The Mechanism of the Negative Point to Plane Corona Near Onset*

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Oscillographic studies have been made of the currents in negative point to plane coronas in air. The oscillograms obtained indicate that the negative corona current is composed of discrete pulses whose magnitude and frequency have a definite relationship to the corona current, point size and gas pressure. The frequency of the current pulses appears to be independent of gap length under the experimental conditions studied. The frequency of the oscillations does not appear to be affected by changes in the electrical constants of the discharge circuit outside the gap. The periodic character of the discharge seems to derive logically from space charge formation in the gap and subsequent clearing under the action of the electrostatic field.

INTRODUCTION

OSCILLOGRAPHIC studies have been made of the corona currents in negative point to plane coronas in air. The circuit arrangement used is shown schematically in Fig. 1.

Direct current at any desired voltage up to 25 kv is obtained from a half-wave Kenetron rectifier which keeps a $\frac{1}{4}$-mf condenser charged. The voltage is regulated by a Variac transformer in the primary circuit of the high voltage transformer. The voltage across the gap is read by means of one section of a White potentiometer across a part of a calibrated resistance tower connected in parallel with the gap. With the galvanometer used a voltage sensitivity of three volts per mm deflection was obtained. The gap consisted of points of several types opposed to a brass plate six inches in diameter. A radio receiver was used to pick up current variations in the gap. This receiver consisted of a 6J7 biased detector and two stages of resistance coupled amplification with 6F6 tubes. The receiver and gap were completely enclosed in a grounded sheet metal box $27\times27\times30$ inches. The output of the radio receiver was condenser-coupled through a shielded cable to the vertical plates of a nine-inch Dumont cathode-ray oscillograph. This oscillograph was equipped with a single sweep device so that photographs could be readily made of a single transit of the electron beam. A Leica camera was used to photograph at a lens aperture of f2 the single sweeps on Agfa ultra-speed panchromatic film. The films were projected to give an oscillogram approximately the full size of the trace on the oscillograph screen and measurements were made on these enlargements. With a sweeping time of 5/10,000 sec. the highest frequency photographed and resolved was 208,000 c.p.s. The time scale of the oscillograms was established by taking oscillograms of the output of a calibrated oscillator with the same sweep setting that was used for the corona oscillograms. Repeated photographs of a constant frequency wave indicate that the sweeping time of the single sweep may vary as much as 10 percent. This must be considered in the evaluation of the oscillograms of negative corona obtained with this instrument.

In earlier experiments a tuned input to the detector was used in order to obtain a maximum sensitivity. This was abandoned to avoid the

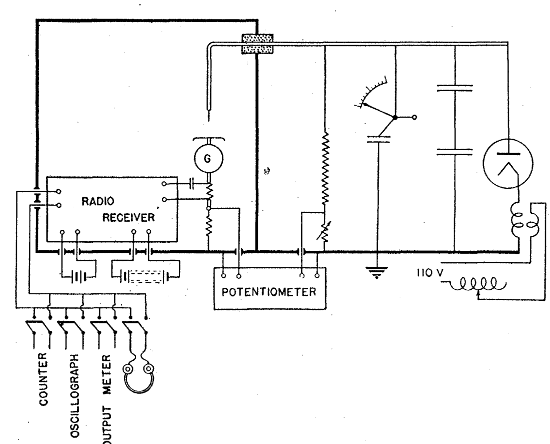

FIG. 1. Schematic diagram of the electrical circuits employed for negative point corona measurements.

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parasitic oscillations set up in the tuned circuit by shock excitation from the corona pulses. In the present experiments the detector was coupled to the corona circuit through a condenser and a 10,000-ohm noninductive grid return. The voltage applied to the set was taken across a 1000-ohm restistor in the ground lead from the plate electrode of the gap. The average current was read by measuring the voltage across this 1000-ohm resistor with the other half of the White potentiometer. Changes in current of the order of 10^{-9} ampere could be detected with this arrangement. A check was made with different values of grid resistor, coupling condenser and ground resistor to determine the effect of these values on the recorded frequency when corona current and gap were constant. These elements appeared to have no effect on the frequency of the recorded impulses but did change the magnitude of the recorded signals.

Four types of points were used as negative electrodes. Points I and II were of platinum wire of 0.5 and 1.5 mm diameter, respectively, having a hemispherical end of the same radius as the body. Point III was of brass, similar in shape, having a diameter of 4.73 mm and point IV was a steel sewing needle having an included angle of approximately 30° at the point.

Oscillograms were made of the transient characteristics of the corona current for different values of corona current, point and gap distance being kept constant. Fig. 2 shows a typical series obtained with point I at a gap distance of 3 cm. The current fluctuations are seen to consist of a succession of very regular impulses similar to those produced by a relaxation oscillator. The frequency varies linearly with the corona current over the range of currents observed. The shape of the impulses remains constant except that the decay curve is interrupted at higher and higher values as the impulses become closer together with increasing current.

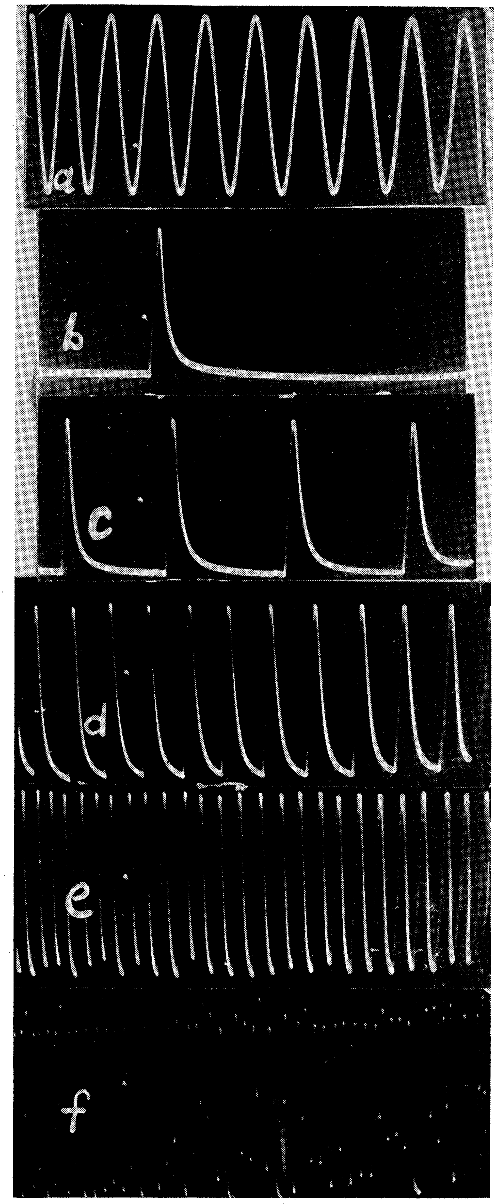

FIG. 2. Typical oscillograms of negative point corona for a 0.5-mm diameter point and 3-cm gap. (a) 8000 cycles calibrating wave; (b) single pulse 0.1μA; (c) 0.7μA; (d) 2.0μA; (e) 5.0μA; (f) 12.0μA.

Figure 3 gives the results of measurements made upon a series of four different points. It appears that frequency is a function of point diameter varying as a complicated and somewhat irregular inverse function of the radius at the point for the same corona current.

Figure 4 gives the results obtained when the same point (point I) was used with different gap distances.

Figure 5 illustrates the behavior of the frequency of the negative impulses when air pressure is varied. To obtain the effect of changes in pressure the electrodes were enclosed in a glass chamber having a grounded screen around the

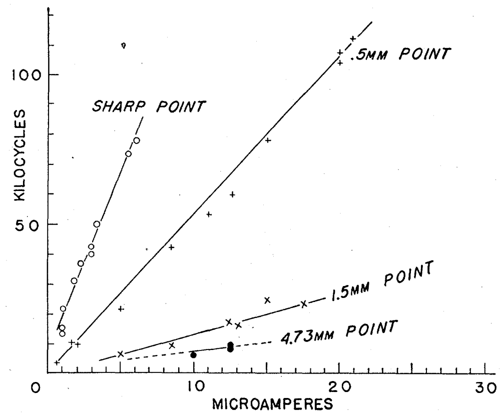

FIG. 3. Plot of the variation of frequency as a function of point size.

inside to prevent the accumulation of charge on the glass. The effects of small changes in pressure are not well resolved but some information can be gained as to the general trend of change in frequency with pressure.

DISCUSSION

Negative point corona phenomena appear to depend almost entirely upon the surface of the

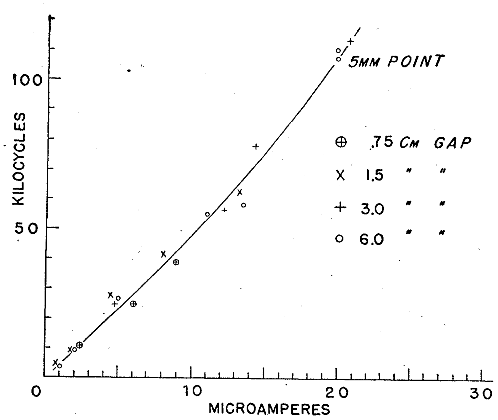

FIG. 4. Plot of the variation of frequency with change in gap distance for a 0.5-mm point.

point and the conditions which exist in the immediate vicinity of the point. The corona starts when a field exists near the point sufficient for a positive ion (produced in the field by some outside agency) to gain enough energy in its last free path to produce at least one secondary electron. The value of this energy depends on the work function of the surface for secondary electron emission on positive ion bombardment. This is described by Townsend's coefficient γ and γ is high when the work function is low. The coefficient γ is dependent on the state of the surface and is altered materially by adsorbed gas films.

The new electron proceeds away from the cathode in a field strong enough for it to form new ions by inelastic collisions with neutral molecules, and the electrons so ejected may continue the process of ionization. The number of ions *per impact* of electrons with molecules decreases as the electrons recede from the electrode to weaker field regions. The electrons, however, initially increase nearly exponentially in number with distance from the electrode until the fields become too weak to cause ionization. In air the electrons, after being slowed down, eventually attach to O_2 molecules to form negative ions. In the region where the electrons attach the accumulation of negative ions builds up a strong negative space charge. After a series of such cumulative electron avalanches, the process has left behind a cloud of positive ions of more or less spindle-shaped density contour with its apex towards the cathode. This process occurs in about 10^{-7} second. The positive ion space charge then moves towards the cathode under the influence of the field in the gap. The presence of this cloud of positive ions in the gap at first causes a greatly increased field near the negative point with increasing ionization by collision in this region and increasing secondary emission of electrons from the cathode. At the same time, the field beyond this space charge in the gap is decreased so that almost no ionization can take place beyond some tens of electron free paths. When this cloud of positive ions has reached a point very close to the cathode, ionization by collision practically ceases, and shortly thereafter the current begins to decrease. This comes about because the distance between the cathode surface and the positive space charge is zero or else too short to permit successive ionizing impacts in this region and through the shielding effect of the positive space charge which reduces the field beyond it to a point below that at which ionization by collision can occur. The current thus declines as the latter part of the dense portion of the ion cloud is drawn into the cathode. As the last individuals of the positive ion cloud reach the cathode, giving a weak current, the field again rises to high values beyond the first few free paths. The few remaining positive ions approach with sufficient energy to release at least one more electron causing the process of multiple ion production to repeat itself. The oscillatory nature of the current therefore depends upon the fact that the great mass of positive ions are produced by ionizing impacts by electrons at some distance from the cathode, in a position where they must ultimately choke off the discharge. This causes the stopping of electron ionization beyond the cathode space charge and results in a marked decrease or cessation of corona current until the normal gradients are restored.

In support of this explanation of the process we have already noted that the frequency is not a function of gap length for a given point, but varies linearly with current independent of gap length. The current however increases as the potential applied to the point increases. Hence the sweeping rate must increase as the fields increase. The added field also enables ionization to begin before as much of the space charge has been dissipated as is the case for lower fields. Thus as the potential increases the new discharge starts at a higher value of the decreasing current, and the discharges are more frequent. The sharply defined frequency and the fact that the current increases *nearly* in proportion to the frequency implies a marked constancy in other factors affecting the current such as area of discharge, etc. This inference indicates that further discussion requires more data concerning the discharge than that given by the oscillograms.

The quantitative studies were accordingly supplemented by a visual observation of the corona with a telemicroscope of some ten cm focal length such as is used with electroscopes. Observations with the dark-adapted eye yielded the following data, some of which may be new. The discharge for sharp needles always localized at the point, in the region of highest field strength and was confined to that region. With larger points the glow extended over limited but greater areas than with sharp points. While the glow was *near* the region of highest field intensity, it was *not always* to be found at that point. The glow, however, always started at the same spot on a given point and always ***remained about constant in size*** irrespective of current until there appeared a new or second spot. The sizes observed varied but lay between 0.15 mm and 0.20 mm in diameter for the point used. Plural spots were confined only to more extended surfaces at higher fields. This action of the active area contrasts sharply

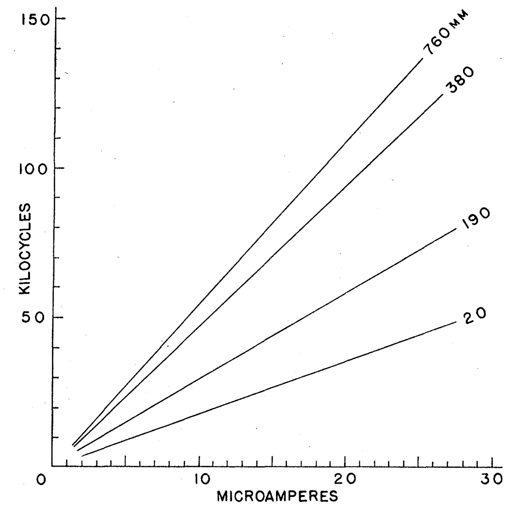

FIG. 5. Plot of the variation of frequency as a function of air pressure.

with the positive point where the glow spread progressively over the point as current and field increased.

Perhaps the most striking observation was that the intense zone of bluish light always appeared slightly detached from the cathode surface, indicating the existence of an exceedingly minute dark space next the cathode, analogous to the Crookes dark space. Beyond this the luminosity gradually faded off to be followed in general by another dark space, analogous to the Faraday dark space, beyond which there was a distinct but faint and very diffuse violet glow. This is shown in the sketch of Fig. 6. As fields and currents increased or pressure decreased this faint glow, analogous to the positive column, spread further into the gap, eventually covering quite a region about the point.

When the field had increased sufficiently with the larger points, a second luminous discharge spot appeared on the point. Frequently the appearance of the second spot caused the first spot to extinguish temporarily and thereafter the discharge alternated from one spot to the other. At still higher currents a third spot was observed, etc. While the regularity of the discharges shown in Fig. 2 at high frequencies is in part disturbed by the limit of resolution of the oscillograph, the indications were that the periodic discharge went over to an irregular discharge at currents and potentials at which the second spot appeared. The discharges always appeared at the same localities and at about the same currents and potentials for a given point.

The discussion of the observed quantitative data indicated that it was necessary to consider the area of the discharge, for the whole previous discussion was confined to electrode areas involving a few electron avalanches which are infinitesimal. However, as was seen, except for the finest points the regular discharge as usually observed covers an area far from infinitesimal, $\sim$0.1 mm. This requires explanation. From what is known of the mechanism, it is clear that the discharge must always start from that region at which we have the lowest work function for secondary electron emission by positive ion bombardment, i.e., the highest γ, and the highest field strength available. This means that for any extended surface spots which have an especially high γ may initiate a discharge even though they are *not* at the point of highest field intensity. Once the discharge initiates at one spot by positive ion impact, the intense photoelectric ionization about the active zone will spread positive ions laterally so that the *area* of the spot will *spread as far as the region of low work function and high field localization* will permit. This lateral spread of ionization over the electrode surface must be very rapid; otherwise the current rise could not be as sharp as observed. Thus the maximum ionization and the positive ion flow must be achieved over the spot in less than 10^{-6} second. If regions of very variable γ exist, a spot will be confined only to a region where the highest γ obtains with the requisite field. Spots will be larger for points of large radius than for small points as the larger high field regions give a greater opportunity for fully utilizing sensitive areas of high γ. Different electrodes may show spots of differing size. For a given electrode material the frequency for a given current should increase at first rapidly as the point becomes larger eventually for large points reaching a constant value characteristic of the particular electrode. As γ does not change *continuously* over the surface, small increases in field strength and current cannot increase the spot area markedly. The current for a given spot will thus be able to increase only by a more rapid sweeping rate and accordingly more rapid discharge rate, as indicated by the results. Hence the frequency is nearly a linear function of the current. Nonlinearity would be accounted for by slight changes in spot area as have been observed. With sharp points the fields are higher for the same current on account of the limited region and surface area available for discharge and consequently the frequency is higher for a given current.

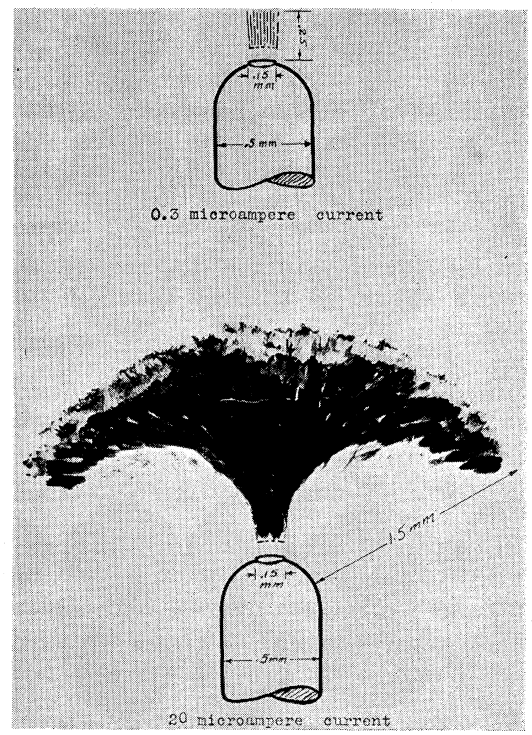

FIG. 6. Visual appearance of negative point corona.

The limit of frequency at which the periodic discharge disappears and gives place to the irregular noisy corona has not as yet been observed. It must occur at currents and potentials where more than one spot appears, as coherence of phase then ceases. The movement of the discharge from one spot to the next and back again can be explained on a classical basis. Positive ion bombardment denudes the surface of its gas film. This decreases γ and the discharge shifts to a spot of higher γ and appropriate field strength. After some time the first spot regains its sensitivity and the discharge returns.

Decreasing the pressure increases the mean free path of the electrons and the mobility of the ions. Thus the potential difference required to give a certain current might be expected to decrease in proportion to the pressure. The potential difference between the electrodes required to produce a given corona current, however, decreases by a factor less than the ratio of pressures. This follows since the reduction of pressure reduces the number of molecules in the high field region. The scarcity of molecules and correspondingly increased mean free path increase the distance between inelastic collisions. Hence if the same number of ions are produced, Townsend's α must have an appreciable value at *greater* and *greater* distances from the electrode as the pressure is decreased which in turn means an increased field. That is, the space charge is produced at a distance from the cathode and increases as pressure decreases thus requiring higher point potentials. This is borne out by the visual observation that the whole discharge appears to extend farther out into the gap at low pressure than for the same current at atmospheric pressure.

The frequency of the negative corona process must depend upon (1) the rate of ion production and (2) the rate of clearing of the space charge by the field. Since the ionizing electrons travel at high speeds the current will rise at a high rate; perhaps the slowest element is the time taken in lateral spread of the spot. The decline of the current depends on the cessation of ionization because of space charge accumulation and the time for a finite travel of the newly created positive ions to the electrode to remove the space charge. This time will vary with the field gradient. The decline of current follows the cessation of ionization and the sweeping out of the positive ion cloud. The decline will thus at first be rapid, becoming slower as the less dense and most distant portions of the positive ion cloud are drawn in. This accounts for the shape of the current pulses shown in Fig. 2. As the fields increase in intensity the positive ions are swept from the critical region in shorter time intervals, and the degree to which the ions are swept out for the next discharge does not need to be nearly as complete. Ionization will therefore begin again at a higher point on the discharge curve exactly as is shown by a comparison of the shapes of the oscillograms made under different discharge current conditions.

Mr. M. Sitney working in this laboratory has made a graphic study of the ionization produced in the vicinity of parabolic points. For these points the field before onset is capable of mathematical solution as a function of the total potential across the gap and the distance from the point. His plots of the ionization produced by a single electron ejected from the point obtained by numerical integration based on Sanders' values[1] of Townsend's α give a space distribution of ions in substantial agreement with the hypothesis of the writer. In this calculation, however, the very important effect of the positive space charge on the character of the curve had to be omitted.

The calculated distance of the *peak* of the positive ion space charge distribution from the electrodes for points of 0.25 and 0.5 mm radius at values of X/p at the surface of 105 and 108 is 0.05 mm and 0.2 mm at 760 mm pressure. In actual practice the effect of the space charge will be to shift the maximum very much nearer the electrode and to steepen the front. Except for various distorting factors in the detector and in current measurement the shape of the *current impulse* due to positive ions may not be far from the actual contour of positive space charge density. Thus one may well expect the distances to the electrode to be *materially less than those calculated*, in agreement with observation; for the thickness of the Crookes dark space was too small to resolve in the telemicroscope. The intensity of ionization at the maxima will cause the maximum luminosity of the spot to be in a very thin region about this point. At the *electrode surface*, despite the high fields and high values of α, however, there will be a relatively dark region akin to the Crookes dark space due to the relatively few ions formed. The exceptionally

[1] F. B. Sanders, Phys. Rev. **41**, 667 (1932); **44**, 1020 (1933).

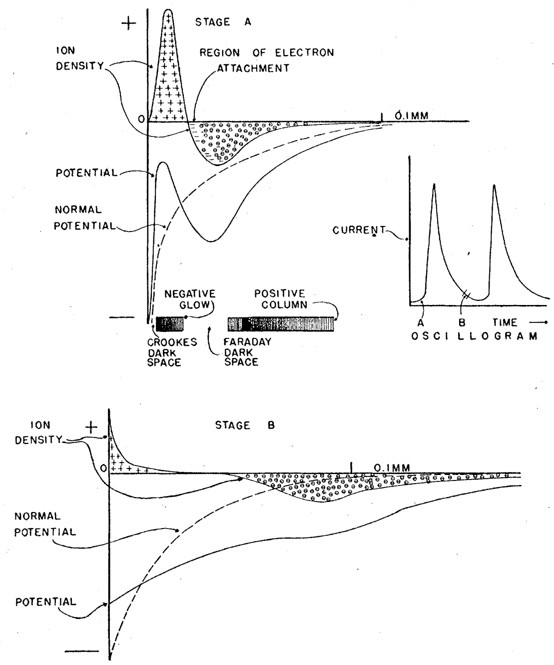

FIG. 7. Space charge distribution before and after the electron avalanches. Stages A and B probably correspond to points A and B on current oscillograms.

high fields between positive space charge and electrode, together with the values of the probability of excitation and ionization, will cause the appearance of the highest states of excitation in the luminous portion or negative glow. Here spark lines should be quite prominent. This is indicated by the color and spectra of the discharge. The progress of the electrons away from the point and their relatively rapid attachment to make slow ions when their energy is reduced at some distance from the point will build up a considerable negative space charge well beyond the luminous region of positive ions. With the weak field over the main length of the gap, the space charge can build up to considerable magnitudes where electrons attach. Hence a marked field distortion can take place. In this region of negative space charge, gradients of sufficient magnitude again might occur to cause ionization and excitation. These fields will be low compared with those at the point but may produce enough ionization and excitation to give a faint luminosity. In the region between the far side of the positive space charge and the negative space charge there appears to be little ionization. The "positive" column observed is probably the region of distortion due to the negative space charge concentration and the Faraday dark space corresponds to the region between this and the positive space charge. At high current densities the extent and intensity of these regions become much increased. The conditions which appear to exist are indicated schematically in Fig. 7, which is self-explanatory. From this it is clear that ultimate breakdown to a spark will occur as a result of the negative space charge accumulation at high current densities.

In conclusion the writer desires to express his gratitude to Professor L. B. Loeb, under whose direction the work was undertaken, for his continual guidance and for his considerable contribution towards the interpretation of the results. The writer also wishes to acknowledge his thanks to Mr. A. F. Kip, Research Corporation Fellow, for his hearty cooperation in many of the measurements and in their interpretation. The writer's thanks are due to Mr. M. Sitney, voluntary research worker, for his assistance in calculations. The writer must also acknowledge his indebtedness to the assistance of Mr. Edward Nunes and Mr. Roy Melton, workers on W.P.A. for their kindness in building up many of the electrical circuits required in this and in the positive corona study.

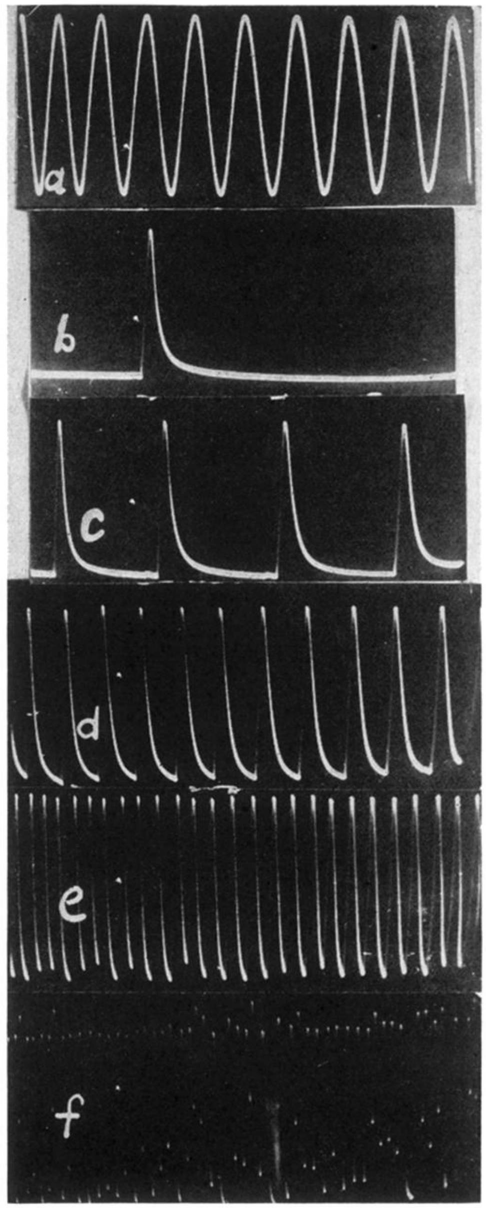

FIG. 2. Typical oscillograms of negative point corona for a 0.5-mm diameter point and 3-cm gap. (a) 8000 cycles calibrating wave; (b) single pulse $0.1\mu A$; (c) $0.7\mu A$; (d) $2.0\mu A$; (e) $5.0\mu A$; (f) $12.0\mu A$.

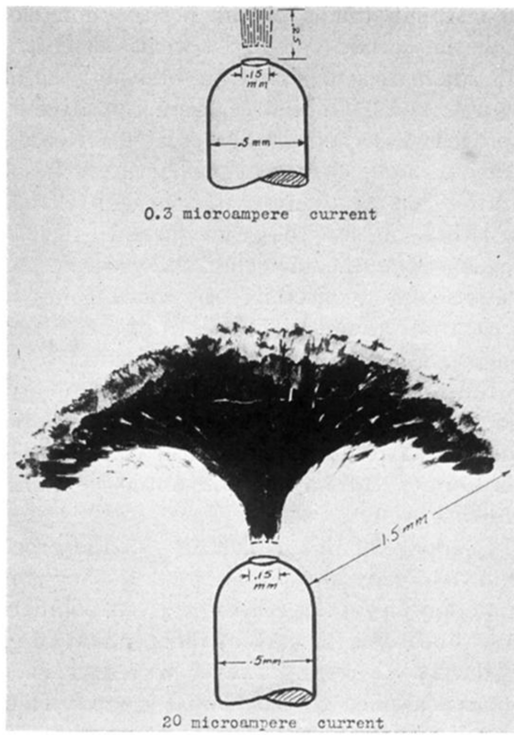

FIG. 6. Visual appearance of negative point corona.