Positive-Point-to-Plane Discharge in Air at Atmospheric Pressure

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Investigations have been carried out on current-voltage characteristics of positive-point-to-plane discharge. All currents start *abruptly* and increase at first linearly and then more steeply with voltage, until finally breakdown into a spark occurs. The corona process in air is shown to be a *discontinuous* one, involving the alternate propagation and space charge quenching of positive streamers out from the point. Photoelectric ionization in the gas is shown to account for the rapid self-propagation of streamers. Attachment of electrons to form negative ions and subsequent detachment of these electrons in the high field near the point provides means of starting new streamers for self-maintaining corona process. Fields at onset are calculated by the use of confocal paraboloids as electrodes, and it is shown that the fields necessary for such corona process are available. Introduction of a radioactive source into the gap indicates that the sharp cut-off of the corona current as the voltage is decreased is due to lack of electrons for initiating new streamers. Offset voltage marks the point at which the self-perpetuating ionization process begins. The initial current rise is found to increase as the gap distance is decreased and this is shown to be caused by the change in field distribution and consequent further extension of streamers into the gap. Below a certain minimum gap distance, depending on the point geometry, the initial streamers propagate completely across the gap and this introduction of the highly efficient ionization at the cathode causes spark breakdown. The initial current-voltage slopes are expressed as a resistance which is found to increase linearly with the gap and to account for approximately 1 percent of the total voltage drop in the gap. Extrapolation of resistance to zero resistance gives the minimum gap at which stable corona will flow. Above the initial current rise, the current increases as the square of the difference between the applied and offset voltage. Evidence indicates that this is caused by a superposition upon the otherwise linear rise in current with voltage, of an increase proportional to the current itself. Visual observation near breakdown indicates that this increase proportional to the current is associated with the utilization by later streamers of the residual paths of their predecessors. This becomes more pronounced as the current and voltage increase; the effect of earlier streamers in this way increases the current in later streamers. Spark breakdown occurs when the amalgamated streamers succeed in crossing to the plate.

INTRODUCTION

THE current-voltage characteristics of positive-point-to-plane discharge in air at atmospheric pressure have been investigated extensively in the past.[1-3] Unfortunately most of the work has consisted in finding empirical equations to satisfy the current-voltage curves for various gap geometries and to indicate the voltages at which the corona breaks down into a spark. This information, while of some importance from an engineering point of view, tells very little with respect to the fundamental processes taking place. In this laboratory, discussions with the late Professor Hillebrand led Professor Loeb[4] to observe, in positive point corona in air and in impure N_2, streamers coming out from the point in an ever-changing pattern, which indicated that there might be discontinuities in the current. It was known that while such discontinuities exist and can be observed on an oscilloscope when the point is at negative potential, no discontinuities can be observed by this means with a positive point. Thus it has always been assumed that positive corona at high pressure is a continuous phenomenon analogous to a glow discharge. Acting on the suggestion by Professor Loeb, G. W. Trichel in these laboratories has verified the existence of these discontinuities. Details of this work will be published soon. The present paper will describe experiments whose purpose was to investigate the fundamental processes occurring in positive point-to-plane discharge in air at atmospheric pressure principally by means of current-voltage measurements. The measurements have determined current-voltage characteristics of the corona as a function of gap geometry, and include the voltages at which the corona breaks down into a spark. Particular attention has been given to the conditions under which the corona begins and to the nature of the starting currents, since this

[1] Warburg, Ann. d. Physik **66**, 652 (1898); **67**, 69 (1899).
[2] Zeleny, Phys. Rev. **25**, 305 (1907); **26**, 129 (1908).
[3] *Handbuch der Physik*, Vol. 14, Chap. IV.
[4] Loeb and Leigh, Phys. Rev. **51**, 149 (1937).

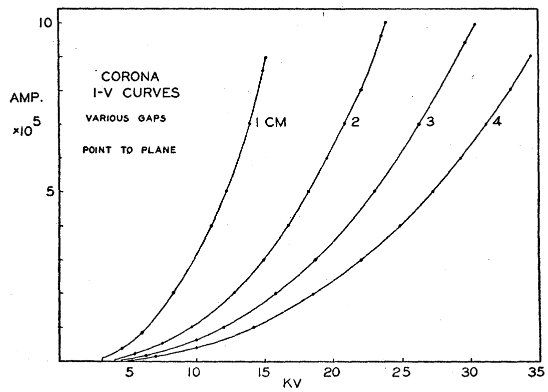

FIG. 1. Corona current-voltage curves for various gap distances. Curves end at voltage at which spark breakdown occurs. Hemispherical point 3*A*, diameter 0.5 mm.

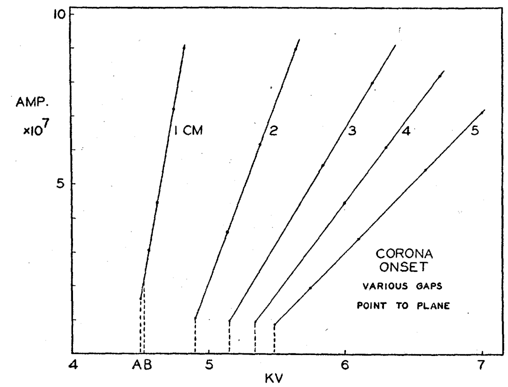

FIG. 2. Onset region of corona current-voltage curves, enlarged, showing initial linear current rise.

information gives many clues as to the kind of processes occurring.

Apparatus

The essential features of the apparatus are the chamber wherein the discharge takes place, the voltage supply, and current and voltage measuring devices. Voltage is supplied by a 500 cycle generator to a 150 kv transformer, which leads to a full wave rectifier and filter circuit. The voltage is maintained and adjusted by a saturable reactor stabilizer in series with the transformer primary. Voltages from one to 50 kv, constant to better than 1 percent are thus available. The voltage is measured by a potentiometer put across a small fraction of a 50 megohm resistance tower in parallel with the discharge. Current is measured by the voltage drop across a resistance in series with the gap. This voltage drop is measured by means of an electrometer, and the resistance can be readily changed to make possible current readings from 10^{-10} to 10^{-3} ampere. The resistance is always small with respect to the gap resistance, so that it does not influence the discharge. In order to protect the electrometer from the large impulse which occurs when the corona goes into a spark, a neon lamp is put in parallel with the electrometer to take a major part of the spark current.

The discharge takes place inside a glass chamber made from a five gallon water bottle with the bottom cut off and replaced by a glass plate. This chamber is covered inside with a grounded monel screen to prevent the accumulation of electrostatic charges on its surface which would alter the field, and can be evacuated and filled with any desired gas. In most of the experiments, dried room air has been used.

The negative electrode is a brass plate 13 cm in diameter, and the positive electrode is a platinum wire with a hemispherical end. Platinum was chosen because it was found that its characteristics suffer a minimum change due to corona currents and sparking. The hemispherical end was used because of ease of maintaining constant point geometry. Various sizes of points have been used, with diameters from 0.5 to 4.7 mm. The gap distance can be varied while the chamber is isolated from room air by means of a threaded point holder which can be turned in a ground glass joint.

Experimental Results

The general shape of the current-voltage curve is plotted in Fig. 1 for various gap distances and a 0.5 mm diameter point. The essential features are the initial sudden rise of current and the increase which is at first linear with voltage and then becomes steeper until finally breakdown into spark occurs, at which point the curves are ended. These curves were taken in dry air and are similar to those of other workers except that the initial sudden rise has not generally been noted.

Figure 2 shows an enlarged view of the onset region. The scale has been changed to show the linear increase after the initial sudden rise. If the voltage is increased gradually from zero to some value B above A, as shown on the curve for a 1.0 cm gap, the current will suddenly start, and then follow the curve shown. The position of B varies with the time a given voltage has been applied. The time delay or lag before the current starts varies in a statistical manner, and is proportional on the average to the difference between the voltage applied and the critical or offset voltage A. The time of starting may vary from a fraction of a second to many seconds for a given applied voltage. If the voltage is decreased after the current has started, the current follows the curve shown until the *offset* voltage A is reached, at which point it goes off suddenly. In contrast to the statistical character of *onset*, the *offset* voltage is found to be extremely sharp, and to remain constant as long as the gap geometry is held constant.

The way in which the offset voltage and current vary with gap distance is shown in Fig. 3. The minimum current which will flow before the process stops completely is found to increase as the gap distance is decreased. When the gap has less than a certain critical length, called the *corona point distance*, the corona process no longer occurs and the gap breaks down completely into a spark.

In view of the theory of the processes occurring, to be discussed later, it was of interest to determine the cause for the sudden cutting off of the corona current at the critical voltage. This problem was attacked by means of inserting radioactive material into the gap and the results are shown in Fig. 4. If a very small quantity of radioactive material is placed in the gap, so as to provide an intermittent source of ions, the corona behaves exactly as without the auxiliary source of ions at voltages above the critical voltage A, except that the corona now goes on immediately when the critical voltage has been reached. Below the critical voltage the corona current is intermittent, with an average frequency which depends on the amount of radioactive material and the difference between the applied and critical voltage. The average current which flows in the voltage range between A and C is dependent on the radioactive strength, but for a particular strength, falls approximately on the broken line 1. A larger radioactive intensity gives no material change in the current when the voltage is above the critical value, but gives currents as shown in curve 2 below the critical voltage. The current in the region below the critical voltage (between A and C) has been found by Trichel to show the same discontinuities observed in regular stable corona at voltages above the critical point A. However, in this region the corona process occurs only by virtue of the auxiliary source of ions provided by the radioactive source. The exact shape of the current curve between A and C is dependent on the amount of radioactive material present. Below this region another process occurs, where the current is perfectly continuous, and decreases more rapidly. If a very intense ion source is provided, the discontinuous corona action no longer occurs until large voltages are applied, and in consequence the current-voltage curves are completely changed. Curve 3 was obtained by the use of an intense radioactive source.

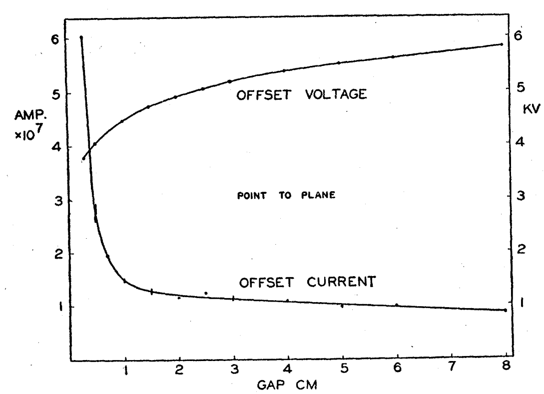

FIG. 3. Offset voltage and current *vs.* gap distance for hemispherical point 3*A*.

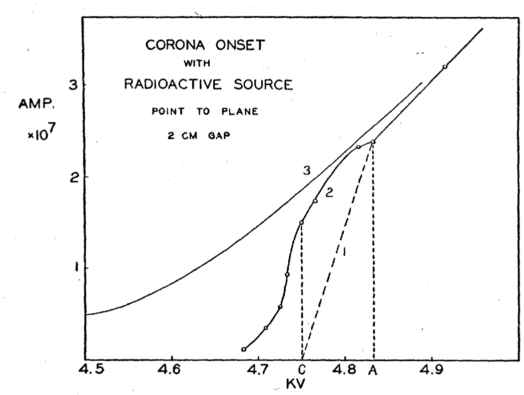

FIG. 4. Effect of radioactive source on corona onset, 2.0 cm gap, point 3*A*. Curve 1, weak source; curve 2, medium source; curve 3, strong source.

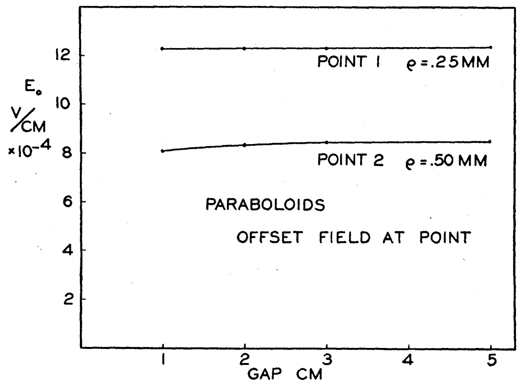

FIG. 5. Field at point surface at onset for confocal parabolic electrodes for various gap distances.

The voltages at current-onset shown in Fig. 3 give no information as to the fields existing, since calculation of the field for the geometry used is not possible. Knowledge of the field strengths existing is of prime importance for the understanding of the processes occurring. To make such calculations possible, the gap geometry was altered by making a set of confocal paraboloids of revolution, one being used for the point, and the others replacing the plate. One pair was used for each gap distance tested. Observation of onset voltages and subsequent calculation of the electrostatic field at the surface of the point just prior to onset gave the curves shown in Fig. 5. Two different points were used, as indicated. The maximum field at onset was thus found to be the same for all gap distances for a given point. The slight curvature in the curve for the larger point is probably due to the fact that necessary departure from true parabolic shape becomes of some importance in the larger point.

The voltages at which the corona breaks down into a spark as a function of gap distance are plotted for a 0.5 mm diameter point in Fig. 6. The maximum current before breakdown occurs is plotted in Fig. 7.

THEORY

The existence of a discontinuous process in positive point corona at once indicated that the character of the discharge mechanism is basically that indicated by Loeb and Cravath[5] for the propagation of the positive leader stroke in lightning discharge. Such a mechanism occurs upon the appearance in the high field region of the gap of either a free electron at E/p of about 30, where E is the field in volts/cm and p is the pressure in mm of Hg, or a negative ion where the value of E/p is greater than 90. Loeb[6] has shown that negative ions lose their electrons in such fields, hence at lower fields if free electrons are present, and in any case in fields extending into the gap space with a value of E/p greater than 90, a single electron will ionize by collision, produce an electron *avalanche* and leave behind a positive ion space charge of high ion density which effectively extends the point out into the gap. This positive column will be relatively stationary because of the very small mobility of the ions as compared to the electron mobility. Such a single electron avalanche does not constitute the discontinuous current observed, inasmuch as the magnitude of the electron multiplication is entirely inadequate. This is evidenced by the fact that the single electron avalanches with medium radioactive source (below C in Fig. 4) do not register any discontinuities. Another indication that a single avalanche does not account for the

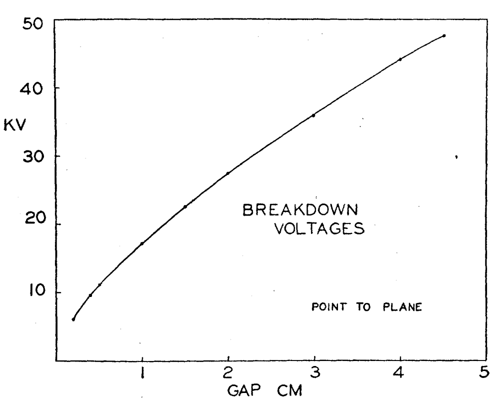

FIG. 6. Breakdown voltage *vs.* gap distance, hemispherical point.

discontinuities is the fact that under certain conditions visible streamers extend out into the gap into regions where the electrostatic fields are entirely inadequate for avalanche formation.[4] Thus a mechanism must be looked for which will allow for the self-extension of the avalanches out into the gap. Accompanying the avalanche there has been intense excitation and the region for

[5] Loeb and Cravath, Physics **6**, 125 (1935).

[6] L. B. Loeb, Phys. Rev. **48**, 684 (1935).

some distance around the positive point is photoelectrically ionized. Evidence of this has recently been obtained by W. S. Gorrill in these laboratories, with the use of a Wilson cloud chamber. The intense field around the extended positive point gives rise to further electron avalanche formation. Thus a positive corona streamer propagates outward from the positive point into the gap space.[5] This propagation continues until the dissipative action of diffusion, space charge and the random entry of electron avalanches into the extended point so distorts the field and reduces the gradients that further propagation is no longer possible. It is clear that the higher the field is in the active region around the point the greater the length of the streamer before the dissipative forces, which require time, choke it off. Under suitable conditions the existence of these individual streamers can be seen; their presence is characterized in air and impure nitrogen by the characteristic brilliant blue color of the spark spectrum of nitrogen, indicating the existence of intense fields along the tip of the propagating channel. The exact duration of propagation of such a streamer has not yet been determined. Evidence based on Trichel's work and knowledge of the propagation time of lightning discharge streamers indicate duration less than 10^{-7} and more likely 10^{-8} second. Once the streamer has ceased propagating, there must follow a period of relaxation in which the positive space charge which has accumulated is swept away from the region around the point by the clearing field until the high field region is again made active.

The period of time during which the clearing field dissipates the positive space charge to an extent sufficient to permit of a new avalanche must depend largely on gap geometry and the potential applied to the positive point; that is, on the steepness of the gradient throughout a considerable portion of the gap. Once the clearing field has acted, the positive point is again in a position to produce a discharge by propagating a new streamer. It can do this *only when a negative ion or a free electron* is available in the limited high field region about the point. The normal ionic and electronic content in the atmosphere is so weak that the chance of a new avalanche *without an auxiliary source of electrons*, in a reasonable time is very small. If electrons were available, the streamers would propagate at the rate of electron appearance in the sensitive region up to a frequency more or less dictated by the time of relaxation necessary to restore the high fields. Owing to the rapid sweeping of electrons, the only possibility in the absence of radioactivity for a repetition of streamer formation lies in a supply of electrons through detachment of electrons from the surviving negative ions produced in the weak field region by ultraviolet light action. The existence of these negative ions is proven by direct evidence from the cloud chamber studies of Gorrill. This mechanism was proposed by Trichel as the mechanism of starting of the new streamer. As has been explained, this necessitates a value of E/p greater than 90 at some distance away from the positive point which is in conformity with observations. On this basis it is *only gases in which the free electrons are trapped to form negative ions which are capable of giving a positive corona showing the characteristics of that in air*. Thus with pure nitrogen in which electrons do not attach, Trichel has shown that the discontinuous process does not occur. The discontinuities which characterize the positive point corona in air are caused by the alternate propagation and choking off of the lightning-like positive streamers.

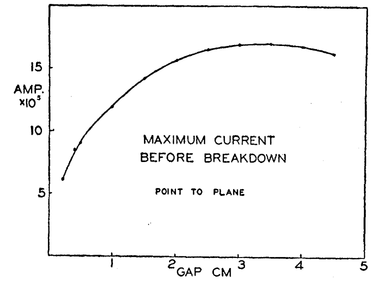

FIG. 7. Maximum current before spark breakdown *vs.* gap distance.

It is therefore necessary in order to have a stable self-maintaining corona discharge that there be a region in the vicinity of the point where E/p is greater than 90, a supply of negative ions, and in addition there must be a weak field region such as to prevent the positive streamers from propagating completely across the gap to produce spark breakdown. With this picture in mind one may now discuss the results observed.

Discussion of Results

Onset phenomena

The phenomena observed in the onset region of the current-voltage curves may now be explained. The voltage B (Fig. 2) at which onset occurs is determined by the arrival of an ion in the sensitive volume around the point, which starts the stable corona process. As explained, this value of voltage for *onset* depends on the time the given voltage has been applied and on the difference between A and B. The greater the applied voltage, the greater is the sensitive high field region around the point wherein a negative ion can lose its electron and start the corona process and therefore the shorter on the average is the time lag before such action occurs. The *offset* voltage A is an important characteristic of the corona. It marks the lowest potential at which the presence of an ion in the sensitive region from the preceding streamer is assured, and therefore the *lowest potential at which the corona process is self-maintaining*. Below this potential, single streamers, or many, may occur before statistical fluctuations in ion arrival cause the final streamer to be unproductive of an effective ion and therefore cause cessation of the process. The lower the potential the smaller on the average is the number of streamers which will succeed in following each other before extinction, and probably eventually only single streamers will be propagated. When an auxiliary source of ions from radioactive material is supplied in this region, between A and C in Fig. 4, the positive point acts as a Geiger point counter for ions entering the sensitive region of the gap, each ion or group of ions causing the initiation of one or a series of streamers. This action can be clearly seen in the current measuring instrument, as the current appears in bursts which become less frequent below A as the potential is lowered and as the strength of the auxiliary ion source is decreased. This production of separate bursts of current stops abruptly below C, which is presumably the voltage below which streamer propagation ceases. With a very weak radioactive source, C marks the point below which no current above 10^{-10} ampere is observed. As the voltage approaches A, the average strength of the current bursts becomes greater because of the increased number of streamers which occur before the process is cut off.

With stronger radioactive sources there is an asymptotic rise in current below C with no discontinuities, as shown in Fig. 4. This current obviously represents a mere multiplication of the radioactively produced ions in the strong field about the point, which is great enough to cause multiplication of ions but not enough to allow streamer propagation. With the more intense ionization the current between C and A represents a superposition of the current due to almost continuous streamer formation made possible by the auxiliary nearly continuous source of ions upon a background of the multiplication current. Above A the current is nearly unaffected by the externally supplied ions and follows the initial linear rise which occurs in the absence of radioactive material. This is no doubt due to the fact that above A, the auxiliary ion source is small with respect to the photoelectrically produced ions and therefore the modification of the weak field region which limits the current is small.

When even stronger radioactive intensity is used, as mentioned in the section on experimental results, streamer propagation no longer occurs until large voltages far above the onset value are applied. In consequence the current-voltage curve is completely changed as shown. The curve no longer shows any discontinuities and the slope of the linear part is changed. This change in the kind of process occurring is unquestionably caused by the change in the character of the field as a result of the large amount of ionization present, and the current is due to simple multiplication of ions. In this case, even above A, the auxiliary source of ions is very much greater than the ionization caused by the photoelectric process in the gap, and hence the space charge is profoundly modified. In effect, the space charge due to the intense radioactive source causes the intense field to be spread out through the weak field region of the gap to such an extent that the intense field necessary for the propagation of streamers no longer exists until voltages are much greater than otherwise would be sufficient. If the ionization is great enough, it may be impossible to establish the discontinuous corona process before breakdown occurs.

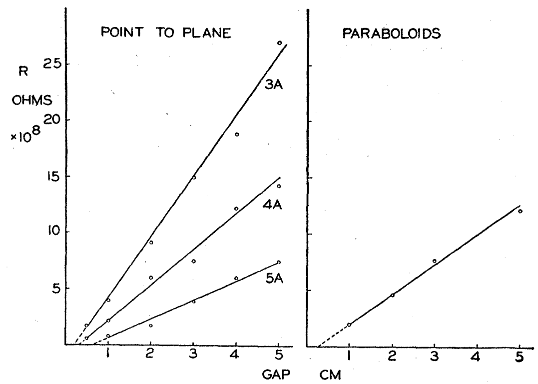

FIG. 8. Effective resistance interposed by clearing field region of gap *vs.* gap distance for point to plane and parabolic gaps. Point 3*A*, diameter 0.5 mm; point 4*A*, diameter 1.5 mm; point 5*A*, diameter 4.7 mm.

Field intensities at onset

As has been stated, confocal paraboloids were used to make possible calculation of the field in the region of the point at onset. Calculations from the data obtained show that the field at the surface of the point is 80 and 120 kv/cm for the small and large points respectively. These may be in error by as much as 10 percent but in any case it is seen that they lie well above the 69 kv necessary for $E/p=90$. Thus fields sufficient for dissociating the electrons from negative ions as well as for multiplication of electrons exist in a considerable region out from the point at onset, as is necessary. Calculation shows that for the unmodified electrostatic field, the region of $E/p>90$ extends out to 0.05 mm along the axis of the point for point 1, and out to 0.1 mm for point 2, at onset voltages. The space charge will of course modify this when current starts to flow, but also the field at the tip of the self-propagating streamer will be greater than as calculated for the electrostatic field. At onset voltages, the electrostatic field in which multiplication of electrons can occur ($E/p>20$), extends out approximately 1 mm from the point.

Under reasonable assumptions as to the time of relaxation and the field existing during this time, calculations show that negative ions formed from 0.5 to 1 cm out from the point will be available to re-kindle the corona process after the time of relaxation.

Effect of gap distance

The manner in which the offset current varies with gap distance (Fig. 3) clearly indicates the effect of the weak field region. For large gaps, d/ρ, the ratio of gap distance to radius of curvature of the point, is large and consequently the clearing field is weak. Therefore at voltages just sufficient to give the necessary high fields for the generation of corona currents, the sweeping out of the positive space charge is relatively slow and the current is correspondingly low, presumably because of a long time of relaxation. As the gap is made smaller, d/ρ becomes smaller and the field consequently tends to be spread out more uniformly across the gap. This gives greater sweeping fields which correspond to voltages just sufficient to produce an active high field region. The minimum current for stable self-maintaining corona is consequently larger for small gaps. As the gap is further decreased, the high field region extends over a still larger proportion of the gap. Finally when the *corona point distance* is reached, the low field region no longer exists, and the stabs propagate themselves completely across the gap. Immediate breakdown into a spark then occurs without the appearance of stable corona.

The spark represents a changed condition in which the streamer reaches the cathode. This introduces a new efficient electron source into the process and the corona current no longer depends on the relatively inefficient photoelectric effect in the gas. Thus it is seen that the low field region is essential for maintenance of stable corona.

The voltage at which breakdown into a spark occurs for various gap distances, as shown in Fig. 6, is determined by the fact that at this point the low field region is no longer sufficient to prevent the streamers from propagating completely across the gap. The maximum in Fig. 7 is due to the fact that the collecting plate does not receive all of the current at high voltages when the gap distance is greater than 3 cm. Thus if the *total* current were taken, the maximum current before breakdown would steadily rise as the gap distance is increased. This instrumental error also affects the 4 cm gap curve in Fig. 1, which gives currents smaller than the total current.

Effective resistance

The fact that the initial rise of current after onset with applied voltage is linear, as shown in

Fig. 2, makes possible further demonstration of the necessity of the low field region in the maintenance of stable corona. The reciprocal of the slope of this initial rise in current may be considered as an effective resistance interposed by the weak field region of the gap. Fig. 8 shows the variation of this effective resistance with gap distance, for various sizes of points. As is shown, the resistance increases linearly with gap distance, and as to be expected, is less for points with larger diameters since for larger points d/ρ is smaller and consequently the fields are more uniform. This means that the sweeping action is more effective and less resistance is interposed by the weak field part of the gap. It is of further interest to note that if these effective resistance curves are extrapolated to zero resistance, they cross the axis at gap distances corresponding within the experimental error to the *corona point*, that is, the distance below which spark breakdown occurs without the formation of stable corona. This corresponds to the fact that when the gap distance is such that the weak field part of the gap no longer interposes a resistance, the streamers propagate completely across the gap, and cause breakdown. It is to be noted that while the resistance so calculated is only of the order of magnitude of 10^8 ohms, the total effective resistance in the gap must be of the order of 10^{10} ohms to account for the magnitude of the current which flows. Thus only about 1 percent of the total *IR* drop is due to the weak field part of the gap. However, it is to be expected that most of the energy provided by the potential source is used in the intense field region in producing ionization and the shape of this intense field region will be only slightly modified by changes in gap distances, whereas the sweeping fields will be greatly changed.

The effective resistance of the weak field region has also been plotted for the confocal paraboloid geometry. In this case, both the points used yield the same values for effective resistance at different gap distances. This is as to be expected, since with the paraboloids, the lines of force in the weak field regions are independent of the size of the point, as long as all surfaces remain confocal, and therefore the sweeping field current-limiting action is the same for both points used.

Shape of current-voltage curves

Above the initial linear rise, it is found that the current is roughly proportional to the square of the difference between the applied and offset voltage. This is to be expected from a visual observation of the streamers at voltages approaching breakdown values. It is seen that the visible streamers have a tendency to follow along somewhat the same paths of others which have gone before. Apparently, at high voltages the new streamer may start propagating before the column of positive ions from the last one in the weak field region has been completely swept away, and the resulting uneven ion distribution around the old positive column out in the gap will give rise to regions where the field is considerably higher than is the case where the last positive column is more completely removed before the starting of the new streamer. This increase in the field in regions contiguous to an old streamer will allow the new streamer to propagate further than would otherwise be the case. Thus two factors influence the increase of current with voltage, first the linear increase in sweeping fields and second the effect of old streamers. The latter effect would be expected to be at least roughly proportional to the size and frequency of the preceding streamers, and thus also to the current which is dependent on the difference between applied and offset voltage. It is thus seen that the nonlinear region of the current-voltage relationship may be ascribed to effects of the preceding discharge proportional to the current, which act to augment the current by modifying the otherwise linear space charge limitations.

In conclusion, the author wishes to express his appreciation to Professor Loeb for his guidance throughout the prosecution of this work and particularly for his aid in the interpretation of the results. He is also indebted to his colleagues, G. W. Trichel and W. S. Gorrill, the results of whose coordinate researches on different aspects of the same problem have been of the greatest help. Finally he wishes to express his appreciation to the Research Corporation of New York whose Research Fellowship Grant at the University of California for the last two years has made this work possible.