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Positive Point-to-Plane Corona Studies in Air*

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Formative time lags for the development of the positive point-to-plane corona in dry air were measured oscillographically at pressures ranging from atmospheric to a few centimeters of Hg. Studies with a photomultiplier tube show that the observed formative lags are associated with a filamentary streamer type of corona. These corona formative lags are of the order of 10^{-7} sec even near threshold and vary much more slowly with overvoltage than do uniform field formative lags in air. The results indicate that no long buildup process is associated with the formation of the filamentary streamer type of corona in air, and in particular rule out any cathode secondary mechanism from playing a role in the formation. Near atmospheric pressure, with the experimental conditions used, the corona formative time lags were often too short to be resolved from the statistical scatter; when resolvable they were found to be too long to be ascribed solely to a single transit time of the initiating electron avalanche across the high field region of the gap. The results therefore do not preclude a fast buildup process in the gas preceding streamer formation.

Threshold measurements on both impulse and dc corona indicate that the steady glow type of corona has a different threshold than the streamer type. No formative lag data on the steady glow corona were obtained.

I. INTRODUCTION

THE clarification of the physical processes active in the positive and negative point-to-plane corona in air (and in other gases) has been carried out in recent years by Loeb and by workers in his laboratory. In particular, one of the important processes occurring in the positive corona is believed to be active in the uniform field breakdown in air near atmospheric pressure. The present study was undertaken to investigate this point.

Earlier studies of the positive point corona in air have shown it to consist of two basic forms: a glow about the point, or thin filamentary streamers extending from the point.[1–5] The glow about the point may be associated with either a steady gap current (steady glow corona) or with a fluctuating current (burst pulse glow corona). The filamentary streamers[6] are associated with a gap current and a luminosity that rise in a very short time (10^{-7} sec).[7] These filamentary streamers have been explained by the streamer mechanism.[1–3,8,9] The streamer mechanism is described as a very rapid extension of ionization from the head of an electron avalanche by means of photons in the short ultraviolet. These photons liberate electrons in the gas and the latter form secondary electron avalanches. A strong distortion of the gap field by the space charge of the initial avalanche is invoked to enhance the electron multiplication of the secondary avalanches, and to guide the propagation of the discharge along a well defined channel. In the positive corona, filamentary streamers on their way to the cathode reach a region of such low electric field that their progress is inhibited.

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[1] A. F. Kip, Phys. Rev. **54**, 139 (1938); **55**, 549 (1939).

[2] G. W. Trichel, Phys. Rev. **55**, 382 (1939).

[3] L. B. Loeb and A. F. Kip, J. Appl. Phys. **10**, 142 (1939).

[4] D. B. Moore and W. N. English, J. Appl. Phys. **20**, 370 (1949).

[5] H. W. Bandel, Phys. Rev. **84**, 92 (1951).

[6] The filamentary streamers discussed here and studied in this experiment are the first streamers which appear in a corona gap when the voltage is raised. Under certain conditions, such as short gap lengths or low pressures, the first filamentary streamers to appear may cross the gap causing breakdown.

[7] W. N. English, Phys. Rev. **77**, 850 (1950).

[8] We designate the luminous filaments observed in the positive point corona as "filamentary streamers" and the mechanism postulated to explain them as the "streamer mechanism" or simply streamer.

[9] L. B. Loeb, *Fundamental Processes of Electrical Discharge in Gases* (John Wiley and Sons, Inc., New York, 1939), p. 527.

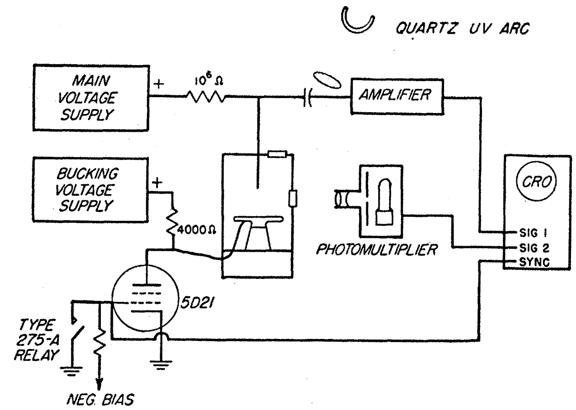

FIG. 1. Block diagram of apparatus.

Loeb[3] suggested that a similar filamentary streamer develops in the uniform field breakdown, and that due to the uniformity of the field the filamentary streamer reaches the cathode and leads to breakdown.[10] Raether[11] came to almost identical conclusions from a study of cloud track pictures of incomplete breakdowns in uniform fields.

One of the principal features of the description of the uniform field breakdown by the streamer mechanism is that it explains the extremely rapid breakdowns (10^{-7} sec and less) observed with overvolted gaps. However, recent experiments with very slightly overvolted plane parallel gaps in air have revealed formative time lags of the order of 10^{-5} and even 10^{-4} sec.[12] These formative time lags are much too long to be in accord with a breakdown theory in which a filamentary streamer follows the first electron avalanche. A modification of the theory seems necessary at low overvoltages wherein a filamentary streamer occurs only after an adequate space charge has been built up after many successive electron crossings. The experimental data indicate that this buildup takes place through a Townsend type of discharge involving photoemission of electrons at the cathode as a secondary mechanism.[13]

Similar formative time lag measurements with impulse voltages very close to threshold were undertaken for the positive corona to see whether the corona discharge near threshold is also preceded by a long buildup time. These studies were carried out to determine what processes are active in the formation of the positive point corona discharge, and in particular to ascertain the role of the streamer mechanism in this discharge.

II. APPARATUS AND EXPERIMENTAL PROCEDURE

The corona gap consisted of a plane circular brass cathode of 11-cm diameter with a polished tungsten needle forming the positive point. Points having radii of curvature of 0.007, 0.02, and 0.03 cm were used with electrode separations of 0.5, 1.0, and 1.5 cm. The gap was enclosed in a cylindrical brass chamber of 14-cm diameter and 12-cm length. A quartz window permitted irradiation of the cathode with ultraviolet light and a second window was used for observation of the discharge. The air admitted to the chamber was dried chemically and passed over a liquid air trap. Pressures of 700, 500, 300, 200, 100, 50, and 30 mm of Hg were used with each gap geometry, the chamber being evacuated and refilled for each pressure.

The measurement of formative time lags was carried out by suddenly applying a voltage to the corona gap, and measuring oscillographically the time lag of the resulting corona current pulses. Continuous ultraviolet illumination of the cathode provided initiating electrons. Measurements of gap current *vs* voltage were made with steady applied voltages up to threshold for all gap geometries and pressures for three intensities of ultraviolet illumination. The light emitted by the discharge under both dc and impulse conditions was observed visually, and oscillographically by means of a photomultiplier tube so arranged that it could "see" any desired part of the gap.

A block diagram of the system is shown in Fig. 1. Because of difficulty involved in switching the full required gap voltage, use was made of an approach voltage. The main voltage was obtained from a power supply with a stability of one part in 5000. This main voltage is sufficient to cause a discharge, the discharge being prevented from occurring by a positive bucking voltage applied to the cathode. The discharge is initiated when the bucking voltage is suddenly shorted out. The dynamic drop of the switching tube (type 5D21) depends on the value of the bucking voltage. This dynamic drop was measured oscillographically and found to be 55 (±15 volts) for the generally used bucking voltage of 1000 volts. However, the time lag data show that this dynamic drop is reproducible to within three volts. The time to switch from the approach voltage (difference voltage) to within five volts of the final voltage was observed to be of the order of 0.03 microsecond.

The current pulses resulting from the corona discharge were amplified, delayed by 0.3 microsecond and displayed on an oscilloscope whose sweep was triggered by the switching tube. The switching tube also couples a small voltage pulse to the amplifier through the capacity of the gap. This pulse served as a time reference mark

[10] For a detailed description of the method by which the streamer leads to breakdown, see L. B. Loeb and J. M. Meek, *The Mechanism of the Electric Spark* (Stanford University Press, Stanford, 1941), p. 39.

[11] H. Raether, Arch. Elektrotech. **34**, 49 (1940); Z. Physik **117**, 375, 524 (1941); Ergeb. exakt. Naturw. **22**, 73 (1949).

[12] L. H. Fisher and B. Bederson, Phys. Rev. **81**, 109 (1951). The existence of long formative lags in uniform field breakdown of air has been confirmed by H. W. Bandel, Washington Gaseous Electronics Conference, October, 1953 (unpublished).

[13] G. A. Kachickas and L. H. Fisher, Phys. Rev. **88**, 878 (1952). See also F. Llewellyn Jones and A. B. Parker, Proc. Roy. Soc. (London) **A213**, 185 (1952).

from which the time lags of the discharge were measured. The over-all rise time of the amplifier circuit was 0.03 microsecond, and the full gain was of the order of 10^4. This permitted current pulses as small as 10^{-6} amp to be observed across an input resistor of 1000 ohms.

Several runs with a bucking voltage of 500 instead of 1000 volts were carried out; after correction for the slightly different switching tube drop, both the threshold and the time lags were in good agreement with those obtained with the full bucking voltage.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Threshold voltages were obtained for both the dc and impulse positive point corona. The dc threshold (sometimes called the onset voltage) is defined as the lowest voltage at which a steady corona discharge with

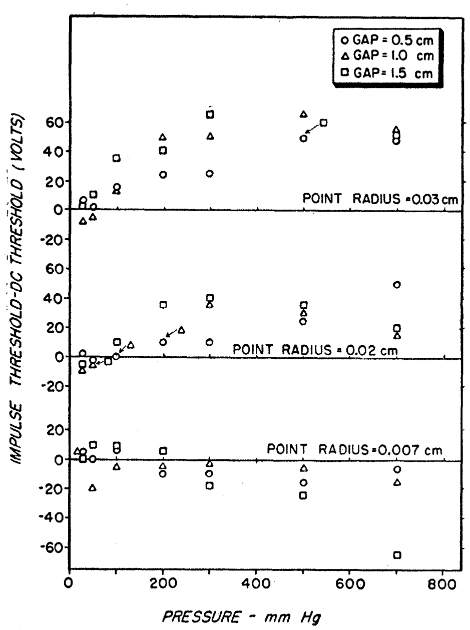

FIG. 2. Voltage difference between the impulse and dc thresholds as a function of pressure for various gap geometries.

constant current maintains itself in the absence of ultraviolet illumination of the cathode. With strong ultraviolet illumination the current-voltage curves are continuous throughout the whole voltage region studied and no sharp threshold is observed. In order to determine the dc threshold, very slight ultraviolet illumination was used to initiate the corona. With such low ultraviolet illumination, there is a region of some ten to twenty volts below the dc threshold where the corona current fluctuates. Because it is difficult to establish a sharp demarcation between this region of fluctuating corona (burst pulse corona) and the region of steady corona, there is an estimated uncertainty of at most five volts in the dc threshold.[14]

[14] Bandel (see reference 5) has also observed this difficulty in determining the dc positive corona threshold in air.

The impulse threshold was taken as the lowest impulse voltage at which discharge pulses could be seen on the oscilloscope. As already mentioned, the absolute accuracy of the impulse voltage is of the order of ± 15 volts. The dc and impulse thresholds were often found to differ by as much as 60 volts; this is in excess of any known experimental error. This difference is plotted in Fig. 2 as a function of pressure for all gaps studied. As may be seen, neither threshold is consistently higher than the other.

A study of the impulse corona with the photomultiplier indicates that the discharge which causes the gap current pulses observed on the oscilloscope is of the filamentary streamer type; visual observation of the steady corona shows it to consist of a glow about the point. It thus appears that the dc and impulse thresholds as determined in this experiment are the threshold voltages for the steady glow corona and the filamentary streamer type of corona, respectively.

The question remains as to why nothing was observed on the oscilloscope for impulse voltages higher than the glow corona threshold but lower than the filamentary streamer threshold. The glow-corona gap current near threshold ranged from 2×10^{-7} to 5×10^{-7} amp. If the discharge current pulses due to the glow corona under impulse conditions are of the same magnitude, they might easily have passed unnoticed due to the inadequate sensitivity of the amplifier.

A typical set of dc current-voltage curves for one gap geometry (point radius 0.03 cm, electrode separation 1.5 cm) and various pressures is shown in Fig. 3. For simplicity, curves for only the highest value of illumination used are shown. Figure 4 is a detailed plot in the region just below threshold of the 500-mm case of Fig. 3 for the three values of ultraviolet intensity.

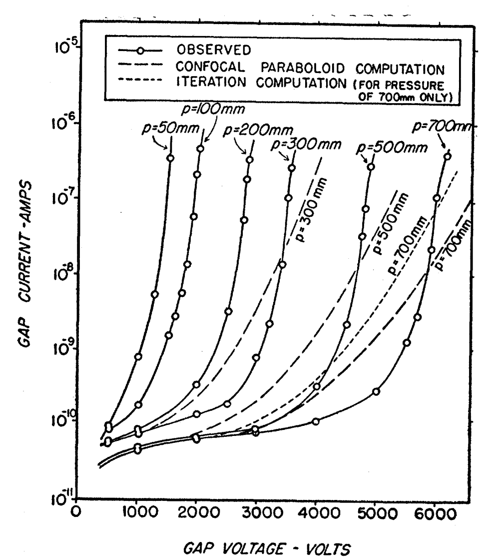

FIG. 3. Observed and computed dc current-voltage curves for one gap geometry and a range of pressures. Point radius 0.03 cm, electrode separation 1.5 cm.

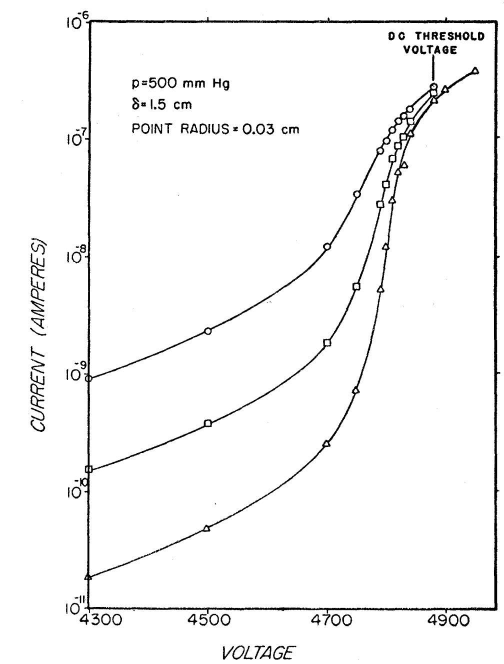

FIG. 4. Detailed plot of current-voltage curves of the 500-mm case of Fig. 3 for three values of ultraviolet intensity.

Also shown in Fig. 3 are computed current-voltage curves for pressures of 700, 500, and 300 mm Hg. These computed curves were obtained by using the field along the axis in conjunction with values of the first Townsend coefficient in air as given by Sanders.[15] For all but one of the computed curves the field was calculated approximately by regarding the gap as composed of two confocal paraboloids; the remaining computed curve is for 700-mm Hg and was obtained from gap fields calculated by an interation method given by Loeb, Parker, Dodd, and English.[16]

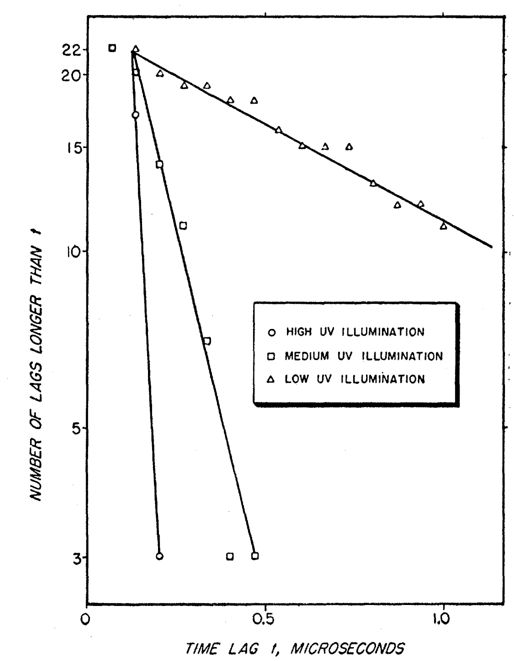

FIG. 5. Laue plots of observed time lags for three intensities of ultraviolet illumination at a fixed overvoltage of 0.18 percent. Point radius 0.03 cm, electrode separation 1.0 cm, pressure 200 mm Hg. Each of the curves is for a total of 22 observations.

Comparison of the observed gap currents with the computed gap currents show three main features which were found in all cases studied:

(a) In the voltage region from 1000 volts below threshold to about 100 volts below threshold, the observed gas multiplication is much less than the computed electron multiplication. This may be due to the attachment of electrons to oxygen molecules or to the inapplicability of the Townsend ionization function in nonuniform fields.[17]

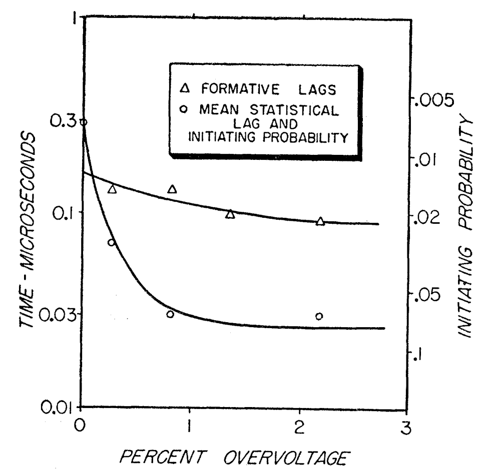

FIG. 6. Formative time, mean scatter time and initiating probability of an electron as a function of overvoltage. Point radius 0.03 cm, electrode separation 1.5 cm, pressure 300 mm Hg.

(b) In the neighborhood of 100 volts below threshold there is a sudden upswing in the observed gap current. This upswing is much sharper than could be expected from the shape of the computed curve, and must thus be attributed to a secondary mechanism.

(c) In the vicinity of the threshold voltage, the current-voltage curve becomes less steep and tends to

[15] F. H. Sanders, Phys. Rev. **41**, 667 (1932). When necessary, at the very high field strengths, use was made of the ionization coefficient for nitrogen as measured by D. Q. Posin, Phys. Rev. Rev. **50**, 650 (1936).

[16] Loeb, Parker, Dodd, and English, Rev. Sci. Instr. **21**, 42 (1950).

[17] Difficulty has been encountered in the use of the first Townsend coefficient in nonuniform fields. This has been studied in hydrogen by L. H. Fisher and G. L. Weissler, Phys. Rev. **66**, 95 (1944), by P. L. Morton, Phys. Rev. **70**, 358 (1946), and in hydrogen and air by G. W. Johnson, Phys. Rev. **73**, 284 (1948). These experiments show that in nonuniform fields, more ionization is produced than is calculated from Townsend's ionization function except for one case in air. At this time, it does not seem possible to decide why our calculated curves are above the observed ones.

flatten out and the gap current is no longer proportional to the primary current emitted from the cathode. This limiting effect is generally attributed to the positive ion space charge in the gap.

Repeated time-lag measurements for a given geometry, pressure, and overvoltage gave a scatter; this scatter decreased with increasing ultraviolet light and increasing overvoltage. Because of the scatter, twenty five measurements of the time lag were made at each setting. Although an analysis by means of Laue plots[18] for various intensities of illumination showed the scatter to be due to the random appearance of initiating electrons, it was not considered desirable because of possible space charge effects to increase the ultraviolet intensity to eliminate the scatter. A typical Laue plot

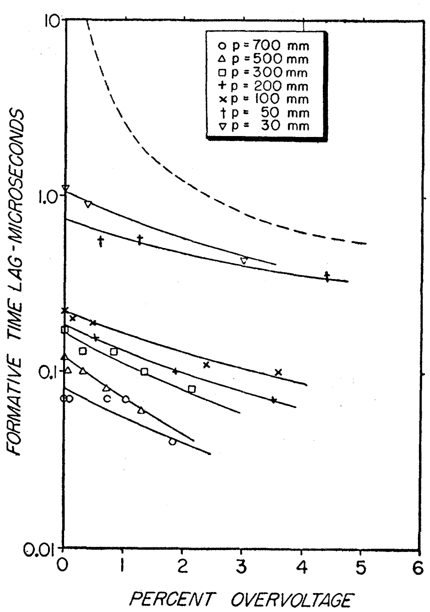

FIG. 7. Formative time lags of the positive point corona as a function of overvoltage for one gap (point radius 0.03 cm, electrode separation 1.5 cm) and a range of pressures. Also shown by the dashed line are formative lags as found by Fisher and Bederson (see reference 12) for a plane parallel gap of one centimeter in air.

for three illuminations under otherwise identical conditions (point radius 0.03 cm, gap length 1.0 cm, pressure 200 mm Hg) is shown in Fig. 5. The formative time lags were obtained from the intercepts of the Laue plots.

Comparison of the mean scatter time of the observed lags with the initial photoelectric current emitted from the cathode makes possible an estimate of the probability which a single electron has of initiating a filamentary streamer. Figure 6 shows the formative time lag, the mean scatter time, and the initiating probability as a function of overvoltage for one gap geometry (point radius 0.03 cm, electrode separation 1.5 cm) at a pressure of 300 mm of Hg. The initiating probabilities

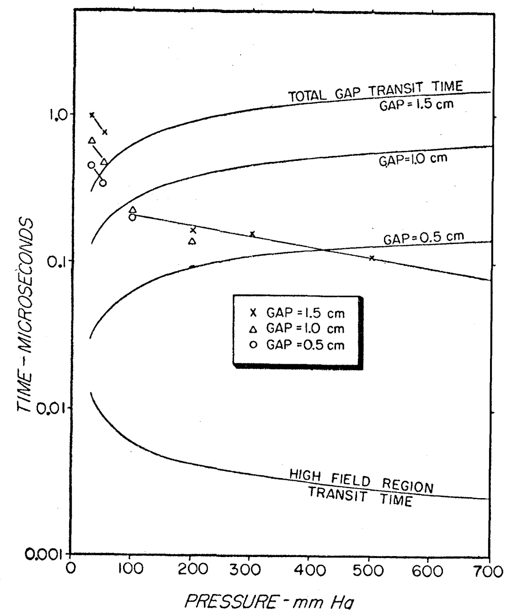

FIG. 8. Threshold formative lags of the positive point corona as a function of pressure for a point radius of 0.03 cm and electrode separations of 0.5, 1.0, and 1.5 cm. Also shown are computed electron transit times at threshold for the whole gap and for the high field region of the gap.

for an electron at other gap geometries and pressures fall in the same general range.

Formative time lags for one gap geometry (point radius 0.03 cm, electrode separation 1.5 cm) are shown in Fig. 7, where they are plotted as a function of

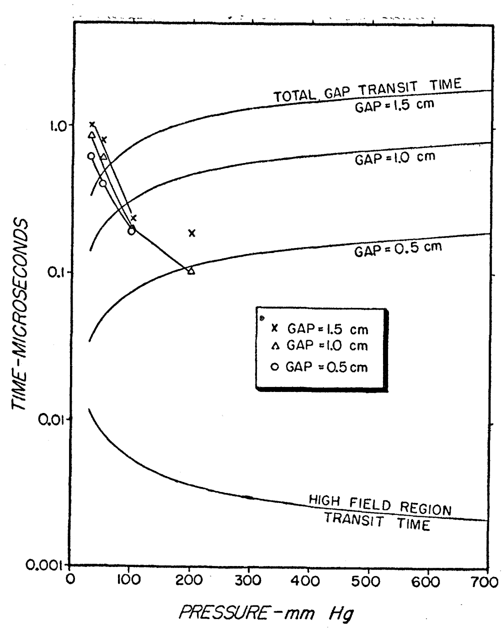

FIG. 9. Threshold formative lags of the positive point corona as a function of pressure for a point radius of 0.02 cm and electrode separations of 0.5, 1.0, and 1.5 cm. Also shown are computed electron transit times at threshold for the whole gap and for the high field region of the gap.

[18] M. von Laue, Ann. Physik 76, 261 (1925).

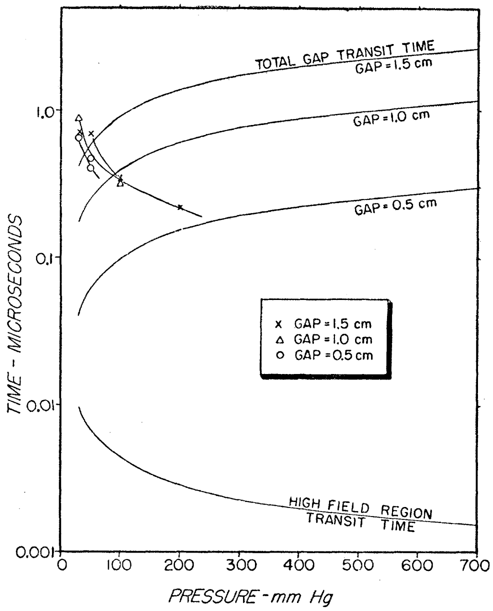

FIG. 10. Threshold formative lags of the positive point corona as a function of pressure for a point radius of 0.007 cm and electrode separations of 0.5, 1.0, and 1.5 cm. Also shown are computed electron transit times at threshold for the whole gap and for the high field region of the gap.

percent overvoltage. This particular gap geometry was the only one for which formative time lags were obtained at all pressures. For the other gaps, formative lags were obtained only at the lower pressures; at pressures near atmospheric the statistical scatter was generally so large that it masked the formative lag. It was, however, possible to set an upper limit to the formative lag from the shape of the statistical distribution; this limit is of the order of 0.1 microsecond.

Also plotted in Fig. 7 for comparison purposes are the formative lags for a plane parallel gap of one centimeter in air as given by Fisher and Bederson.[12] The corona formative lags do not become longer and longer as threshold is approached (the plane parallel gap formative lags do show this behavior), but tend toward a definite limiting value at threshold. These threshold formative lags for the various gap geometries are shown plotted as a function of pressure in Figs. 8, 9, and 10. Also plotted in these figures are electron transit times, both for the whole gap, and for the region of the gap where electron multiplication is appreciable (field strength to pressure ratio greater than 30 v/cm mm Hg). These transit times were computed at threshold using the confocal paraboloid approximation and values of electron mobility extrapolated from the measurements of Nielsen and Bradbury.[19]

Since the formative lags are shorter than the total gap transit time, this eliminates the cathode as playing any role in the formation of the filamentary streamer. However, the formative lags are much longer than the high field region transit time. There is thus an indication that an ionization buildup process taking place wholly in the gas near the point precedes the formation of a filamentary streamer.[20]

[19] R. A. Nielsen and N. E. Bradbury, Phys. Rev. 51, 69 (1937).

[20] Evidence for such an ionization buildup preceding the streamer has also been found with photomultiplier techniques by M. R. Amin, Washington Gaseous Electronics Conference, October, 1953 (unpublished).