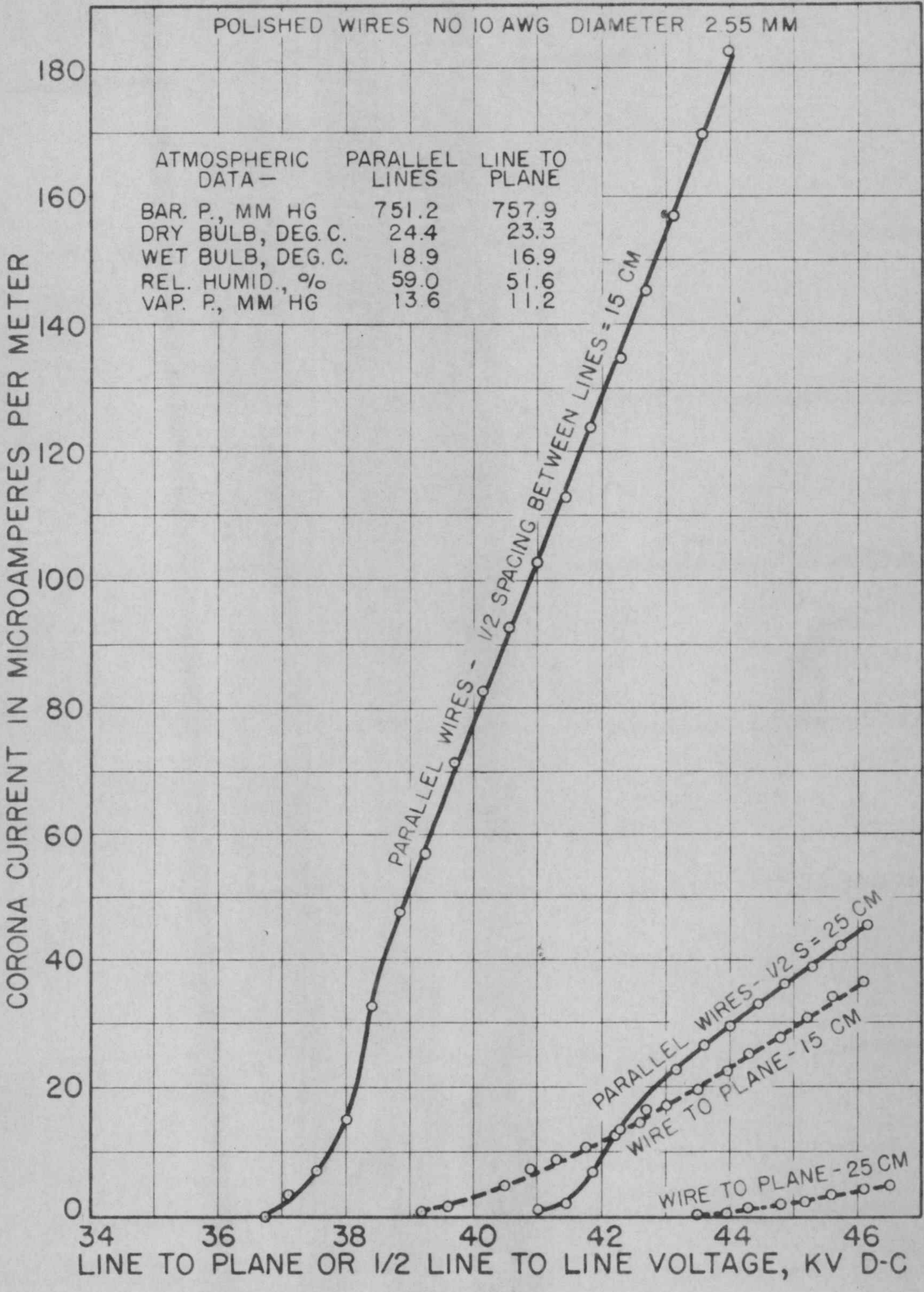


FIGURE 19

D-C CORONA DISCHARGE CURRENT
FROM POSITIVE WIRE TO GROUND PLANE
COMPARED WITH PARALLEL WIRES



LINE TO PLANE OR 1/2 LINE TO LINE VOLTAGE, KV D-C resents the line-to-plane or one half the line-to-line voltage for each arrangement respectively. It will be recalled that the line-to-plane voltage and spacing is comparable to one half the line-to-line voltage and spacing, that is; neglecting the effect of space charge, the theoretical field surrounding the conductor is identical in either case.

The positive wire-to-plane data were chosen in preference to the negative for the purpose of comparison because the positive critical voltage was consistently lower than the negative. While the critical voltage of the parallel wire arrangement might be expected to coincide with the positive or lower wire-to-plane value, it was actually found to be even lower by an appreciable amount. This appears to be in harmony with Stockmeyer's results.

If, as has been suggested, the corona current from a wire to a plane is space charge limited an increase of current could be expected from the parallel wire arrangement. Where ions of both signs participate the space charge is partially neutralized with a resulting increase in current. A similar result is obtained in ionic tubes by the inclusion of a small amount of gas. Stockmeyer anticipated twice the single wire current. However, the results of this test fully corroborate his test results, which indicated that the parallel wire corona discharge current is many times that from a single wire opposite a plane.

These comparative results are further summarized in Table IV. The negative, positive and parallel wire data tabulated were taken from the curves of Figures 10 to 16 inclusive. The data credited to Stockmeyer was taken from curves presented in his paper, "Koronaverluste bei hoher Gleichspannung"[11] in 1934. The polarity was not given, it being of small consequence for this purpose. The last column of Table IV represents the positive wire current expressed as a per centage of the parallel wire current. It indicates that for the range of voltage used the positive current ranged from zero to a maximum of 23 per cent of the comparable parallel wire current. That is; the magnitude of the corona discharge current within the limits of voltage employed was in every case more than four times the current obtained from the wire-to-plane arrangement.

The d-c corona power loss P was computed from the simple relation

$$P = E I \tag{18}$$

in which E represents the line to plane or line to line voltage and I the line current. Figures 20 to 25 represent the square root of the loss plotted as a function of the voltage. This method of plotting illustrates to good advantage the striking similarity of the d-c power loss characteristics from the wire-to-plane and parallel wire

TABLE IV

COMPARISON OF THE CORONA DISCHARGE CURRENT FROM A POSITIVE AND NEGATIVE WIRE TO A PLANE WITH THAT FROM PARALLEL WIRES

D. C. Potential Kv	Corona Current Microamperes per Meter Wire to Plane Neg.	Pos.	Parallel Wires	Pos. Current in % of Parallel
	Wire Size No. 12 AWG 2.03 MM Spacing 15 Cm			
36	0	5	47	10
38	11	13	81	16
40	23	23	114	20
42	36	35	149	23
	Spacing 25 Cm			
40	0	2	22	9
42	3	5	33	15
44	7	8	46	17
	Wire Size No. 10 AWG 2.55 MM Spacing 15 Cm			
40	0	3	78	4
42	9	12	129	9
44	23	23	180	13
	Spacing 25 Cm			
44	0.6	1.0	30	3
45	2.7	2.5	37	7
46	4.9	3.7	45	8
	RESULTS OF WALTER STOCKMEYER Wire Size 1 MM Spacing 9.5 Cm (Polarity Unknown)			
24	0		13.3	0
26	5		48.5	10
28	16.6		105.0	16
30	37.5		186.6	20

Note: 1. The D.C. potential represents line to plane or ½ line to line voltage.
2. The spacing represents line to plane or ½ line to line spacing.

FIGURE 20

D-C CORONA POWER LOSS
FROM WIRE TO GROUND PLANE
WIRE POSITIVE

POLISHED WIRE NO 12 AWG DIAMETER 2.03 MM

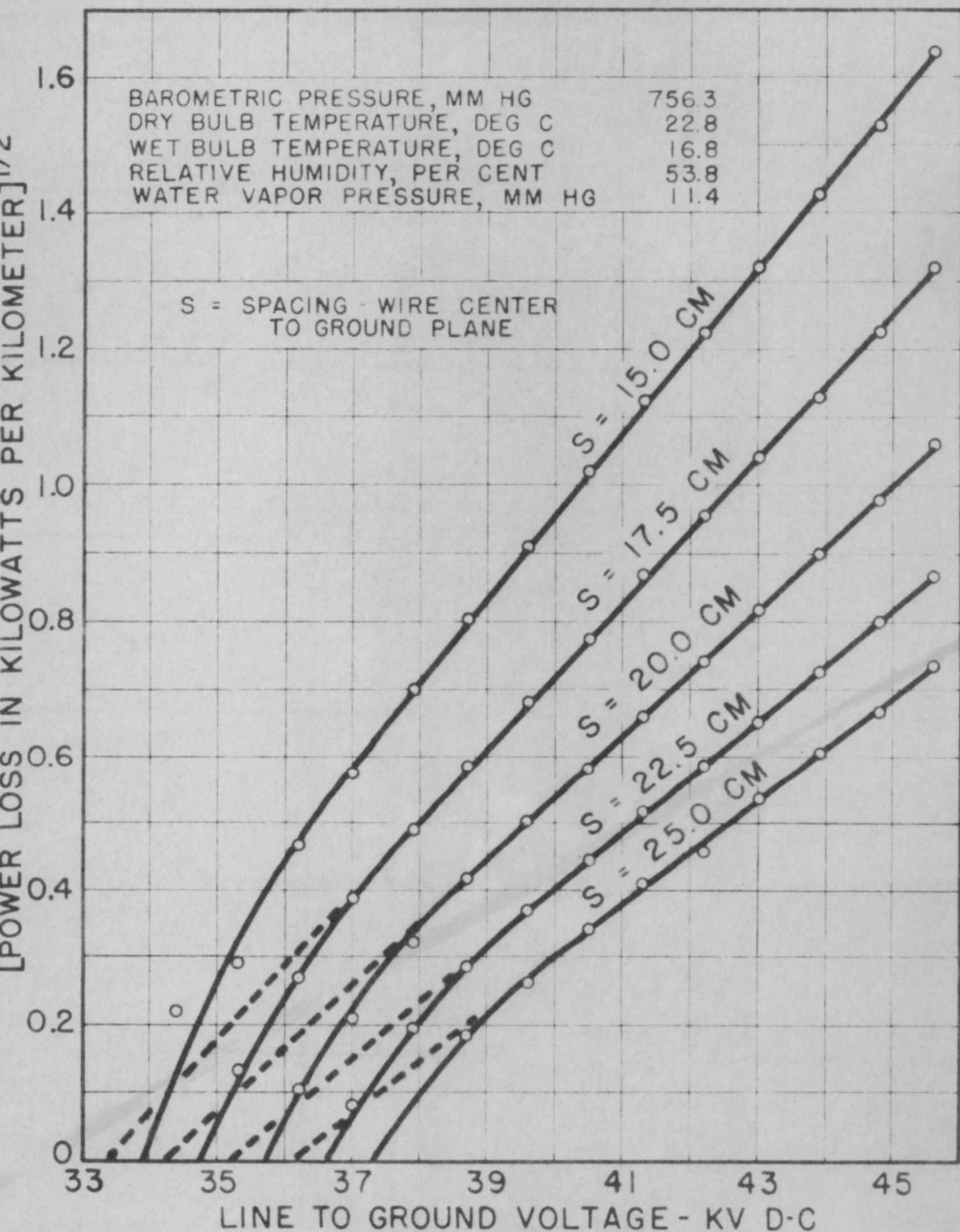


FIGURE 21

D-C CORONA POWER LOSS
FROM WIRE TO GROUND PLANE
WIRE NEGATIVE

POLISHED WIRE NO 12 AWG DIAMETER 2.03 MM

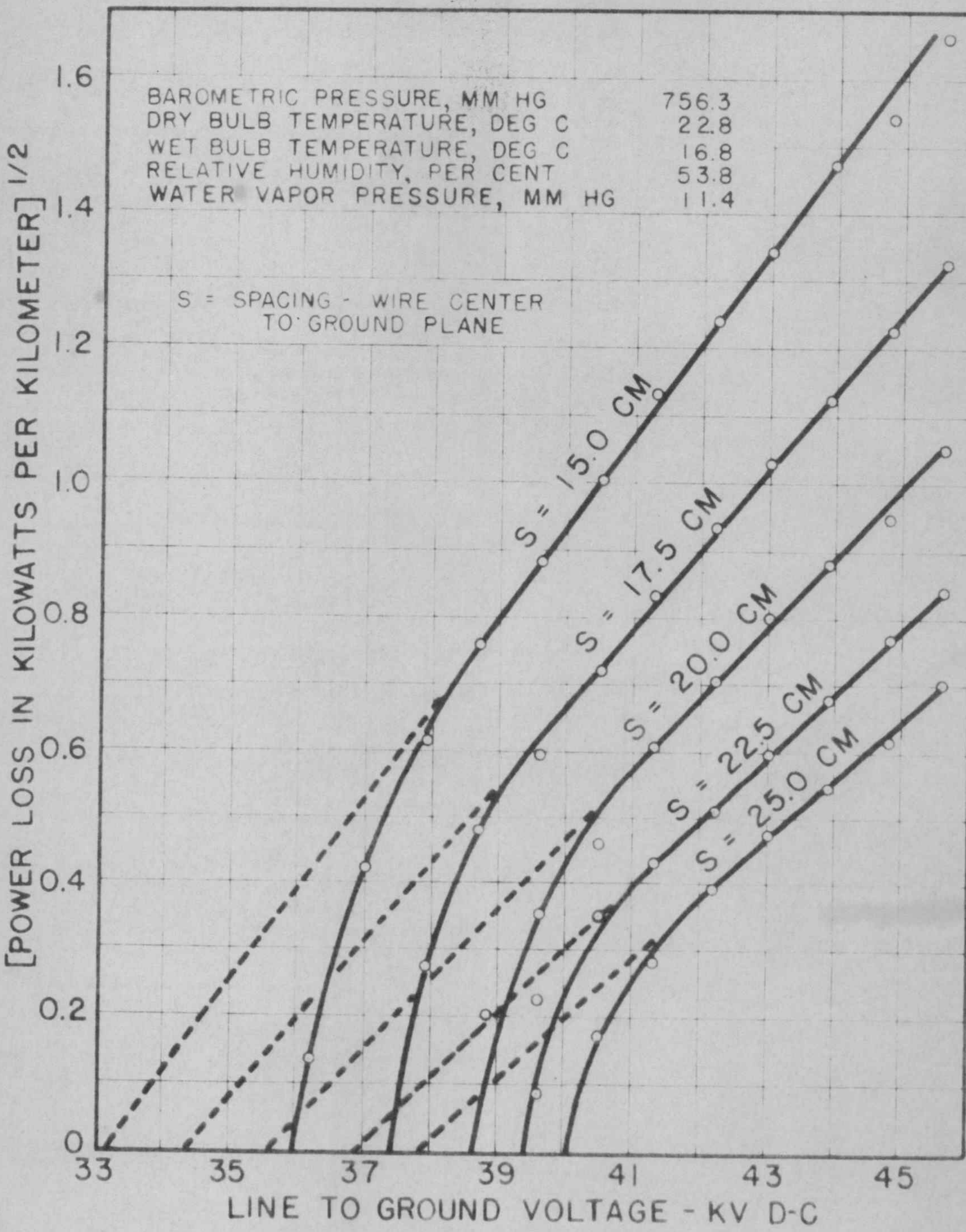


FIGURE 22

D-C CORONA POWER LOSS
FROM WIRE TO GROUND PLANE
WIRE POSITIVE

POLISHED WIRE NO 10 AWG DIAMETER 2.55 MM

BAROMETRIC PRESSURE, MM HG	757.9
DRY BULB TEMPERATURE, DEG C	23.3
WET BULB TEMPERATURE, DEG C	16.9
RELATIVE HUMIDITY, PER CENT	51.6
WATER VAPOR PRESSURE, MM HG	11.2

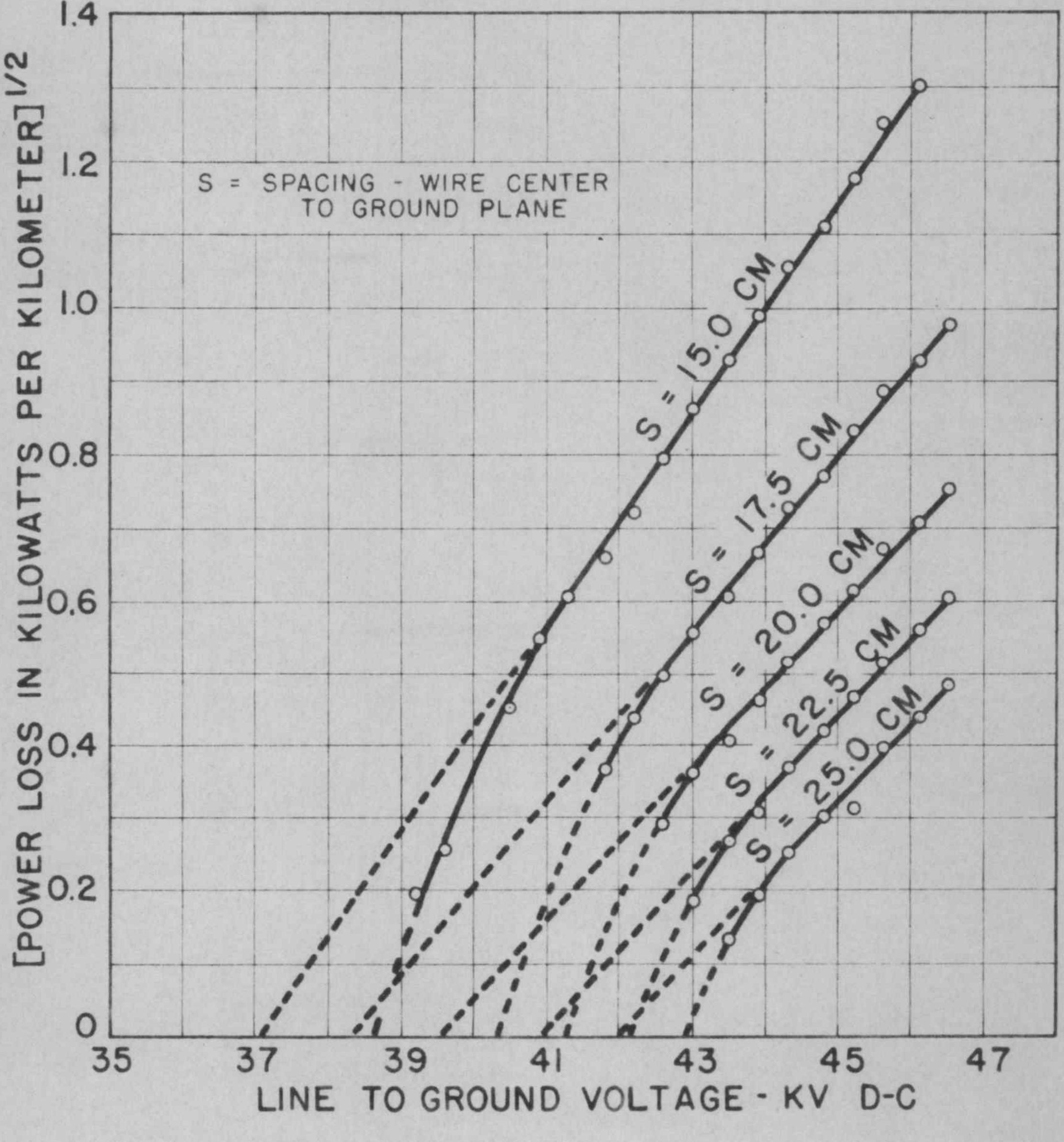


FIGURE 23

D-C CORONA POWER LOSS FROM WIRE TO GROUND PLANE WIRE NEGATIVE

POLISHED WIRE NO 10 AWG DIAMETER 2.55 MM

BAROMETRIC PRESSURE, MM HG	757.9
DRY BULB TEMPERATURE, DEG C	23.3
WET BULB TEMPERATURE, DEG C	16.9
RELATIVE HUMIDITY PER CENT	51.6
WATER VAPOR PRESSURE, MM HG	11.2

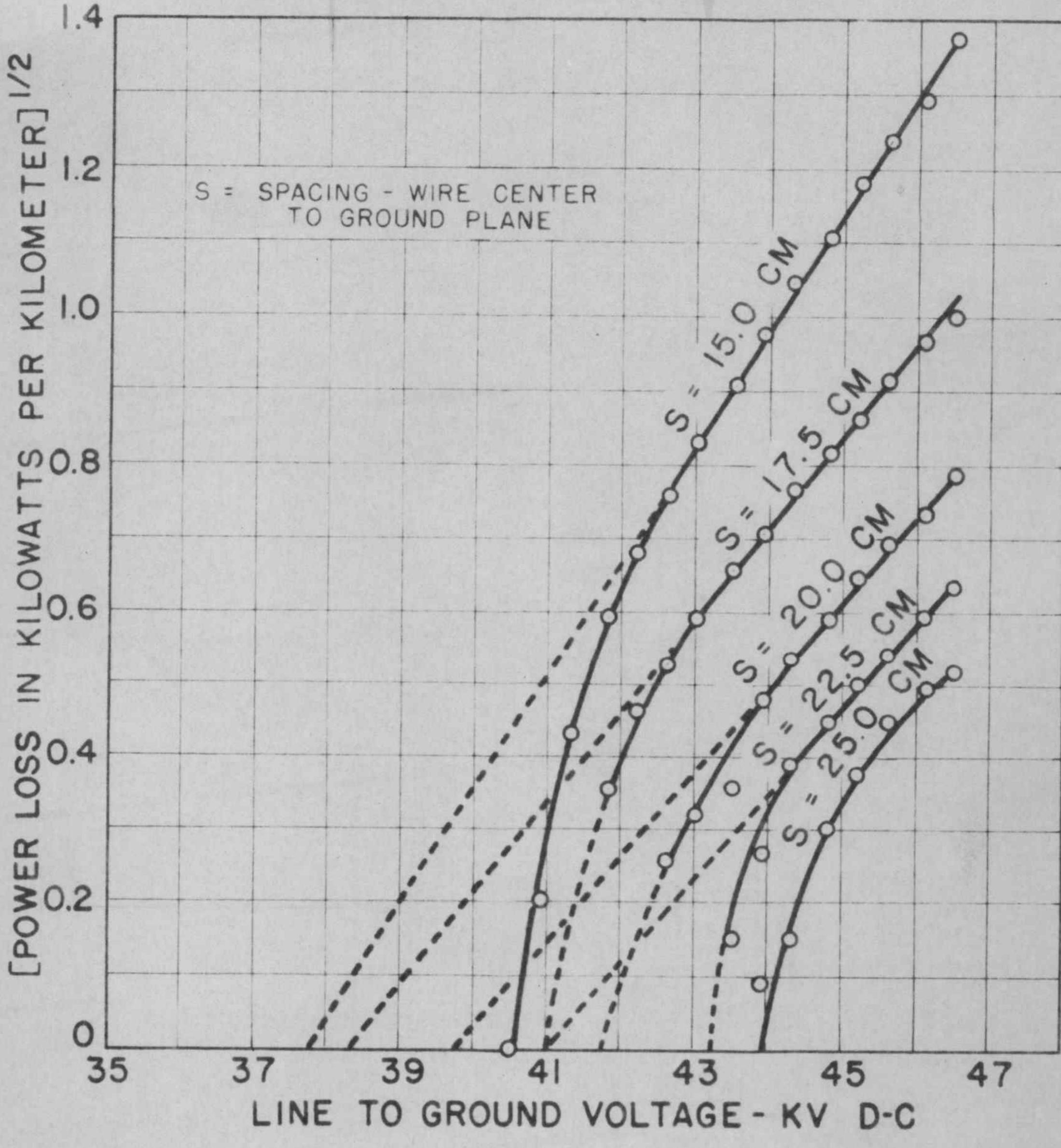


FIGURE 24

D-C CORONA POWER LOSS
FROM PARALLEL WIRES IN AIR

POLISHED WIRES NO 12 AWG DIAMETER 2.03 MM

BAROMETRIC PRESSURE, MM HG	759.4
DRY BULB TEMPERATURE, DEG C	22.9
WET BULB TEMPERATURE, DEG C	16.6
RELATIVE HUMIDITY, PER CENT	52.5
WATER VAPOR PRESSURE, MM HG	11.0

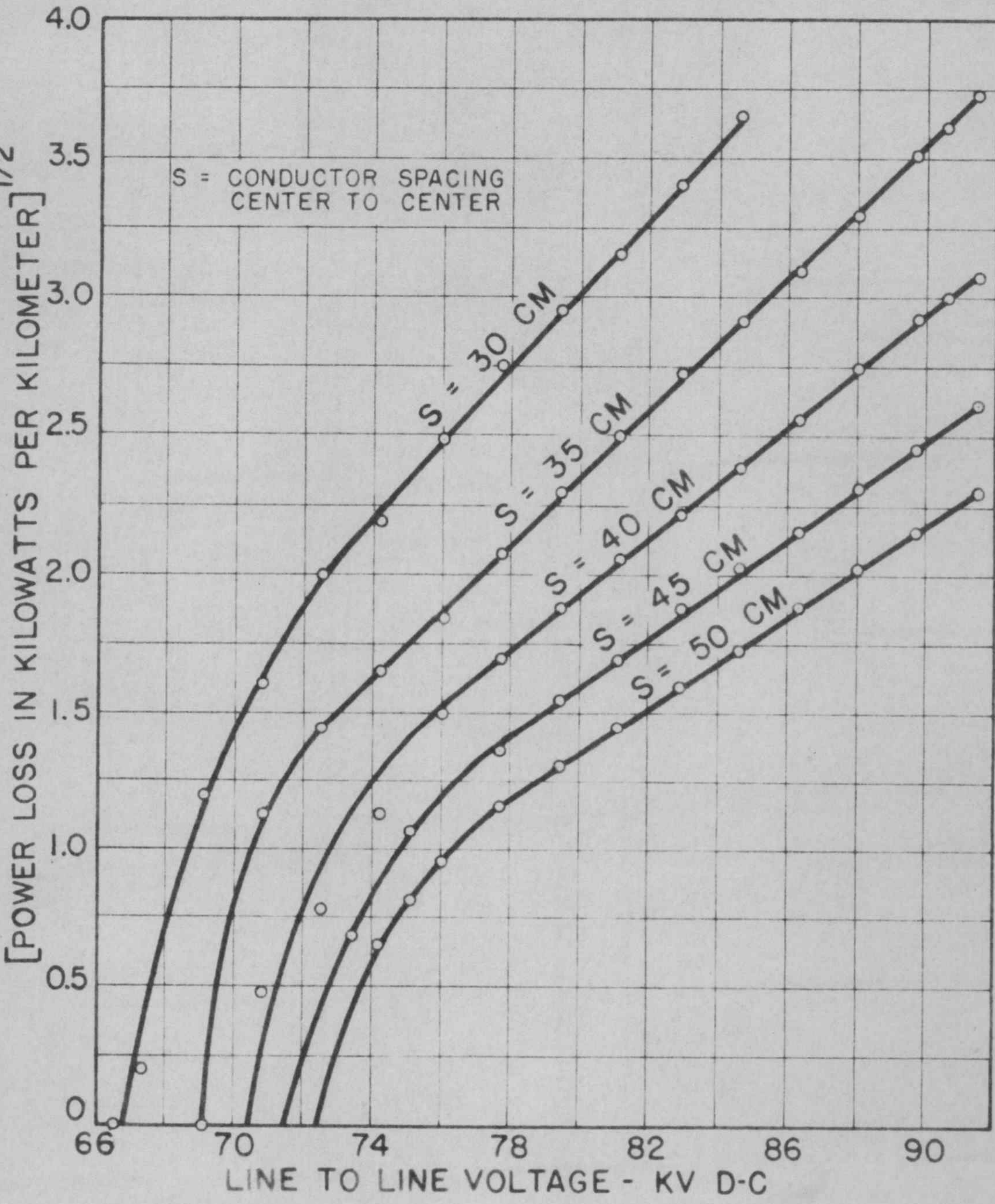
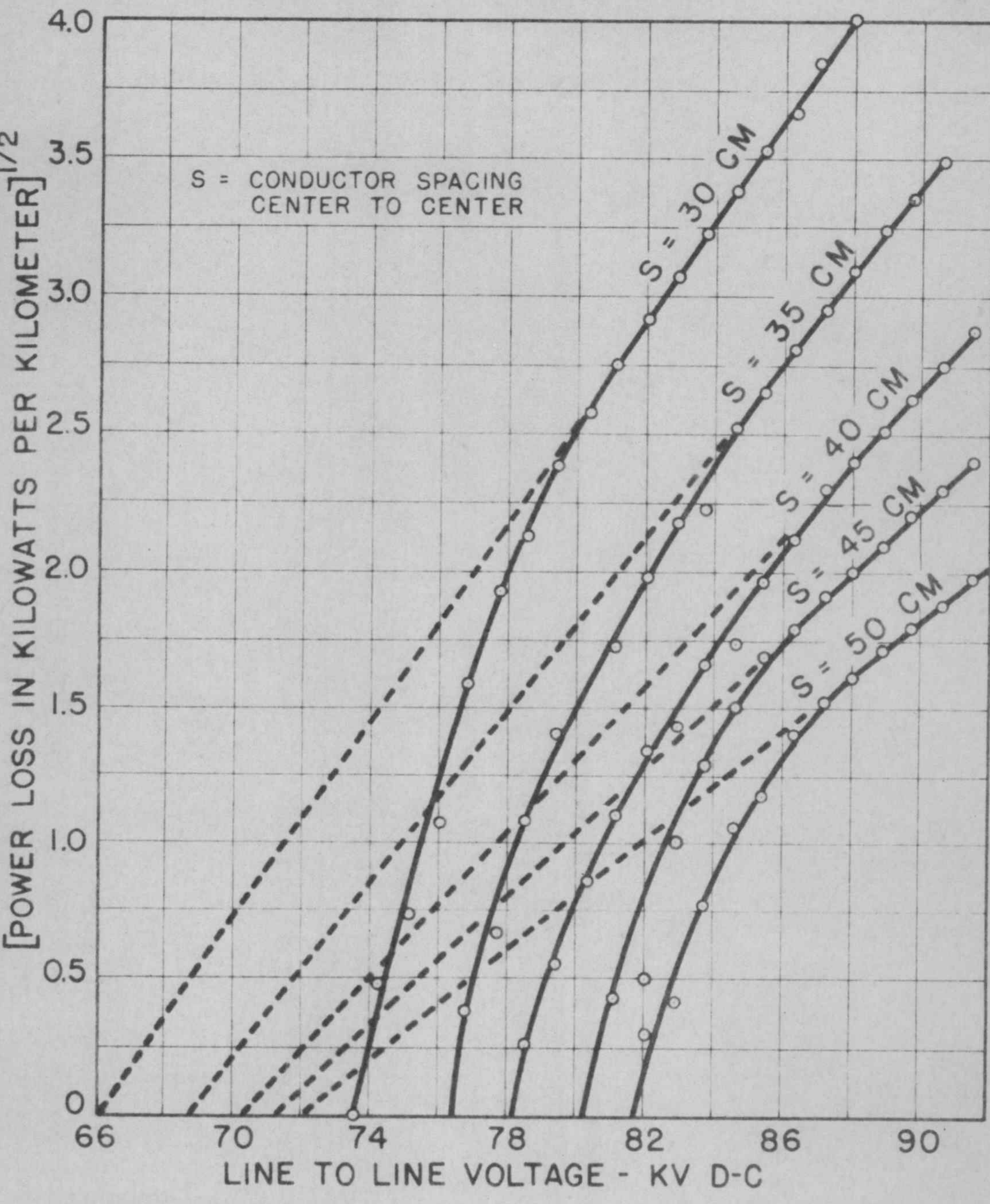


FIGURE 25

D-C CORONA POWER LOSS
FROM PARALLEL WIRES IN AIR

POLISHED WIRES NO 10 AWG DIAMETER 2.55 MM

BAROMETRIC PRESSURE, MM HG	751.2
DRY BULB TEMPERATURE, DEG C	24.4
WET BULB TEMPERATURE, DEG C	18.9
RELATIVE HUMIDITY, PER CENT	59.0
WATER VAPOR PRESSURE, MM HG	13.6



arrangements shown in Figures 20 - 23 and 24 and 25 respectively. It further demonstrates that the second or upper branch of the d-c corona power loss characteristics follow Peek's quadratic law developed for a-c corona loss. It is of the form

$$P = k (E - E_d)^2 \qquad (19)$$

By extrapolating the linear portion of the power loss curves to the intersection with the voltage axis (as indicated by the broken lines) one arrives at a value appreciably lower than the visual critical voltage. Peek refers to this lower value as the "disruptive critical voltage" E_d which follows the law

$$E_d = g_d\, r\, m_o \log_\epsilon (S/r). \text{ Kv effective.} \qquad (20)$$

Here m_o is a roughness factor approaching unity for polished smooth conductors, r the radius of conductor in centimeters, S the spacing between parallel lines or twice the spacing from conductor to plane in centimeters, g_d the "disruptive critical gradient". Peek using parallel wires found that the a-c value of g_d is practically equal to the value of the critical gradient of air g_o for wire sizes greater than 0.25 cm radius and approaches the visual critical gradient g_v as the wire radius decreases.

In Table V is given a comparison of the disruptive critical voltages calculated from Peek's law with those obtained from the positive and parallel wire d-c power loss curves. As might be expected the d-c values of dis-

TABLE V

COMPARISON OF DISRUPTIVE CRITICAL VOLTAGES

Spacing in Cm.	Disruptive Critical Voltage in Kilovolts to Neutral — Calculated: a-c E_d(eff.) kv.	Calculated: a-c E_d(Max.) kv.	Experimental Values: Positive Conductor to Plane Kv.	Experimental Values: Parallel Conductors Kv.
	No. 12 AWG Conductor			
30	21.4	30.3	32.1	28.7
35	22.5	31.8	33.3	30.2
40	23.1	32.7	34.2	30.5
45	23.4	33.1	35.2	31.1
50	23.8	33.7	36.1	32.4
	No. 10 AWG Conductor			
30	24.3	34.4	37.1	33.0
35	24.9	35.2	38.3	34.4
40	25.6	36.2	39.5	35.1
45	26.2	37.0	40.9	35.6
50	26.6	37.6	42.0	36.0

Peek's emperical equations for disruptive critical voltage:

$$E_d \text{ (eff.)} = g_d \, r \, m_o \log_\epsilon (S/r) \quad \text{kv}$$

$$E_d \text{ (Max.)} = E_d \text{ (eff.)} \times \sqrt{2}$$

$$g_d = g_o \cdot \left[1 + \left(\frac{0.3}{\sqrt{r}} \times \frac{1}{(1 + 230 \, r^2)} \right) \right]$$

When $r = 0.101$ Cm $g_d = 38.1$

$r = 0.127$ Cm $g_d = 35.1$

S = spacing in Cm between wire centers, or twice the distance from wire to plane.

ruptive critical voltage are comparable to the a-c crest values. A comparison of the a-c and d-c corona power loss is beyond the scope of this paper. Suffice it to say that as shown previously the a-c and d-c corona loss begins at a comparable value of crest voltage and that the power loss characteristics based on effective values of voltage have been found by Strigel to cross, the a-c loss ultimately becoming the larger. Peek's quadratic expression for a-c corona power loss

$$P = 241\,(f + 25)\sqrt{\frac{r + \frac{6}{S} + 0.04}{S}}\,(E - E_d)^2\,10^{-5} \text{ kw. per km of conductor} \quad (21)$$

cannot be made to apply to the case of d-c corona loss by the substitution f = zero frequency. By using maximum values of a-c voltage the 60-cycle loss as computed from equation (21) gave results in reasonably close agreement to the d-c loss from the No. 12 parallel conductors.

VIII. CONCLUSIONS

1. For the case of a single wire opposite a parallel plane the positive critical voltage was consistently lower than the negative.
2. This polarity effect was more pronounced at the close spacings and smaller conductor used.
3. Peek's expression for a-c critical voltage from parallel conductors

$$E_o = 29.8 \left(1 + \frac{0.301}{\sqrt{r}} \right) r \log_\epsilon (S/r)$$

   yields results approximately one to two per cent lower than the d-c positive wire-to-plane critical voltage.
4. The d-c parallel wire critical voltage was lower than the wire-to-plane values by an appreciable amount.
5. There appeared to be no appreciable polarity effect from the parallel wire arrangement
6. Although the d-c visual critical voltage is extremely sensitive to the conductor surface conditions the current ultimately appears to be independent of the surface conditions.
7. In the range tested the d-c volt-ampere characteristic curves for parallel wires are very similar in appearance to those for a single wire opposite a plane, in each case following a linear law after

general corona had set in.

8. In the range of voltage between the critical value and that value for which the volt-ampere characteristic approaches a linear function, the d-c corona current evidenced an erratic nature difficult of prediction.
9. The magnitude of the parallel wire d-c discharge current was found to be many times the corresponding wire-to-plane current.
10. The d-c corona power loss characteristics from the wire-to-plane and parallel wire arrangement were similar in nature, consisting of two branches. In each case the second branch followed Peek's quadratic law of corona expressed

$$P = k(E - E_o)^2$$

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APPENDIX

DEMONSTRATION THAT A MICROAMMETER SHUNTED WITH CAPACITANCE INDICATES THE AVERAGE VALUE OF A FLUCTUATING D-C CORONA CURRENT

The fluctuating d-c corona current may be represented as the sum of a steady d-c component $\underline{a}$ and a fluctuating component which may be represented by $f(t)$ an unknown function of time.

Then refering to Fig. 26

$$i_L = a + f(t) \qquad 1$$

$$i = i_m + i_c \qquad 2$$

$$Ri_m = e_c = \frac{1}{C}\int i_c\,dt \qquad 3$$

$$i_c = RC\,di_m/dt = T\,di_m/dt \qquad 4$$

Hence

$$T\,di_m/dt + i_m = a + f(t) \qquad 5$$

The differential equation 5 has the solution

$$i_m = a + \epsilon^{-\frac{t}{T}} \int \frac{\epsilon^{\frac{t}{T}}}{T} f(t)\,dt + k\epsilon^{-\frac{t}{T}} \qquad 6$$

Now the integral in equation 6 may also be written as follows

$$\int \frac{\epsilon^{\frac{t}{T}}}{T} f(t)\,dt = \epsilon^{\frac{t}{T}} f(t) - \int \epsilon^{\frac{t}{T}} f'(t)\,dt \qquad 7$$

in which $f'(t)$ represents the first time derivative of $f(t)$

Equation 6 may therefore be written

$$i_m = a + \epsilon^{-\frac{t}{T}}\left[\epsilon^{\frac{t}{T}} f(t) - \int \epsilon^{\frac{t}{T}} f'(t)\,dt\right] + k\epsilon^{-\frac{t}{T}} \qquad 8$$

$$= a + f(t) + \epsilon^{-\frac{t}{T}}\left[k - \int \epsilon^{\frac{t}{T}} f'(t)\,dt\right]$$

But $\quad i_L = a + f(t)$

and hence

$$i_L - i_m = \epsilon^{-\frac{t}{T}}\left[\int \epsilon^{\frac{t}{T}} f'(t)\,dt - k\right] \qquad 9$$

Therefore since the instantaneous difference between the actual line current and the current flowing through the microammeter ultimately becomes zero, theoretically in an infinite time but practically in a few seconds, the average value of the actual line current is given by the microammeter reading

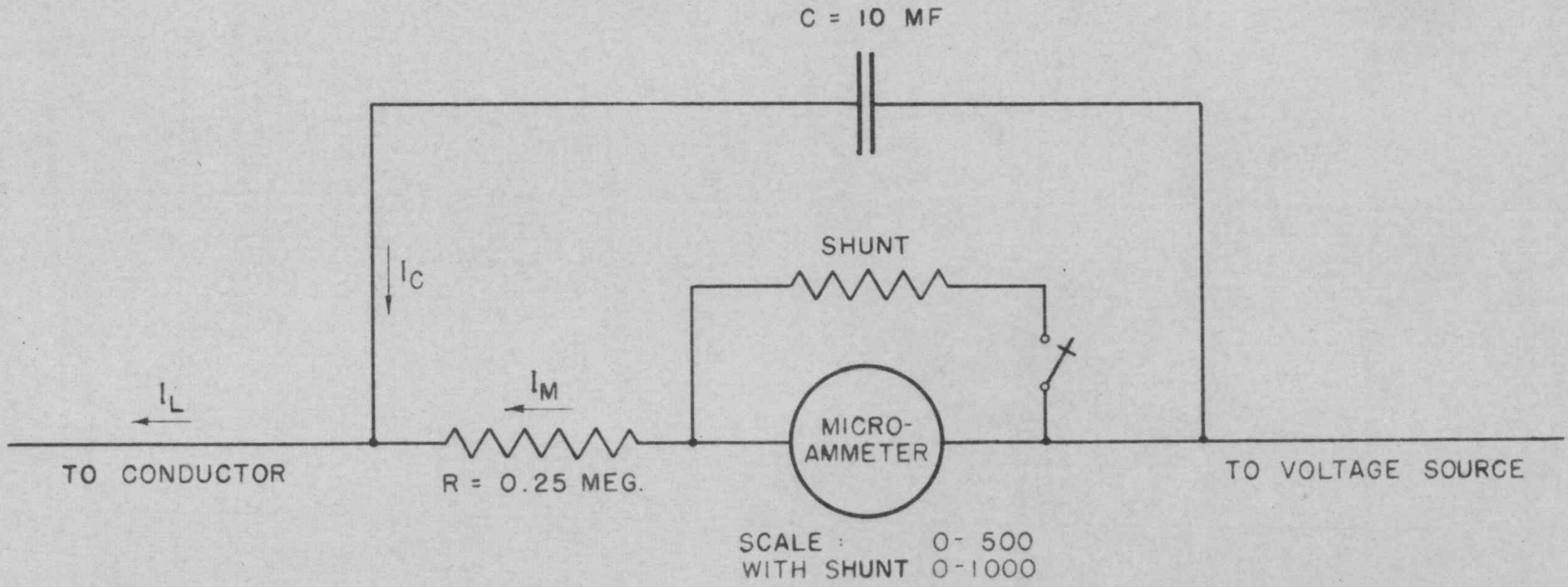

FIG. 26 SCHEMATIC DIAGRAM OF CIRCUIT USED TO INDICATE THE AVERAGE VALUE OF A FLUCTUATING D-C CORONA CURRENT

TABLE VI

CALIBRATION DATA FOR HIGH VOLTAGE,
INVERTED VACUUM TUBE VOLTMETER

A. Line to Line Calibration

Sphere Gap Spacing Cm.	Sphere Gap Spark Voltage Kilovolts Max.	Vac. Tube Voltmeter Deflection
0.00	0.0	150.0
0.50	16.3	132.2
1.00	31.2	114.1
1.50	45.4	97.5
2.00	58.5	82.5
2.50	70.8	68.0
3.00	81.9	54.8
3.50	91.9	43.5

B. Line to Ground Calibration

0.00	0.0	150.0
0.25	8.3	130.0
0.50	16.2	112.2
0.75	23.8	93.1
1.00	31.0	76.5
1.25	37.9	61.5
1.50	44.5	46.5
1.60	47.1	41.0

Calibration spheres: 6.25 cm. Above voltages are corrected for air density prevailing at time calibration was made.

Equation for line to line voltage E_1

$$E_1 - 129.4 - 0.862V$$

Equation for line to ground voltage E_2

$$E_2 - 64.6 - 0.862V$$

V = Vacuum tube voltmeter deflection.
Equations determined by method of least square.

TABLE VII

D-C CORONA DISCHARGE CURRENT FROM WIRE TO GROUND PLANE

Polished Wire No. 12 AWG Diameter 2.03 MM

Barometric Pressure, MM HG	756.3
Dry Bulb Temperature, Deg C	22.8
Wet Bulb Temperature, Deg C	16.8
Relative Humidity, Per Cent	53.8
Water Vapor Pressure, MM HG	11.4

A. Wire Positive

D-C Kv. to Ground	Spacing - Center of Wire to Ground Plane 15.0 Cm.	17.5 Cm.	20.0 Cm.	22.5 Cm.	25.0 Cm.
	I - ua/M	I - ua/M	I - ua/M	I - ua/M	I - ua/M
34.4	1.5				
35.3	2.5	0.5			
36.2	6.0	2.0	0.3		
37.0	8.9	4.0	1.2	0.2	
37.9	12.9	6.4	2.7	1.0	
38.7	16.8	8.9	4.5	2.1	0.9
39.6	21.0	11.9	6.4	3.5	1.7
40.5	25.7	14.8	8.4	4.9	2.9
41.3	30.6	18.3	10.6	6.5	4.1
42.2	35.6	21.7	13.1	8.1	4.9
43.0	40.5	25.2	15.5	9.9	6.7
43.9	46.5	29.1	18.5	12.1	8.4
44.8	52.3	33.6	21.5	14.3	9.9
45.6	58.8	38.3	24.5	16.5	11.8

B. Wire Negative

D-C Kv. to Ground	15.0 Cm.	17.5 Cm.	20.0 Cm.	22.5 Cm.	25.0 Cm.
36.2	0.5				
37.0	4.9				
37.9	9.9	2.0	0.3	0.2	
38.7	14.8	5.9	1.6	1.1	
39.6	19.8	8.9	3.2	1.3	0.2
40.5	25.6	12.8	5.2	3.0	0.7
41.3	31.1	16.8	8.9	4.5	1.9
42.2	36.5	20.8	11.8	6.1	3.7
43.0	42.0	24.7	14.8	8.3	5.2
43.9	49.4	28.6	17.8	10.5	6.8
44.8	52.9	33.6	20.2	12.8	8.4
45.6	60.2	38.3	24.2	15.4	10.8

Active section of ground plane 0.716 x 2.022 meters.

TABLE VIII

D-C CORONA DISCHARGE CURRENT FROM WIRE TO GROUND PLANE

Polished Wire No. 10 AWG Diameter 2.55 MM

Barometric Pressure, MM HG	757.9
Dry Bulb Temperature, Deg C	23.3
Wet Bulb Temperature, Deg C	16.9
Relative Humidity, Per Cent	51.6
Water Vapor Pressure, MM HG	11.2

A. Wire Positive

D-C Kv. to	Spacing - Center of Wire to Ground Plane				
Ground	15.0 Cm.	17.5 Cm.	20.0 Cm.	22.5 Cm.	25.0 Cm.
	I - ua/M	I - ua/M	I - ua/M	I - ua/M	I - ua/M
39.2	1.0				
39.6	1.6				
40.5	5.0				
40.9	7.3				
41.3	8.8				
41.8	10.4	3.2			
42.2	12.3	4.5			
42.6	14.8	5.7	2.0		
43.0	17.3	7.2	3.0	0.8	
43.5	19.7	8.4	3.8	1.6	0.4
43.9	22.2	10.1	4.8	2.1	0.8
44.3	25.1	11.8	5.9	3.0	1.4
44.8	27.6	13.3	7.2	3.9	2.0
45.2	30.8	15.3	8.4	4.8	2.1
45.6	34.0	17.3	9.8	5.8	3.4
46.1	36.5	18.7	10.8	6.8	4.1
46.5	----	20.5	12.2	7.8	5.0

B. Wire Negative

D-C Kv. to Ground	15.0 Cm.	17.5 Cm.	20.0 Cm.	22.5 Cm.	25.0 Cm.
40.5	0.0				
40.9	1.0				
41.3	4.5				
41.8	8.4	3.0			
42.2	10.9	5.0			
42.6	13.3	6.4	1.5		
43.0	16.0	8.1	2.3		
43.5	18.8	9.9	2.9	0.5	0.1
43.9	21.7	11.4	4.9	1.6	0.2
44.3	24.7	13.3	6.4	3.4	0.5
44.8	27.2	14.8	7.7	4.4	2.0
45.2	30.6	16.3	9.2	5.5	3.1
45.6	33.4	18.3	10.4	6.4	4.3
46.1	36.0	20.2	11.6	7.6	5.3
46.5	40.5	21.6	13.3	8.6	5.7

Active section of ground plane 0.716 x 2.022 meters.

TABLE IX

D-C CORONA DISCHARGE CURRENT
FROM PARALLEL WIRES IN AIR

Polished Wire No. 12 AWG Diameter 2.03 MM

Barometric Pressure, MM HG	759.4
Dry Bulb Temperature, Deg C	22.9
Wet Bulb Temperature, Deg C	16.6
Relative Humidity, Per Cent	52.5
Water Vapor Pressure, MM HG	11.0

Line-Line Voltage D-C Kv.	Spacing - Center to Center 30.0 Cm. I - ua/M	35.0 Cm. I - ua/M	40.0 Cm. I - ua/M	45.0 Cm. I - ua/M	50.0 Cm. I - ua/M
66.5	0.0				
67.3	0.6				
69.1	20.5	0.0			
70.8	36.3	18.0	3.2	---	0.3
71.6	----	----	---	1.6	---
72.5	55.2	28.4	8.2	---	2.4
73.4	----	----	---	6.3	---
74.2	64.7	37.2	20.8	---	5.5
75.1	----	----	----	14.2	8.7
76.0	81.4	45.8	29.0	----	11.7
77.7	96.2	55.8	36.9	23.7	17.4
79.4	110.2	66.2	44.1	29.7	21.3
81.1	122.5	77.3	52.4	35.3	26.0
82.9	139.0	90.0	59.3	42.3	30.9
84.6	157.2	99.8	66.9	48.6	35.3
86.3		110.4	75.7	53.6	41.0
88.0		123.1	85.8	60.6	46.4
89.7		137.5	94.7	67.5	52.1
90.6		143.5	99.3	----	----
91.5		151.4	103.8	74.2	57.6

Wire length 6.34 meters.

TABLE X

D-C CORONA DISCHARGE CURRENT
FROM PARALLEL WIRES IN AIR

Polished Wire No. 10 AWG Diameter 2.55 MM

Barometric Pressure, MM HG	751.2
Dry Bulb Temperature, Deg C	24.4
Wet Bulb Temperature, Deg C	18.9
Relative Humidity, Per Cent	59.0
Water Vapor Pressure, MM HG	13.6

Line-Line	Spacing - Center to Center				
Voltage	30.0 Cm.	35.0 Cm.	40.0 Cm.	45.0 Cm.	50.0 Cm.
D-C Kv.	I - ua/M	I - ua/M	I - ua/M	I - ua/M	I - ua/M
73.5	0.0				
74.2	3.4				
75.1	7.2				
76.0	15.0				
76.8	32.6	1.9			
77.7	47.8	5.7			
78.5	57.0	14.8	0.9		
79.4	71.3	24.6	3.8		
80.3	82.8	25.0	9.3		
81.1	92.8	36.4	14.8	2.3	
82.0	102.8	47.8	21.8	3.0	1.1
82.9	112.8	57.6	24.6	12.1	2.1
83.7	123.8	59.5	32.6	19.9	7.0
84.6	134.5	75.0	35.4	26.5	13.3
85.4	145.2	82.0	44.5	33.0	16.1
86.3	157.0	91.0	52.6	37.0	22.6
87.2	169.7	99.3	60.7	41.7	26.4
88.0	182.6	108.4	65.3	45.5	29.4
88.9		117.4	71.1	49.2	33.0
89.7		125.0	77.6	54.2	35.8
90.6		134.5	83.4	58.5	38.8
91.5			90.0	63.0	42.1
92.3			95.6		45.5

Length of conductor 5.28 meters.

TABLE XI

D-C CORONA DISCHARGE CURRENT
FROM PARALLEL WIRES IN AIR

Weathered Wire No. 8 AWG Diameter 3.23 MM

Barometric Pressure, MM HG	754.8
Dry Bulb Temperature, Deg C	23.4
Wet Bulb Temperature, Deg C	18.0
Relative Humidity, Per Cent	58.8
Water Vapor Pressure, MM HG	12.8

Line-Line	Spacing - Center to Center				
Voltage	30.0 Cm.	32.5 Cm.	35.0 Cm.	40.0 Cm.	45.0 Cm.
D-C Kv.	I - ua/M	I - ua/M	I - ua/M	I - ua/M	I - ua/M
64.7	2.4	1.4	1.6	0.8	0.6
69.1	4.8	3.0	2.4	1.6	0.8
73.4	9.1	5.8	5.6	3.2	2.9
75.1	---	8.0	---	---	---
76.8	13.6	---	---	---	---
77.7	----	11.3	9.6	6.4	4.0
79.4	16.8	12.9	---	---	---
81.1	21.6	16.3	---	---	---
82.0	----	----	15.2	10.4	7.2
82.9	26.2	19.5	----	----	---
84.6	32.0	24.0	----	----	---
86.3	38.3	29.6	23.2	15.2	10.9
87.2	43.1	33.6	----	----	----
88.0	49.5	36.7	27.6	18.4	12.8
88.9	54.3	40.0	----	----	14.4
89.7	63.8	48.7	33.6	21.9	15.6
90.6	75.0	54.3	37.6	24.0	16.8
91.5	----	58.3	----	25.9	----

Length of conductor 6.26 meters.

TABLE XII

D-C CORONA POWER LOSS FROM WIRE TO GROUND PLANE

Polished Wire No. 12 AWG Diameter 2.03 MM

Barometric Pressure, MM HG	756.3
Dry Bulb Temperature, Deg C	22.8
Wet Bulb Temperature, Deg C	16.8
Relative Humidity, Per Cent	53.8
Water Vapor Pressure, MM HG	11.4

A. Wire Positive

Wire-Grnd. Voltage D-C Kv.	Spacing - Center of Wire to Ground Plane 15.0 Cm. P-Kw/Km	17.5 Cm. P-Kw/Km	20.0 Cm. P-Kw/Km	22.5 Cm. P-Kw/Km	25.0 Cm. P-Kw/Km
34.4	0.052				
35.3	0.088	0.018			
36.2	0.217	0.072	0.011		
37.0	0.330	0.148	0.044	0.007	
37.9	0.490	0.242	0.102	0.038	
38.7	0.650	0.345	0.174	0.081	0.035
39.6	0.832	0.471	0.253	0.138	0.067
40.5	1.04	0.600	0.340	0.199	0.118
41.3	1.26	0.755	0.438	0.268	0.170
42.2	1.50	0.915	0.553	0.342	0.207
43.0	1.75	1.08	0.666	0.425	0.288
43.9	2.04	1.28	0.812	0.530	0.368
44.8	2.34	1.50	0.962	0.640	0.443
45.6	2.68	1.75	1.12	0.753	0.538

B. Wire Negative

Wire-Grnd. Voltage D-C Kv.	15.0 Cm. P-Kw/Km	17.5 Cm. P-Kw/Km	20.0 Cm. P-Kw/Km	22.5 Cm. P-Kw/Km	25.0 Cm. P-Kw/Km
36.2	0.018				
37.0	0.182				
37.9	0.375	0.076	0.011	0.008	
38.7	0.573	0.228	0.062	0.043	
39.6	0.784	0.352	0.127	0.052	0.008
40.5	1.04	0.519	0.210	0.122	0.028
41.3	1.28	0.694	0.368	0.186	0.079
42.2	1.54	0.878	0.498	0.258	0.156
43.0	1.81	1.06	0.637	0.357	0.224
43.9	2.17	1.25	0.782	0.460	0.299
44.8	2.37	1.51	0.905	0.573	0.376
45.6	2.74	1.75	1.11	0.704	0.493

Active section of ground plane 0.716 x 2.022 meters

TABLE XIII

D-C CORONA POWER LOSS FROM WIRE TO GROUND PLANE

Polished Wire No. 10 AWG Diameter 2.55 MM

Barometric Pressure, MM HG	757.9
Dry Bulb Temperature, Deg C	23.3
Wet Bulb Temperature, Deg C	16.9
Relative Humidity, Per Cent	51.6
Water Vapor Pressure, MM HG	11.2

Wire-Grnd.	Spacing - Center of Wire to Ground Plane				
Voltage	15.0 Cm.	17.5 Cm.	20.0 Cm.	22.5 Cm.	25.0 Cm.
Kv. D-C	P-Kw/Km	P-Kw/Km	P-Kw/Km	P-Kw/Km	P-Kw/Km
	A. Wire Positive				
39.2	0.039				
39.6	0.063				
40.5	0.203				
40.9	0.299				
41.3	0.364				
41.8	0.435	0.134			
42.2	0.519	0.190			
42.6	0.631	0.243	0.085		
43.0	0.744	0.309	0.129	0.034	
43.5	0.857	0.365	0.165	0.070	0.017
43.9	0.975	0.443	0.211	0.092	0.035
44.3	1.11	0.523	0.261	0.133	0.062
44.8	1.24	0.596	0.323	0.175	0.090
45.2	1.39	0.692	0.380	0.217	0.095
45.6	1.55	0.789	0.447	0.265	0.155
46.1	1.68	0.862	0.498	0.314	0.189
46.5	----	0.955	0.568	0.363	0.233
	B. Wire Negative				
40.5	0.000				
40.9	0.041				
41.3	0.186				
41.8	0.351	0.125			
42.2	0.460	0.211			
42.6	0.566	0.273	0.064		
43.0	0.688	0.348	0.099		
43.5	0.818	0.430	0.126	0.022	0.004
43.9	0.952	0.500	0.215	0.070	0.009
44.3	1.09	0.590	0.284	0.151	0.022
44.8	1.22	0.663	0.345	0.197	0.090
45.2	1.38	0.737	0.416	0.249	0.140
45.6	1.52	0.835	0.475	0.292	0.196
46.1	1.66	0.932	0.535	0.351	0.244
46.5	1.88	1.00	0.618	0.400	0.266

Active section of ground plane 0.716 x 2.022 meters.

TABLE XIV

D-C CORONA POWER LOSS FROM PARALLEL WIRES IN AIR

Polished Wire No. 12 AWG Diameter 2.03 MM

Barometric Pressure, MM HG	759.4
Dry Bulb Temperature, Deg C	22.9
Wet Bulb Temperature, Deg C	16.6
Relative Humidity, Per Cent	52.5
Water Vapor Pressure, MM HG	11.0

Line-Line Voltage D-C Kv.	Spacing - Center to Center 30.0 Cm. P-Kw/Km	35.0 Cm. P-Kw/Km	40.0 Cm. P-Kw/Km	45.0 Cm. P-Kw/Km	50.0 Cm. P-Kw/Km
66.5	0.00				
67.3	0.04				
69.1	1.42	0.00			
70.8	2.57	1.27	0.226	-----	0.021
71.6	----	----	-----	0.115	-----
72.5	4.00	2.06	0.595	-----	0.174
73.4	----	----	-----	0.463	-----
74.2	4.80	2.76	1.55	-----	0.408
75.1	----	----	----	1.07	0.654
76.0	6.19	3.48	2.21	----	0.890
77.7	7.47	4.33	2.87	1.84	1.35
79.4	8.75	5.26	3.50	2.36	1.69
81.1	9.94	6.27	4.25	2.86	2.11
82.9	11.5	7.46	4.92	3.51	2.56
84.6	13.3	8.45	5.66	4.12	2.99
86.3		9.55	6.53	4.63	3.54
88.0		10.83	7.55	5.33	4.08
89.7		12.34	8.50	6.05	4.68
90.6		13.0	9.00	----	----
91.5		13.9	9.48	6.80	5.27

Wire length 6.34 meters.

TABLE XV

D-C CORONA POWER LOSS FROM
PARALLEL WIRES IN AIR

Polished Wire No. 10 AWG Diameter 2.55 MM

Barometric Pressure, MM HG	751.2
Dry Bulb Temperature, Deg C	24.4
Wet Bulb Temperature, Deg C	18.9
Relative Humidity, Per Cent	59.0
Water Vapor Pressure, MM HG	13.6

Line-Line	Spacing - Center to Center				
Voltage	30.0 Cm.	35.0 Cm.	40.0 Cm.	45.0 Cm.	50.0 Cm.
Kv. D-C	P-Kw/Km	P-Kw/Km	P-Kw/Km	P-Kw/Km	P-Kw/Km
73.5	0.00				
74.2	0.23				
75.1	0.54				
76.0	1.14				
76.8	2.50	0.15			
77.7	3.71	0.44			
78.5	4.47	1.16	0.07		
79.4	5.66	1.95	0.30		
80.3	6.65	2.01	0.75		
81.1	7.53	2.95	1.20	0.19	
82.0	8.43	3.92	1.79	0.25	0.09
82.9	9.35	4.77	2.04	1.00	0.17
83.7	10.4	4.98	2.73	1.67	0.59
84.6	11.4	6.34	2.99	2.24	1.13
85.4	12.4	7.00	3.80	2.83	1.38
86.3	13.6	7.85	4.45	3.20	1.95
87.2	14.8	8.67	5.30	3.64	2.30
88.0	16.1	9.53	5.75	4.00	2.59
88.9		10.4	6.32	4.37	2.93
89.7		11.2	6.96	4.86	3.21
90.6		12.2	7.56	5.30	3.52
91.5			8.23	5.76	3.86
92.3			8.83		4.20

Wire length 5.28 meters.