DIRECT CURRENT CORONA FROM DIFFERENT SURFACES AND METALS.

BY SYLVAN J. CROOKER.

I. INTRODUCTION.

IT has been shown by F. W. Peek[1] and by S. P. Farwell[2] that the corona discharge is quite different when the wire is positive and when it is negative. The starting point of the corona as well as the characteristic curves depend on the polarity of the wire. When the wire is negative the corona assumes the form of bright " beads " which are strung along the wire more or less evenly, the number of the beads per unit length depending on the pressure of the gas and the potential difference between the wire and the cylinder. This beautiful but complicated phenomenon suggested that probably the surface conditions and the chemical nature of the wire might influence at least the negative corona in the form of beads.

It became the purpose of these experiments then to find out the influence of the surface condition of the wire upon the starting point and the characteristics of the corona discharge phenomena.

The apparatus used consisted of a metal cylinder (inside diameter 3.63 cm.), with a longitudinal slot for observation (1.53 cm. wide), sealed in a glass cylinder and arranged in such a manner that wires of different sizes could be easily strung along the cylinder axis. It was possible to readily connect the tube to a vacuum pump for varying the pressure. The high potential direct current was taken from forty 500-volt D.C. generators connected in series. The machines were self-exciting and could be cut in or out by closing or opening the field switches. Smaller variations than 500 volts could be obtained by varying the speed of the driving motors or by the adjustment of a rheostat which was connected in the field of one of the machines.

The voltage was read on a Kelvin electrostatic voltmeter which had been calibrated with an attracted-disc electrometer. The current was measured with a D'Arsonval galvanometer whose figure of merit was found to be 6.25×10^{-6} amperes.

[1] F. W. Peek, Jr., Dielectric Phenomena in High Voltage Engineering, p. 27.

[2] S. P. Farwell, "The Corona Produced by Continuous Potentials," A. I. E. E., November 13, 1914.

PLATE I.
To face page 344.

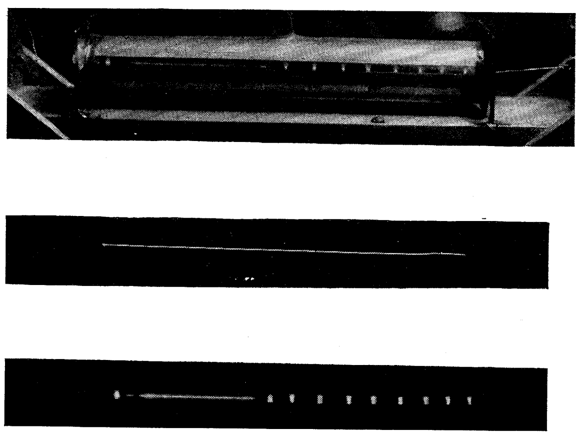

Fig. 1.

Steel Wire, 0.28 mm. Diameter.

	Corroded.	Polished.	Pressure.
No. 1.	Wire −,	2,000 volts,	30 mm.
No. 2.	Wire +,	2,300 volts,	40 mm.
No. 3.	Wire −,	2,300 volts,	40 mm.

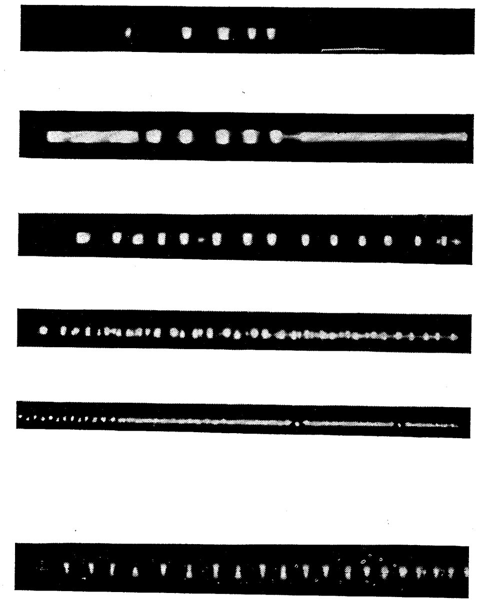

Fig. 2.

Steel Wire, 0.28 mm. Diameter.
All wires negative.

Abrased.	Polished.	Corroded.	Pressure.
No. 4.	990 volts,		21 mm.
No. 5.	1,080 volts,		25 mm.
No. 6.	1,400 volts,		39 mm.
No. 7.	2,300 volts,		68 mm.
No. 8.	8,900 volts,		370 mm.

Steel Wire, 0.41 mm. Diameter.

Abrased.	Polished.	Corroded.
No. 9.	1,650 volts,	30.2 mm.

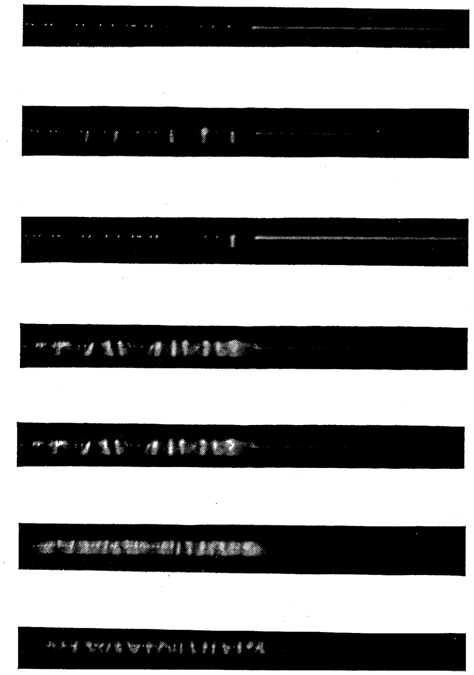

Fig. 3.

German Silver Wire, 0.65 mm. Diameter.

Enameled.			Polished.
No. 10.	Wire +,	1,460 volts,	23.5 mm.
No. 11.	Wire +,	1,700 volts,	25.5 mm.
No. 12.	Wire +,	1,830 volts,	35.5 mm.
No. 13.	Wire +,	2,800 volts,	91.5 mm.
No. 14.	Wire −,	3,920 volts,	185.5 mm.
No. 15.	Wire +,	4,400 volts,	185.5 mm.
No. 16.	Wire +, arc in series,	4,450 volts,	185.5 mm.

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Preliminary Experiments.—Preliminary experiments were made using a steel wire the surface of which was polished over one half its length and corroded with nitric acid over the other half. When the wire was placed in the tube and corona made to form on it at low pressures, the effect of the surface condition was made evident at once. Nos. 1 and 3 in Fig. 1 show this experiment. The right half of the wire is polished and has the characteristic negative beads, while the left half is chemically corroded and only a soft glow appears there. This glow is different from the characteristic positive glow in that it is much greater in diameter and has a fuzzy appearance like eider down.

Of course it must be noted here that this condition is for a slightly higher potential than that at which the glow first appears and that the fuzzy glow eventually breaks into the beads upon raising the potential. However the beads on the corroded end do not have the sharp clear-cut appearance as those on the polished end, but are fuzzy and less well defined. The positive glow is also shown in Fig. 1, No. 2, under these same conditions, but it presents the same appearance for both parts of the wire.

The first experiment led to the trial of a wire whose surface was not only (1) polished and (2) corroded, but also (3) mechanically abrased. The differences existing here were also very striking and clearly shown at once. Fig. 2 contains photographs of the negative wire, the left end being abrased, the center polished, and the right end chemically corroded.

No. 4 shows the starting of the corona at low pressures and correspondingly low voltages. It will be seen that the beads start first on the polished surface (1), while the corroded surface (2) shows no glow and the abrased surface (3) has but a slight brush discharge on it. The beads on (1) are very large, clear, steady and quite evenly spaced.

No. 5 shows the effect of a slight increase in voltage where the glow now appears on surface (2) and the beads begin to form on surface (3). Gradually increasing the voltage and the pressure as well causes the glow to become brighter on (2), the beads to increase on (1) and (3). The beads on the abrased portion have a lateral movement, while those on the polished part are still very steady and clear.

With still greater increase in pressure and voltage it is possible to reach a condition where the whole length of the wire is covered with clear, steady and evenly spaced beads (see No. 6). Here it seems that the surfaces all act very nearly the same regarding the formation and building up of the corona discharge.

Now when the pressure is increased to 370 mm. and the voltage is increased to produce the discharge it is found that the corona starts first on the abrased portion and that it is only on this part clear steady beads can be obtained (see No. 8). The beads on the corroded part are fairly well defined but they are in an agitated state, moving back and forth on the wire. Under these conditions it is found impossible to get steady beads on the polished part of the wire; instead of the clear beads there is a rather knobby glow on the wire, the condensations in which seem to be beads trying to form.

This reversal of the phenomena, as shown in Fig. 2, where the clear beads form on the polished surface at low pressures and on the abrased surface at high pressures, has been found to be a real one for steel wire. The corona starts first on the polished wire for low pressures and begins on the abrased or corroded wire at much lower potentials for high pressures.

An enameled german silver wire was fitted in the tube after one half of its length had been freed from the enamel and polished. At low pressures for the positive wire the characteristic glow would appear on the polished end. The enameled end would have several small star-like spots of light irregularly distributed over it appearing at points where the insulation had broken down. Keeping the wire positive and increasing the voltage caused very bright "streamers" of purple light to shoot out from a few of these small stars. At higher pressure and higher

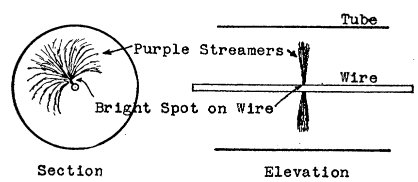

Fig. 4.

voltage these streamers increased greatly in number, the glow spreading out into a thin fan-shape. This fan would slowly oscillate or rock back and forth about the bright spot on the wire as a center. Between these fans a hazy fog-like glow was everywhere present. Upon placing an arc in series with the wire and the tube this fog would disappear and the fans would become more sharply defined and more steady.

For the wire negative (see Fig. 3, No. 14) it was impossible under any conditions to get the characteristic negative beads. Neither could a glow be produced on the polished end, the only discharge present was on the enameled end similar in appearance to the small stars for the positive wire. However for the negative wire the stars were intensely bright and in slight movement. Fig. 3 shows the appearance of the discharge from the enameled wire when both positive and negative. Fig. 4 gives details of the structure of the positive purple fans. For the enameled wire negative the starting potential was much lower than for the opposite polarity.

Figs. 1 and 3 suggest that the starting point of the corona and the characteristic curves depend on the surface conditions. In order to test this suggestion the following experiments have been performed.

II. Visual Corona and Starting Potentials.

Many characteristic curves were obtained for different sizes of copper wire where the surfaces were polished and abrased and many more characteristic curves were taken, using wires of copper, steel, aluminum, and silver where the surfaces were polished, abrased or roughened, and chemically corroded or oxidized. The more striking results will be given in the following paragraphs.

Preparation of Surfaces.—For the polished surfaces care was taken in choosing wires without kinks or surface scratches. These wires were polished with fine emery cloth and finished with chamois and jeweler's rouge just before placing in the tube.

The abrased surfaces were prepared by rolling the wire in emery powder between two hard plane surfaces. Care was taken to have the surface abrased uniformly over the whole length.

The corroded surfaces were prepared by different methods. The surface of the steel wire was corroded by dipping in a solution of nitric acid, a black surface resulting. The aluminum wire was corroded by allowing it to remain in a solution of sulphuric acid for a few days. The result was a thin white coating. For copper it was necessary to oxidize the surface by passing a heating current through the wire in the presence of oxygen. Since large quantities of ozone are produced by the corona discharge the silver wire was coated with a layer of silver peroxide by allowing the corona to play on the wire for some time.

The phenomena are very complicated. Their description will be carried out according to the surface condition of the wire, and for each individual condition three pressures will be considered.

Wires Polished.—The general appearance of the corona is the same for all polished positive wires, and differs but slightly for negative wires at the different pressures. At pressures of about 50 mm. when the potential is brought up to the glow potential, wire positive, a very faint flashing glow is seen over the whole length of the wire, which becomes uniform and steady as the potential is raised slightly. The potential may be carried up to the arcing point without changing the general appearance of the uniform glow. The only noticeable change is an increase in the brightness of the bluish glow.

For pressures of 50 mm. and negative wire, the first appearance of the corona is a flashing glow, similar to that for positive wire, but of much greater diameter and brighter. Increasing the potential causes this glow to remain steady on the wire, becoming uniform and very bright. Very little current flows until a stage is reached not far above the starting point, where the bright uniform glow breaks into large clear characteristic negative beads. From this point on the current increases rapidly with the potential. As the potential is increased the beads increase in number but remain large and well defined, this will be discussed more fully later on.

For the polished surfaces and pressure of 50 mm. the negative corona on copper begins at a lower potential than the positive. Corona appears at the same potential for both polarities in the case of steel, but for aluminum and silver the positive glow begins at the lower potential. This

TABLE I.

COMPARISON OF STARTING VOLTAGES FOR DIFFERENT SURFACES AND WIRES.
All wires about 0.41 mm. diameter.

Polished			Abrased			Corroded		
Press. mm.	Wire Volts. −	Wire Volts. +	Press. mm.	Wire Volts. −	Wire Volts. +	Press. mm.	Wire Volts. −	Wire Volts. +
Copper.								
50	1,700	1,780	53.2	1,680	1,820	50.3	1,650	1,660
252	2,650	2,600	253	2,550	2,800	250	2,010	2,500
731	6,010	5,760	743	5,600	6,200			
Steel.								
51.6	1,710	1,710	52.2	1,690	1,740	52.3	1,750	1,700
252.4	2,600	2,600	253.2	2,770	2,770	252	2,550	2,710
727.6	5,660	5,960	736	4,560	5,830	739.4	4,810	5,760
Aluminum.								
50	1,760	1,720	52	1,660	1,800	51.9	1,240	1,690
251	2,820	2,900	251.5	2,490	2,900	252	2,370	2,660
741.1	5,880	6,180	741	5,010	5,800	745.3	4,680	5,880
Silver.								
53.2	1,850	1,820	52.3	1,730	1,740	52.5	1,850	1,780
252.1	3,150	3,050	252.2	2,600	2,900	252.2	3,150	3,000
744.8	4,210	6,130	743.2	5,060	5,850	746	5,760	6,320

is shown by Table I., which contains the starting potentials for the different metals and different surface conditions. Table I. shows no general law. With the exception of the silver wire at a pressure of 746 mm. the starting potential for the corroded wire is smaller for both polarities than for the polished wire. For the negative abrased wire the starting point is in general lower than for the polished wire with only two small exceptions. With the exception of silver the starting point of the abrased positive wire is higher than that of the polished wire. With increasing pressure the differences involved by abrasion and corrosion diminish. The largest influence is found for aluminum wire, negative corroded at 51 mm.

For pressures of about 250 mm. the glow for wires positive is the same as before, being uniform and increasing in brightness as the potential increases. For wires negative and polished it was almost impossible to break the glow up into clear-cut beads at this pressure. With increasing potential the glow would become brighter and would condense at certain ill-defined points apparently attempting to form beads, but these condensed regions would be in rapid motion back and forth along the wire.

For atmospheric pressure, wires polished and positive, the glow would appear faint but uniform and would increase in brightness as the potential was increased. For negative wires a faint flashing glow would appear at break-down potentials increasing in brightness with the potential increase. A very few scattered beads would at times be formed, but they would be small and unstable having very rapid lateral motion. This motion would increase in amplitude and speed with increasing voltage. Clear cut beads over the whole wire was impossible here as in the last case.

Wires Mechanically Abrased.—With wire surfaces mechanically abrased or roughened and pressure of 50 mm. the positive glow begins with faint flashes as in the case of the polished surfaces, the glow becoming steady, uniform and increasing in brightness as the potential is increased. The starting glow voltage is in general higher than for the positive polished wires, and is also higher than for the abrased negative wires. For wires abrased and negative the corona begins with bright flashes of a fuzzy glow, part of which might have one or two large flashing beads. This flashing glow seemed to pulsate in synchronism with the impulses of the driving machinery. A slight potential increase above the first noticeable glow would cause the glow to break into well-defined beads which would soon become steady and clear, increasing in number with a potential increase. The negative starting voltage for abrased wires is lower than for the polished surfaces.

For wires abrased and pressures of 250 mm. the positive visual glow is the same as before. The positive starting potential is in general higher than for the negative abrased and also positive polished surfaces. The negative glow voltage causes very faint "spears" or small brushes of light to flash out from sharp points here and there on the rough surface. These spears increase in size and number with increased potential, some being much brighter than others. As the potential is increased these spears unite into definite, clear beads which at times may be very steady and at other times may have more or less violent lateral movements. The negative starting voltage for abraised surfaces is much smaller than for the polished surfaces.

At atmospheric pressures the positive glow on the abrased wire surfaces usually begins with a few small flashing purple streamers or brushes extending from the wire almost to the tube. These streamers are similar in appearance to the positive fans and streamers emitted from the surface of the enamel covered wire, see Figs. 3 and 4. These streamers increase in brightness and are accompanied by soft glow as the potential is increased. After a certain increase has taken place in the voltage these streamers disappear only the uniform glow remaining and increasing in brightness.

For the abrased negative wire at atmospheric pressure the corona starts

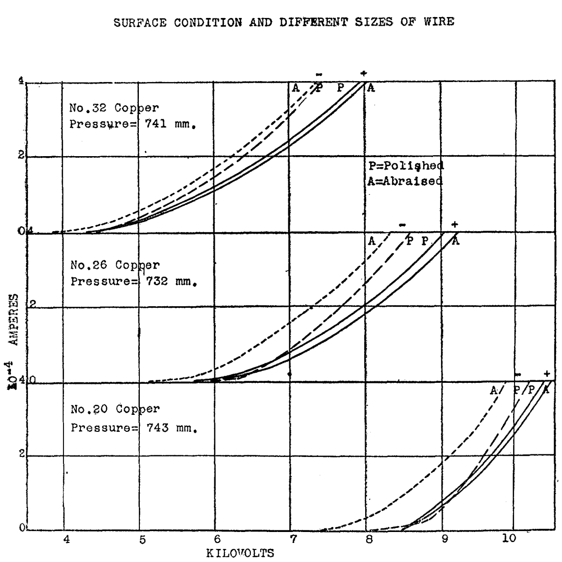

Fig. 5.

with small flashing spears the same as for the abrased wire at 250 mm. These spears increase in number very rapidly with an increase in voltage, some of them collecting, so to speak, into small bright beads and then breaking up again. As the potential is still more increased the beads become more steady and definite, so that at times the abrased wire may be covered with many small, bright, steady and evenly spaced beads.

Chemically Corroded Surfaces.—The positive visual corona for corroded surfaces is essentially the same for all pressures as has been described for the abrased surfaces. At low pressures it begins with a faint flashing glow which becomes steady and uniform, increasing in brightness. At pressures of 250 mm. the appearance is the same as above, and for atmospheric pressure the corona may start with the small purple brushes or fans and an accompanying glow, the fans soon disappearing and the glow becoming uniform and increasing in brightness. The positive glow generally begins at lower voltages for the corroded surfaces than for the polished.

The negative visual corona for the corroded surfaces is likewise similar to that for abrased surfaces at the different pressures. Clear cut and steady beads are obtained at the lower pressures but are not as stable for the higher pressures. In general the negative starting voltage is lower than for polished surfaces.

III. Characteristic Curves for Different Wires and Surfaces.

Varying the Radius of the Wire.—The curves in Fig. 5 are taken for different sizes of copper wire. They show that the effect of abrasion in general lowers the starting point for copper wires at atmospheric pressure. The negative abrased curves are widely displaced from the polished ones, showing that more current flows in the corona discharge for the same voltage for wire abrased than for the smooth wire. The positive abrased curves quickly cross the polished ones and then continue to rise slightly displaced, less current flowing for the same potential abrased than for polished. Thus the abrased surface has the effect of restraining the flow of the positive current.

The effect of abrasion is much greater in the case of the negative current. The curves also show that this effect is greater for the larger sizes of wire, which might be expected. The higher starting potentials for the larger-sized wires is also evident.

The negative current builds up very slowly at first on the polished surface but finally reaches a point where it builds up much faster than the positive; at this point the beads are formed. The starting voltage for the abrased surface negative is much lower than for polished negative. The characteristic curve of the abrased wire is a smooth rising one eventually crossing the polished negative curve for large current values. This same phenomenon has been observed for different metals.

Different Surface Conditions for the Same Metal.—Fig. 6 gives the characteristic positive and negative curves for aluminum wires at about 50 mm., showing the effect of the three surface conditions; namely, polished, abrased and corroded. The starting positive wire voltage for the smooth surface is slightly lower than that of the negative, but the curves cross low, the positive current building up quite slowly with increased potential, while the negative curve is almost a straight line rising

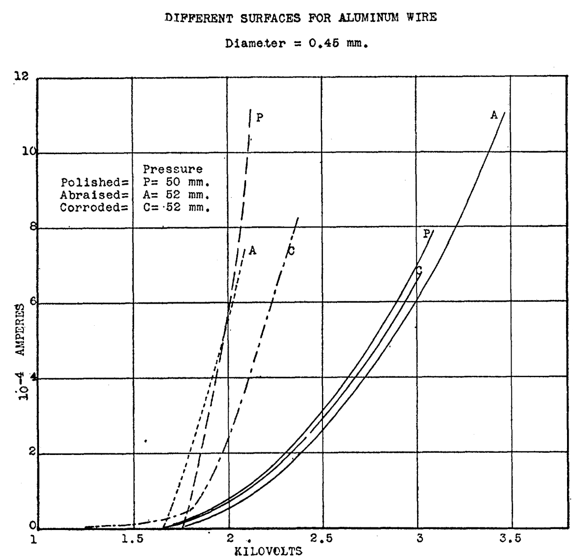

Fig. 6.

very rapidly. The positive starting potential is higher for the abrased surface than for the polished, while that for the negative abrased surface is lower. The negative polished and abrased surface curves cross but the positive do not. For the corroded surface the positive glow voltage is about the same as for the polished surface, the curve for the former condition becoming displaced shortly, less current flowing for the same voltage. The negative starting potential is very much lower in the latter case than that for the polished surface, but crosses at a low current value and rises to the right, less current flowing for the same potential.

Thus it is seen that the surface condition has a very marked effect on the starting point of the corona as well as on the characteristic curves. All the wires were about 0.41 mm. in diameter. In general the abrased surface has the effect of lowering the starting potential for negative wire and raising it for positive wire. The starting point for both positive and negative in the case of corroded wires is in general lower than for the polished surfaces, but the corroded surface characteristics behave in rather an erratic manner, sometimes being displaced in one way and sometimes in the opposite.

Table II. gives a comparison between the corroded and polished wire characteristics for both positive and negative at different pressures.

Table II.

Comparing Corroded with Polished Wire Characteristics.

Wire.	Press.	Starting Pot.	Corroded Surface Characteristic.
		Copper.	
−	50.2	Lower	Raised.
+	50.4	"	"
−	250.0	"	Crosses high.
+	250.8	"	Raised.
		Steel.	
−	53.2	Higher (press. diff.)	Corsses high.
+	52.4	Lower	" "
−	252.0	"	" low.
+	252.4	"	Lowered.
−	739.4	"	Crosses high.
+	739.4	"	" low.
		Aluminum.	
−	51.9	Lower	Crosses low. (For instance see Fig. 4.)
+	51.9	"	" "
−	252.0	"	" midway.
+	252.0	"	Raised.
−	745.3	"	Crosses midway.
+	745.4	"	Raised.
		Silver.	
−	52.5	Same	Lowered.
+	52.5	Lower	"
−	252.2	Same	Crosses low.
+	252.2	Lower	" midway.
−	745.8	Higher	Lowered.
+	746.1	"	"

Different Metals of the Same Radius and Surface Condition.—Farwell[1] by electrolytic processes covered the surface of a wire with different metals to determine their effect. He observed slight discrepancies but attributed them to experimental errors and concluded with Whitehead[2] that the formation of the corona is independent of the material of the wire.

Table I. compares the starting voltages for wires of the same size but

[1] S. P. Farwell, "The Corona Produced by Continuous Potentials," A. I. E. E., November 13, 1914.

[2] Whitehead, "The Electric Strength of Air, I.," A. I. E. E., July, 1910.

of different kinds of metal for different surfaces and pressures. Curves in Fig. 7 show a comparison between the characteristics of different metals. Very marked differences are evident in the characteristic curves, showing directly that the metal itself has a part to play in the corona formation. The positive and negative characteristics, especially

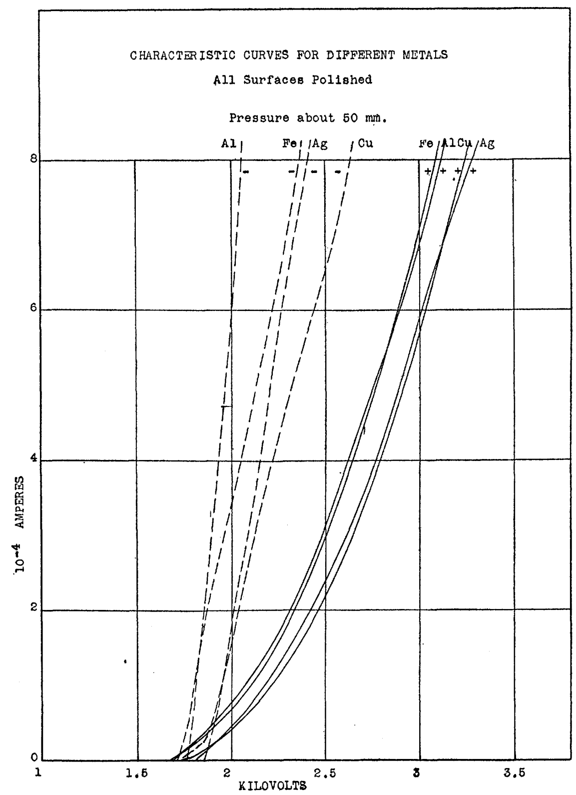

Fig. 7.

for the case of aluminium, become widely separated for large currents, the curves for the other metals separate at different rates for increasing current values, but in such a manner that each metal behaves in its own characteristic way.

Slight differences in the starting points for the different metals were noticed; these differences however are of such a nature that they cannot be explained as being experimental errors. Steel and copper seem to have about the same starting point, while that for aluminum is a little higher and silver has a value still greater. The different metals not only affect the behavior of the characteristic curves but also the starting points of the corona glow.

The Effect of Ozone on the Corona.—The presence of ozone has a definite effect on the appearance of the corona as well as on the characteristic curves. If ozone is present in the corona tube in any quantity the negative beads do not form quite as distinctly as they do when a stream of air is passing through the tube, carrying the ozone away. The effect on the negative characteristic curve is very slight, displacing it a little to the right, such that less current can flow for the same potential (see Fig. 8). For the positive characteristic the effect is somewhat larger

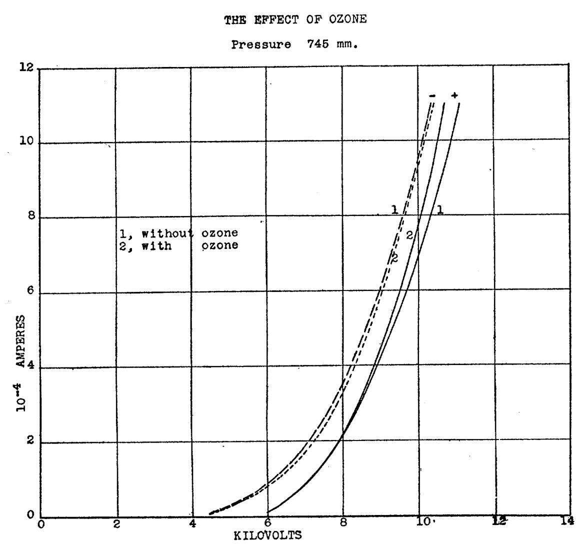

Fig. 8.

and in the opposite direction, the curve being displaced to the left, showing that more current for the same potential flows through the tube with ozone present than does in its absence. At atmospheric pressure ozone is formed quite rapidly but its effect is not large. At lower pressures with less gas present the formation of ozone is very much less and its effect on the corona is proportionately smaller.

The presence of ozone does not explain the differences in the characteristic curves for the different metals, unless it is a secondary effect between the wire and the ozone.

Formation of the Negative Beads.—The formation and number of the negative beads depends not only on the pressure and potential, but also on the surface condition and the material of the wire. (See Farwell on Material of Wire.) Fig. 9 shows the relations between the number of beads and the current for different surfaces of copper wire. The current per bead is larger for the abrased and corroded surfaces than for the polished surface, assuming the whole current to be carried by the beads. For an increase in pressure it is also seen that the current per bead is much less, but the beads are smaller in size. However, for the higher pressures it takes a larger voltage to produce the same number of beads. For the lower pressures the beads have about the same degree of stability

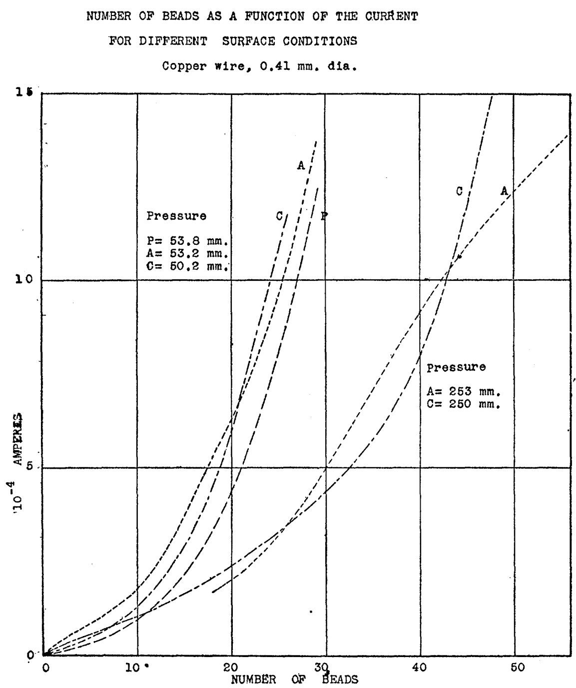

Fig. 9.

for all the different surfaces, while for higher pressures the beads are more stable on the abrased or corroded surfaces than on the polished, it being almost impossible to get definite beads on the polished wire for atmospheric pressures.

The number of beads increases rapidly with increasing voltage. Here again the effect of the materials is compared. For the production of the same number of beads it takes in general a greater voltage on the steel than on the copper and aluminum wires.

IV. Theoretical.

Electronic and Ionization Effects Combined.—The theories by Townsend[1] and Bergen Davis,[2] which have been proposed to explain the corona phe-

[1] Townsend, "A Theory of Glow Discharges from Wires," Electrician, June 6, 1913.

[2] Bergen Davis, A. I. E. E., April, 1914.

nomena, have been based upon the assumption that only an ionization of the gas takes place. These theories have explained some parts of the observed phenomena very well, but as for other parts it is impossible to produce a complete explanation by this one assumption. It is conceded that the ionization effect has a great deal to do with the corona action but it is not possible that there are other effects which are working in conjunction with this one.

In the following an attempt will be made to explain the corona phenomena not as an ionization effect alone but as a combined action of ionization with electronic discharges.

In the experiments which have been described on the direct current corona the striking difference between the positive and negative corona is everywhere apparent, not only in the visual corona but also in the characteristic curves. The difference between positive and negative electricity has been noticed by many observers in different experiments. For example, when a metal is heated it is known that electrons are shot off, these being negative charges of electricity which come from the metal itself. The same electronic discharge is obtained when a large force is acting between two cold electrodes in a vacuum. The example is seen in any X-ray or cathode discharge tube.

It will make no essential difference whether we assume the electrons to come from the metal itself, from the gas which the metal has absorbed, or from a thin layer of gas adhering to the surface of the metal.

On the other hand a discharge of positive electrons from a metal has never been observed. It always requires the presence of a gas to produce the positive charges of electricity. Experiments have also shown that these positive charges are atomic in size and hence are to be considered as positive ions.

The assumptions which are made in this theory then, are that there is a combined action of electronic discharge from the metallic surface along with ionization in the gas. In some cases the electrons will predominate in determining the character of the phenomena, while in others the ionization may be the determining factor.

Wire Surfaces Bare and Insulated.—It might ordinarily be supposed that to insulate the wire would increase the starting potential for the corona and cut down the loss. However, just the reverse of this was observed in Fig. 3 where part of the wire is covered with insulation and part bare and polished. It would seem almost like a paradox to say that insulation increases the corona loss, but it is found possible to explain this phenomenon by assuming electronic discharge from the metal and ionization in the gas.

Fig. 10 represents the conditions in this experiment. A potential V is impressed between the wire and the tube.

R_1 = the radius of the wire,

R_2 = the radius of the insulation, and

R_3 = the inside radius of the cylindrical tube.

The electric force E at the surface of the wire which is covered with insulation is given by the equation,

$$Ek2\pi R = 4\pi e,$$

where k = dielectric constant, R = point in which the force is being measured, and e = charge on the surface of the wire per unit length.

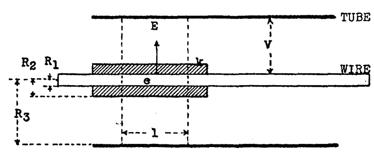

Fig. 10.

For a unit length of the surface,

$$E = \frac{4\pi e}{k2\pi R} = \frac{2e}{kR}. \qquad (1)$$

To calculate the potential or the work done in carrying unit charge through the distance dR, multiply by dR,

$$EdR = \frac{2e}{k}\frac{dR}{R}.$$

The work done in transporting the charge from R_1 to R_2 is

$$\int_{R_1}^{R_2} EdR = \frac{2e}{k}\int_{R_1}^{R_2}\frac{dR}{R} = \frac{2e}{k}\log\frac{R_2}{R_1}. \qquad (2)$$

Similarly, the work done through the distance R_2 to R_3, where $k = 1$, is

$$\int_{R_2}^{R_3} EdR = 2e\int_{R_2}^{R_3}\frac{dR}{R} = 2e\log\frac{R_3}{R_2}. \qquad (3)$$

The potential

$$V = \int_{R_1}^{R_2} EdR + \int_{R_2}^{R_3} EdR = 2e\left(\frac{1}{k}\log\frac{R_2}{R_1} + \log\frac{R_3}{R_2}\right), \qquad (4)$$

$$e = \frac{V}{2\left(\frac{1}{k}\log\frac{R_2}{R_1} + \log\frac{R_3}{R_2}\right)} \qquad (5)$$

$$E = \frac{2e}{kR} = \frac{V}{kR\left(\frac{1}{k}\log\frac{R_2}{R_1} + \log\frac{R_3}{R_2}\right)} = \frac{V}{kR\log\left(\frac{R_2}{R_1}\right)^{\frac{1}{k}}\frac{R_3}{R_2}}. \qquad (6)$$

The capacity when the wire is insulated is readily calculated since,

$$C = \frac{e}{V} = \frac{1}{2\left(\frac{1}{k}\log\frac{R_2}{R_1} + \log\frac{R_3}{R_2}\right)} \tag{7}$$

Then when air only is the intervening medium, $k = 1$ and $R_2 = R_1$, therefore,

$$C_1 = \frac{1}{2\log\frac{R_3}{R_1}} \tag{8}$$

and from (5),

$$e_1 = \frac{V}{2\log\frac{R_3}{R_1}} \tag{9}$$

By comparing (7) and (8) it is seen that the capacity is increased by placing insulation on the wire and we can therefore conclude that with the same potential difference the charge e on the surface will also be increased.

The force necessary to draw unit electric charge out from the metal when it is insulated is expressed by the relation

$$F = \frac{2\pi\delta^2}{k}, \tag{10}$$

but

$$\delta = \frac{e}{2\pi R_1},$$

then

$$F = \frac{e^2}{k2\pi R_1^2}$$

and from (5)

$$e^2 = \frac{V^2}{4\left(\frac{1}{k}\log\frac{R_2}{R_1} + \log\frac{R_3}{R_2}\right)^2};$$

therefore

$$F = \frac{V^2}{k8\pi R_1^2\left(\frac{1}{k}\log\frac{R_2}{R_1} + \log\frac{R_3}{R_2}\right)^2}. \tag{11}$$

Since the insulation is very thin R_2 is very nearly equal to R_1, and

$$\frac{1}{k}\log\frac{R_2}{R_1} = 0,$$

approximately and (11) becomes,

$$F = \frac{V^2}{k8\pi R_1^2\left(\log\frac{R_3}{R_1}\right)^2}. \tag{12}$$

When there is no insulation on the wire, $R_2 = R_1$ and only air remains between the electrodes, $k = 1$, and (11) reduces to,

$$F_1 = \frac{V^2}{8\pi R_1^2 \left(\log \frac{R_3}{R_1}\right)^2} \tag{13}$$

F and F_1 differ only by the constant $1/k$ so it is easily seen that the force F necessary to pull the electrons from the wire surface which is covered with insulation is much smaller than F_1, the force necessary to draw the electrons from the free surface after the insulation has become punctured. Therefore when the wire is negative, as is the case in No. 14, Fig. 3, there will be glow on the insulated side appearing at points where the insulation has broken down and there will be no glow on the polished surface. The discharge in this case is essentially electronic, the spots of light which appear are intensely bright and the potential at which glow begins is very much lower than when the wire is positive.

When the wire is charged positively as in Fig. 3, No. 15, there appears a faint uniform glow on the polished surface. This is the characteristic positive glow which has a pale blue color. This may be explained as being essentially an ionization effect. That is, the wire being charged to a certain positive value has force enough to split up the gas molecules by collisions in its immediate neighborhood and when the energy is large enough light is emitted. The negative particles are attracted to the wire while a layer of positive ions collect at the wire surface.

On the enameled end of the wire the density of electricity is larger per unit length. The streamers or fans of purple light approach the appearance of the direct current arc both in form and color, so we might say that these streamers are negative ions moving toward the positive wire with a great velocity. An analogy to this brush discharge phenomenon would be the stream lines of air entering small holes in a pipe carrying vacuum. The particles of air which are drawn to the pipe with increasing velocity are analogous to the negative ions which are drawn to the wire with velocity increasing as the wire is approached. These purple brushes have been noticed at different times for bare wires when positively charged. They seem to come especially from irregularities or points on the wire where there would be a great surface density.

The starting potential for corroded surfaces has in general been found to be much lower than for polished surfaces. An explanation is easily found by considering either one of two effects. Either the size of the wire is slightly reduced by corrosion, enabling the corona to start at lower voltages or the corroded surface acts as an insulator giving the same condition as has been explained for the phenomena in Fig. 3. The difference in starting potentials for corroded and polished surfaces is in general so large that the former explanation is hardly feasible, since the size of the wire could not have been greatly reduced. The latter seems to give the best explanation, since it is known that most of the oxides when dry are good insulators, and it would be possible with such an insulating layer to get a large difference in the starting potentials.

The Negative Beads.—The negative beads may be considered as being unstable in two senses. First, they move back and forth along the length of the wire, and, second, they give rise to oscillations. For instance it is known that a gas column or stream of electrons as in the Poulson arc is very unstable and gives rise to high frequency oscillations.

At the very beginning of the negative corona the glow covers the whole wire. A certain amount of energy is stored up in this layer which is in an unstable condition and easily breaks up into the characteristic beads. This is similar to a film of water covering a wire or string. The film will be uniform until a certain point of instability is reached when it will break up into drops or beads. This breaking up of an original uniform layer into beads has been observed over and over again. As soon as a bead is formed a large current starts in that region which heats the gas and the metal at that point. A thin metal wire may easily melt. If the temperature rises and the potential difference decreases at these points, the metal will be oxidized and the discharge will take place at a different point, causing the beads to move backward and forward along the wire.

Moreover the beads assume the shape of a fan whose plane is perpendicular to the wire, so that in these planes the temperature will be higher than in the neighboring regions. This will give rise to an unstable temperature distribution which will cause the beads to move along the wire. This effect is more pronounced when the wire is in a vertical position.

This instability is also shown by the fact that the pressure increase due to ionization when the wire is negative is very erratic and cannot be measured accurately, and by the fact that the field in the tube cannot be investigated by a third sounding-electrode, since very irregular results are obtained due to the presence of the beads, while the positive wire gives very regular results which can easily be repeated and show a marked distortion of the field between the wire and the cylinder.

There are several other cases in which the negative elctricity escapes from surfaces; for instance, in the mercury arc the glow from the negative terminal does not come from the whole surface of the electrode but from a bright spot on the surface of the mercury which moves about irregularly. Another case would be that of the ordinary carbon arc under certain conditions when the negative end of the flame moves about, and still another, Dr. Knipp's cylindrical cathode.[1] Indeed the negative bead resembles the arc in several respects; it may be called a small arc which by increasing the voltage gradually goes over into the more definite arc.

The beads represent in the second place a more or less unstable discharge in so far as oscillations are very easily set up. S. P. Farwell has shown that a small spark gap in series with the corona tube gives rise to oscillations in the electric circuit. Bennett[2] has shown that oscillations arise readily in the negative part of the corona for alternating currents. The arc, for instance the Poulson arc, is a transformer of direct current into alternating current of a very high frequency.

The beads are always brighter and steadier at low pressures that at high pressures. At low pressures the electronic discharge from the metal predominates over the ionization by collision in the gas. With increasing pressure the ionization by collision becomes more and more important, the beads become smaller and more numerous.

For a certain pressure and potential difference beads will appear on the abrased, polished and corroded surfaces of a steel wire in exactly the same way (see fig. 2, Nos. 6 and 9). This happens between the pressures of 30 and 40 mm. At a lower pressure (25 mm.) and a smaller potential difference beads appear only on the polished part, while a more or less uniform glow covers the corroded and the abrased portions; the surface irregularities on the corroded and abrased parts giving rise to very many overlapping beads, forming a soft glow. There are, as it were, too many but too weak opportunities for the formation of well-defined beads. For still lower pressures and potential differences the original glow covers only the polished portion first and it is only on that part that the clear beads will form.

Returning to the pressure, 30 to 40 mm., where the beads are evenly distributed over the whole wire, and increasing the pressure and the potential difference, then the number of beads increases. They become unsteady and fuzzy especially along the corroded and polished parts and finally with still higher pressures the beads are only well defined on the abrased part, where they probably are fixed by rough surface irregularities which act like small lightning rods. During all of these changes of the negative corona the positive glow remains perfectly constant, forming a well-defined uniform bluish glow along the wire.

It has already been shown that one should expect for corroded surfaces a smaller starting voltage than for the polished wire for both polarities.

[1] Dr. C. T. Knipp, Science, May, 1916.

[2] Bennett, Trans. A. I. E. E., Vol. 32 (1913).

For the negative abrased wire the starting voltage also is smaller than for the negative polished wire, a result which is evident. As clear beads are formed for the abrased wire at higher pressures one should expect that the negative characteristic curve is higher than that for the polished wire and that is actually the case (see Fig. 2, No. 8, and Fig. 5). On the other hand if at low pressures bright beads are formed on the polished wire one should expect the current to be larger than for the abrased and corroded wire and this also is the case. (Compare Fig. 2, No. 4, and Fig. 6.) Bright beads are always accompanied by a large current. Corrosion and abrasion have little influence on the positive characteristics.

Conclusions.

1. The surface conditions as well as the metal itself has an effect on the starting voltage and on the characteristic curves.

2. The number and brightness of the negative beads depend in a very complicated way on the surface conditions.

3. A thin layer of insulation on the wire renders the escape of negative electricity easier. This paradox has been explained.

4. The formation of beads and their instability has been explained on the assumption that the current is due to an emission of electrons from the surface of the metals and due to ionization by collision. Most of the complicated phenomena have been explained by this assumption.

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May 15, 1916.

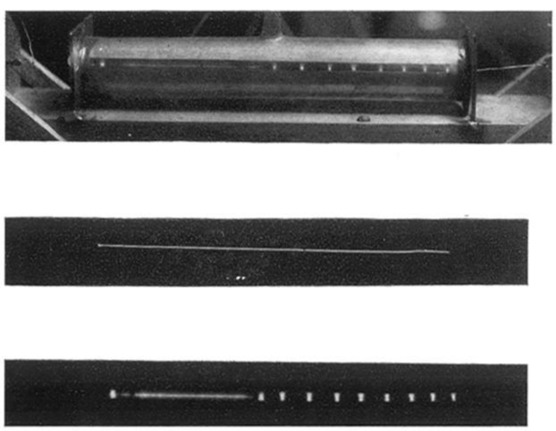

Fig. 1.

Steel Wire, 0.28 mm. Diameter.

	Corroded.	Polished.	Pressure.
No. 1.	Wire −,	2,000 volts,	30 mm.
No. 2.	Wire +,	2,300 volts,	40 mm.
No. 3.	Wire −,	2,300 volts,	40 mm.

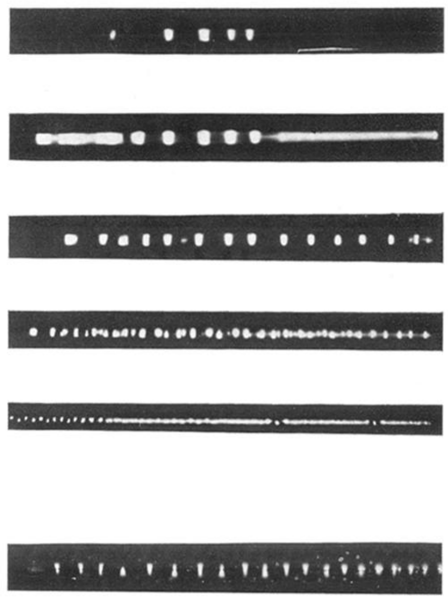

Fig. 2.

Steel Wire, 0.28 mm. Diameter.
All wires negative.

	Abrased.	Polished.	Corroded.	Pressure.
No. 4.		990 volts,		21 mm.
No. 5.		1,080 volts,		25 mm.
No. 6.		1,400 volts,		39 mm.
No. 7.		2,300 volts,		68 mm.
No. 8.		8,900 volts,		370 mm.

Steel Wire, 0.41 mm. Diameter.

	Abrased.	Polished.	Corroded.
No. 9.		1,650 volts,	30.2 mm.

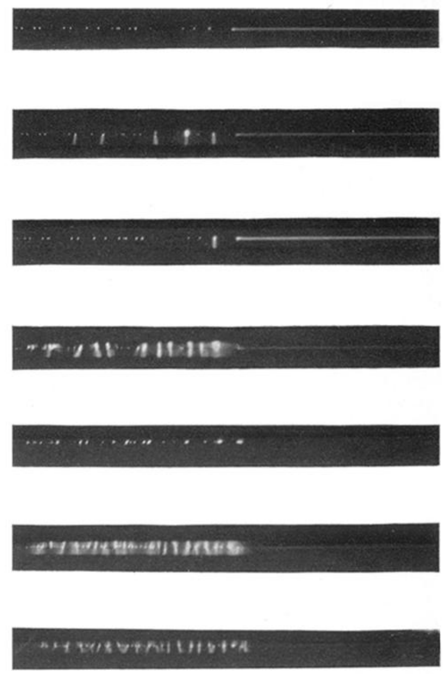

Fig. 3.

German Silver Wire, 0.65 mm. Diameter.

	Enameled.		Polished.
No. 10.	Wire +,	1,460 volts,	23.5 mm.
No. 11.	Wire +,	1,700 volts,	25.5 mm.
No. 12.	Wire +,	1,830 volts,	35.5 mm.
No. 13.	Wire +,	2,800 volts,	91.5 mm.
No. 14.	Wire −,	3,920 volts,	185.5 mm.
No. 15.	Wire +,	4,400 volts,	185.5 mm.
No. 16.	Wire +, arc in series,	4,450 volts,	185.5 mm.