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# Ionization Processes in a Long Discharge Tube with Application to Lightning Mechanism

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Properties of the progressive breakdown, occurring when an impulsive potential is applied to an electrode in one end of a discharge tube 14 cm in diameter and 12 meters long, have been investigated, principally by means of a high speed cathode-ray oscillograph. Potentials from 25 kv to 115 kv and pressures from 0.006 to 8.0 mm Hg were used, with dry air and hydrogen in the tube. Conditions in the discharge, when comparatively large over-voltages are impressed, have been discussed by several investigators, particularly with respect to impulses of positive polarity and in tubes of smaller diameter. These observations now have been extended to include the negative polarity. In addition, a low speed, low potential process has been obtained and its properties analyzed.

A possible application of the lightning theory to such discharges is given. The low speed impulse resembles the hypothetical lightning pilot streamer as to speed and current, and the speed is of the order of magnitude of the drift speed of electrons in the tip field, as assumed for the pilot streamer. The high speed processes are more similar to the lightning dart leaders. It is pointed out that conditions in the tube are such that propagation in this case may be controlled more by the presence of photo-electrons ahead of the tip than by a preliminary ionizing leader.

THE progressive character of the breakdown in long discharge tubes upon the application of impulsive potentials to an electrode in one end of the tube was first discussed by J. J. Thomson.[1] More recent investigations by Beams[2] and by Snoddy, Beams, and Dietrich[3] with the rotating mirror and with the high speed cathode-ray oscillograph have shown the similarity between such ionization processes and the general features of the lightning discharge. Impulses in

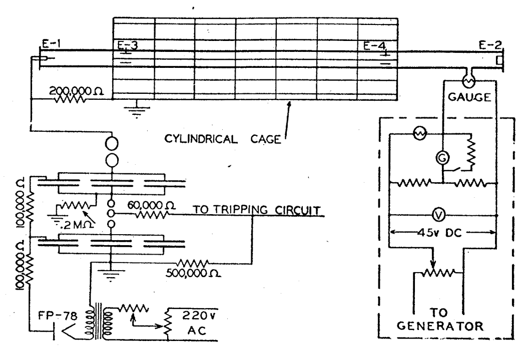


FIG. 1. Diagram of discharge tube with Marx circuit, cylindrical shielding cage, vacuum gauge circuit, and electrodes. Distance from $E$-3 to $E$-4 is 642 cm. Resistance values are approximate.

tubes have been found to travel from the high potential end and, if the far end contains a grounded electrode, a return discharge of greater intensity and higher speed progresses back to the input electrode.

Similar processes have been found by Schonland and others[4] in the lightning discharge, and by Allibone and Meek[5] in long sparks in the laboratory. The lightning stroke is ordinarily initiated by a downward moving "leader," followed by an upward moving "return" stage of much greater intensity. The cloud end of the discharge is usually of negative polarity with respect to ground. Leaders for strokes over the same channel after the first discharge has occurred are generally continuous processes, called "dart" leaders, in contrast to the initial leader, which moves downward in a series of steps and is known as the "stepped" leader. The speeds of these leaders are fairly uniform for various strokes, averaging $1\times10^{10}$ cm/sec for return strokes, $1\times10^{9}$ cm/sec for stepped leaders, and $2\times10^{7}$ cm/sec for the average speed of the stepped leader computed from the total time of its travel.

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[1] J. J. Thomson, *Recent Researches* (Clarendon Press, Oxford, 1893).
[2] J. W. Beams, Phys. Rev. **36**, 997 (1930).
[3] L. B. Snoddy, J. R. Dietrich, and J. W. Beams, Phys. Rev. **50**, 469 (1936); L. B. Snoddy, J. R. Dietrich and J. W. Beams, Phys. Rev. **52**, 739 (1937); J. R. Dietrich, "Progressive Breakdown in Long Discharge Tubes," dissertation, University of Virginia (1939), unpublished.
[4] B. F. J. Schonland and H. Collens, Nature **132**, 407 (1933); B. F. J. Schonland and H. Collens, Proc. Roy. Soc. **A143**, 654 (1934); **A152**, 595 (1935); B. F. J. Schonland, Proc. Roy. Soc. **A164**, 132 (1938); Phil. Mag. **23**, 503, (1937); K. B. McEachron and W. A. McMorris, G. E. Rev. **39**, 487 (1936); K. B. McEachron, J. Frank. Inst. **227**, 149 (1939); E. J. Workman, J. W. Beams, and L. B. Snoddy, Physics **7**, 375 (1936).
[5] T. E. Allibone and J. M. Meek, Proc. Roy. Soc. **A166**, 97 (1938); **A169**, 246 (1938).

It has been supposed that there may be a constantly moving preliminary "pilot" streamer preceding the stepped leader and furnishing a preionized path for the other stages.

The ionizing process in a long discharge tube offers certain advantages in the study of the mechanism of leader propagation. The channel is definitely fixed, and the time intervals are long enough for satisfactory measurements with the oscillograph. Furthermore, the return stage with its high luminosity and large current can be eliminated by insulating the far end of the tube from the ground. In the present work, observations in a 14-cm diameter tube have been extended in order to determine the applicability of the theory of lightning mechanism to discharges of this type.

**APPARATUS**

Most of the apparatus has been previously described.[3] The tube consisted of 15 sections of glass tubing each 80 cm long, 14 cm in internal diameter, and 5 mm thick, making a total length of 12 meters. The ends of the sections were ground flat and joined together with picein wax. Four brass electrodes were placed in the tube as in Fig. 1. Between $E$-3 and $E$-4 there was a grounded electrostatic shield (cylindrical cage, Fig. 1), and near $E$-2 were the drying traps of phosphorus pentoxide, the pumping system, a Pirani vacuum gauge, and an insulating column which could be evacuated sufficiently to prevent the discharge at $E$-2 from reaching the ground. Impulsive potentials were supplied by a Marx potential doubling circuit. The high speed cold cathode oscillograph of the single sweep Dufour type had a maximum sweep speed of $2\times10^8$ mm/sec with a cathode potential of 70 kv. Various auxiliary circuits were used to synchronize the oscillograph with the impulse in the tube.

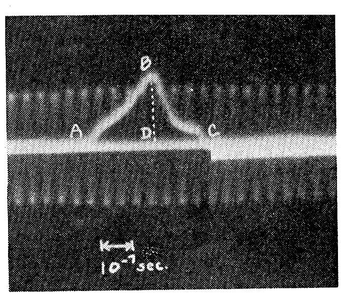



FIG. 2. Oscillogram for computing speed in air at 0.034 mm Hg pressure with −85 kv applied potential. Frequency of timing wave is 19.0 megacycles per sec.

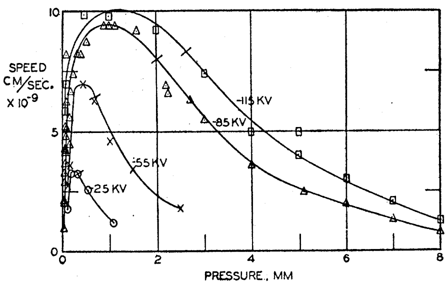



FIG. 3. Speed-pressure curves for high potential discharge in air. Negative applied potential.

**HIGH POTENTIAL MEASUREMENTS**

The term "high potential discharge" is used here to indicate the discharges in the tube which are propagated throughout its length without marked variation in speed, current, or luminosity. On the other hand, it is possible that the character of the impulse may change rapidly as it travels. In this case the speed, current, and luminosity vary greatly during the process of propagation. The latter condition gives rise to what are called "low potential discharges." In general, a high potential discharge results from large over-voltages at low pressures, and a low potential discharge from smaller potentials at higher pressures.

The speed of the ionizing process was computed from oscillograms such as Fig. 2. Electrodes $E3$ and $E4$ (Fig. 1) were connected through a potential divider unit to the vertical deflection plates of the oscillograph, while the sweep potential was applied to the horizontal plates. The sequence in this oscillogram was as follows: as the impulse progressed from $E$-1, it raised the tube potential. At $A$ (Fig. 2) the potential of $E3$ began to rise, the potential difference between $E3$ and $E4$ continuing to increase to the point $B$ and then decreasing. At $B$ the discharge has reached $E4$. At $C$ the potentials of $E3$ and $E4$ were approximately equal. The horizontal distance $AD$ and the corresponding time interval on the timing wave shown in the background allowed computation of the average speed in this section of the tube, which was about 6 meters long. The distance to the ends of the tube was large enough

TABLE I. Input current in dry air as a function of pressure at −85 kv applied potential.

| Pressure mm Hg | Max. current amperes |
|---|---|
| 0.05 | 81 |
| 0.15 | 95 |
| 0.32 | 96 |
| 0.65 | 96 |
| 1.6 | 88 |
| 4.0 | 56 |

to reduce the effect of the electrode $E1$ as well as to avoid the effect of the reflected wave from $E2$.

The potential dividers were made symmetrical by making adjustments until an impulse applied simultaneously to both leads on the high potential side produced no oscillograph deflection. Leads to the oscillograph were kept symmetrically placed and about the same length. The effect of the charging current to the electrodes and oscillograph deflection system on the speed of the discharge was investigated by means of oscillograms of the potential across a resistance in series with one condenser bank of the Marx circuit. All connections to $E3$ and $E4$ were removed. From these, the time required for the discharge to travel the whole length of the tube was obtainable. There were no significant variations in speeds found by the two methods, indicating that the effect of the electrodes was comparatively small, also that the average speed between $E3$ and $E4$ was not greatly different from the average over the whole tube.

Figure 3 shows the speed-pressure curves for four negative applied potentials with dried air in the tube. The speeds were roughly 50 percent higher than for the positive potential as measured by Dietrich.[3] Under the same conditions, the speed was 20 percent to 50 percent higher in hydrogen than in air.

The current supplied to the tube by the input circuit was computed by Ohm's law from oscillograms of the potential drop across a 25-ohm resistance between one bank of condensers of the Marx circuit and ground. The maximum current varied from 50 to 100 amperes. At the lower speeds, it was approximately the value required to charge a conductor the size of the tube at the center of the shielding cage up to the applied potential in the required time. At the higher speeds the current was still increasing when the discharge reached the far end of the tube; its maximum was limited by the tube length in this case, rather than by the rate of charging. In Table I are given the values of current at several pressures.

At the lower pressures, the maximum potential at any given point in the tube was very nearly equal to the applied potential. As the pressure was increased, the potential sometimes remained at an intermediate value for a short time, then rose steadily to its maximum. This is illustrated in Fig. 4 and it was especially noticeable that speed and current were comparatively small. The magnitude of the initial rise was generally less with increasing pressure, and was always less at $E4$ than at $E3$ for the same conditions. When this situation existed, the potential drop along the tube was such that the maximum potential was not attained until further energy from the input circuit was fed into the ionized stem extending back to $E1$.

## THE LUMINOUS COLUMN

Visual and photographic observations have previously shown[3] that, at low pressure and with positive applied potential, there occurs a marked contraction of the luminous column toward the tube axis. No such contraction has been found for the negative polarity at any pressure, as the column appeared to fill the tube uniformly.

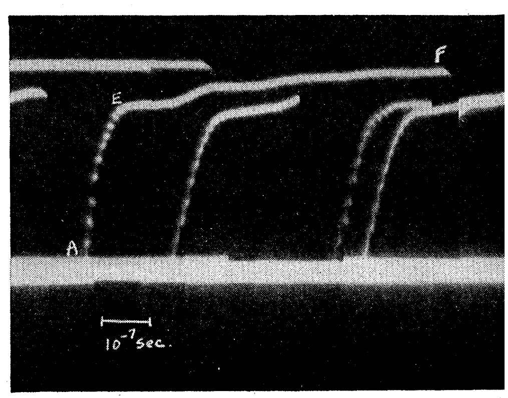



FIG. 4. Several oscillograms of potential from $E$-4 to ground. The maximum of the initial rise is at $E$ and the final maximum at $F$. Hydrogen at 2.5 mm Hg pressure, −85 kv applied potential.

## LOW POTENTIAL MEASUREMENTS

With a constant input potential the pressure in the tube was increased until the character of the impulse changed appreciably during its progress along the tube. Such a condition is characteristic of the above defined low potential discharge. To investigate this kind of discharge, the pressure was raised until there was a marked reduction in luminosity with distance. The speed in 50-cm lengths of the tube at various distances was measured in the same manner as before. Copper foil strips two inches wide wrapped on the outside of the glass were used as electrodes. For these readings, the oscillograph was used at full sensitivity (24 volts/mm). Figure 5 shows average speeds in various sections at 8 mm Hg for both positive and negative polarity. For the negative potential, oscillograms could not be obtained past $E4$, where the speed was $2.5\times 10^8$ cm/sec. The positive discharge continued past this point and was still measurable at $1\times 10^8$ cm/sec. The average speed between $E3$ and $E4$ from Fig. 5 is about half the speed for the corresponding conditions from Fig. 3 for negative polarity. The discrepancy may be attributed to the effect of the current taken to charge the electrodes and their circuits, which was a greater factor here than in the preceding measurements, since the speed from $E3$ to $E4$ would probably be less affected than that measured over a shorter section. Any effect at an electrode which reduces the speed makes it desirable to have the distance between electrodes as large as possible. We assume the actual change of speed is less than the apparent change caused by the oscillograph deflection circuit charging current. It is probable that the curves of Fig. 5 should be considered as showing the general characteristics of speed variation with distance and polarity rather than absolute values.

Another method of obtaining a low potential discharge consisted of placing a grounding spark gap at $E3$ to reduce the potential after the discharge had started in the tube. A damping resistance (minimum 250 ohms) was placed in series with the input circuit to prevent oscillations between $E1$ and $E3$, also to control the rate of energy supply. Values of speed in the section past the end of the visible luminosity are given in Fig. 6, and the corresponding maximum potentials in Fig. 7. Variation of applied potential and the spacing of the gap at $E3$ produced no noticeable effect except a displacement of the low potential discharge along the tube length. As would be expected, increase of the series resistance caused a slow decrease in the rate of charging of the tube. Oscillograms were obtainable for input series resistances up to $7\times 10^4$ ohms at 85 kv. At pressures below 0.1 mm Hg the delay in breakdown at $E3$ allowed the high potential impulse to travel the length of the tube. On the other hand, above 0.6 mm Hg the low potential section was crowded into a distance too short for oscillographic measurement.

TABLE II. Distance $d$ in meters ahead of the stem in which ionization by collision can occur, from Eq. (3).

| Volts | $d$ $p=10$ mm Hg | $d$ $p=1.0$ mm | $d$ $p=0.1$ mm |
|---|---|---|---|
| $1\times 10^6$ | 1 | 3 | 10 |
| $1\times 10^5$ | 0.3 | 1 | 3 |
| $5\times 10^4$ | 0.2 | 0.7 | 2 |
| $1\times 10^4$ | — | 0.3 | 1 |

TABLE III. Comparison of calculated and observed speed.

| Applied potential volts | Pressure mm Hg | Speed cm/sec calculated | Speed cm/sec observed |
|---|---|---|---|
| $1\times 10^5$ | 1.0 | $^*1\times 10^{10}$ | $1\times 10^{10}$ |
| | 2.5 | $5\times 10^9$ | $8\times 10^9$ |
| | 4.0 | $3\times 10^9$ | $4\times 10^9$ |
| | 8.0 | $1\times 10^9$ | $1\times 10^9$ |
| $5\times 10^4$ | 1.0 | $7\times 10^9$ | $5\times 10^9$ |
| | 2.5 | $4\times 10^9$ | $2\times 10^9$ |

* Adjusted by fixing $n_0$.

All the oscillograms of the low potential discharge were taken with positive applied potential. No negative readings in the tip could be obtained under any of the conditions available in the experiments. In the negative case, as the distance of the foil electrodes from $E1$ was increased beyond $E3$ to the end of the high potential region of the discharge, there was a transition in the course of a few centimeters to a potential too low for the oscillograph to record.

The time rate of increase of potential, together with the speed, allowed the computation of approximate values of the ratio of field strength to pressure in the tip of the low potential discharge. This time rate could be obtained since the oscillograph was capable of recording a faster rise than was present in the low potential discharges. The ratio $X/p$ in volts/cm/mm Hg is

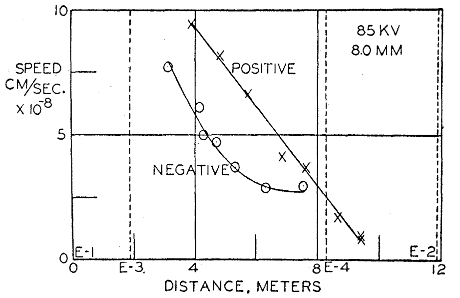



FIG. 5. Speed-distance curves of low potential discharge in air at 8.0 mm pressure and with 85 kv applied potential. Position of fixed electrodes is indicated by vertical dotted lines.

plotted against speed at the three pressures from 0.20 to 0.50 mm Hg in Fig. 8, from which it may be seen that the speed generally increased with $X/p$. The lowest speed recorded was $1.7\times10^7$ cm/sec at an $X/p$ near 20.

## DISCUSSION

The theory of the mechanism of leader propagation has yielded satisfactory explanation of the observed speeds and currents in the lightning leaders. They are thought to progress by electron motion in the high field near their tips. The region in which ionization by collision occurs extends some distance ahead of the highly ionized stem, and the presence of a comparatively few free electrons in this region is fundamental to the theory.[6] The drift velocity of electrons in a field is approximately[7]

$$S=(2EeL/\pi m)^{\frac{1}{2}}, \qquad (1)$$

where $S$ is the speed, $E$ the field strength, $L$ the electron mean free path, $e$ and $m$ the charge and mass of the electron respectively. For the minimum breakdown field at the cloud level, this equation yields a speed of $3.7\times10^7$ cm/sec, which is lowered somewhat by several corrections. The value of $X/p$ taken is about 40.

From such treatments it has been shown by Schonland[4] that the pilot streamer speed is of the order of magnitude of the drift velocity in the breakdown field. The stepped leader, on the other hand, makes use of electrons left from a preceding streamer and it travels much faster. On the assumption that the advance is caused by the filling of the region ahead of the tip, in which ionization by collision can occur, by avalanches starting from the original free electrons, it is found that the speed of propagation is given by

$$S=N^{\frac{1}{3}}\bar{v}d, \qquad (2)$$

where $d$ is the distance in which the ionization can take place, $\bar{v}$ is the mean drift velocity, and $N$ is the original concentration per cubic cm. Therefore, $S$ depends on the number of electrons left from the previous discharge, and on the field at the tip, which determines $\bar{v}$ and $d$. For conditions supposed by Schonland to be reasonable in the lightning leader, $N$ is about 1000, $d$ about 6 cm, and the tip radius about 1 cm. In this manner the high velocities are explained without the assumption of excessively high fields.

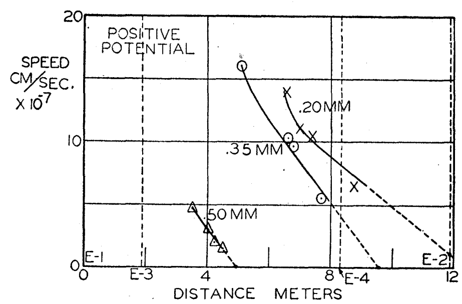



FIG. 6. Speed-distance curves of low potential discharge in air with $E$-3 grounded.

The stepped leader is explained by Meek[8] as arising from recombination in the leader channel, resulting in decreasing conductivity and increasing fields at the cloud end of the steps. A new step is initiated when this field again reaches the breakdown value; for a pilot streamer current of about one ampere, the computed time between steps is fairly near the observed 50 microseconds.

The low potential leaders in the tube were obtained both by raising $p$ and by lowering $X$. The ratio $X/p$ was found to determine the speed and the possibility of propagation. The minimum $X/p$, substituted in Eq. (1), gives speeds near the measured minimum of $1.7\times10^7$ cm/sec. That is, the low potential discharges progressed

[6] A. M. Cravath and L. B. Loeb, Physics 6, 125 (1935); L. B. Loeb, Rev. Mod. Phys. 8, 267 (1936); L. B. Loeb, *Fundamental Processes of Electrical Discharges in Gases* (Wiley and Sons, 1939); G. Simpson, Proc. Roy. Soc. **A111**, 56 (1926).

[7] H. Jehle, Zeits. f. Phys. **82**, 785 (1933).

[8] J. M. Meek, Phys. Rev. **55**, 972 (1939).

until $X/p$ reached 20, the minimum required for Townsend ionization,[9] and the speed at this point was approximately the pilot streamer speed. One ampere was about the minimum current in the tube, since the streamer would barely propagate at 85 kv with $7\times10^4$ ohms in series; the pilot streamer current is generally considered to be of this magnitude. In the tube a marked difference in conditions at the tip of the negative and the positive leaders was indicated. The rate of increase of potential on the oscillograms was greater for negative polarity, and it is consequently probable that the negative wave front was considerably steeper. It may be that the predominance of negative leaders in the lightning discharge is partly due to this effect. The existence of this low speed positive discharge points to the possibility that local positive irregularities in field distribution arising in a cloud may be somewhat smoothed out by a low energy discharge, while a negative distribution may build up until the discharge which finally occurs initiates a lightning leader.

The high potential impulse appears more analo-

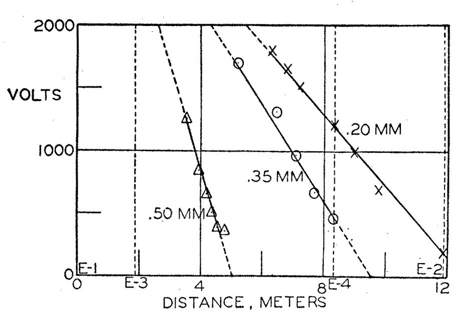



FIG. 7. Maximum positive potential above ground as function of distance with $E$-3 grounded and conditions same as for Fig. 6.

gous to the continuous lightning leaders in that the speed indicates a propagation in an ionized channel. It seems likely, however, that the free electrons are in this case photoelectrons, because of the brightly illuminated stem, an effect which might be considerably more important because of ultraviolet reflections at the glass walls. By assuming the same general mechanism of advance that Schonland has given for the lightning leader, Eq. (2) may be modified to apply to the case in which the photoelectric effect is important, the difference being that $N$ can no longer be considered constant, because of absorption of the ionizing radiation by the air in the tube. Under the same assumptions for which Eq. (2) was derived by Schonland,[4] it is found that the field strength at the tip is, at least approximately, $X = V/2r$ volts/cm, where $V$ is the applied potential and $r$ the tube radius. Then the distance $d$ in which a breakdown can occur (that is, when $X/p > 40$) is given approximately by

$$d = (rV/80p)^{\frac{1}{2}}. \qquad (3)$$

Table II shows values of $d$ for the 14 cm diameter tube at various pressures and applied potentials.

At a distance $l$ the number of photoelectrons is given by $n = n_0 \exp(-alp/760)$, where $n_0$ is the concentration just ahead of the tip and $a$ is the absorption coefficient whose value is 10 $\text{cm}^{-1}$, according to Cravath.[10] A minimum speed of propagation may be found by assuming as before that the entire region $d$ must be filled with conducting filaments starting at the original photoelectrons; then the minimum speed is controlled by the time required for the region of $d$ farthest from the stem to be so covered. Equation (2) becomes

$$S = n_0^{\frac{1}{3}} 3\times10^7 d \exp[-10dp/2280]. \qquad (4)$$

Substituting the value of $d$ from Eq. (3), we obtain

$$S = 3\times10^7 n_0^{\frac{1}{3}} (rV/80p)^{\frac{1}{2}} \times\exp[-(prV)^{\frac{1}{2}}/228(80)^{\frac{1}{2}}]. \qquad (5)$$

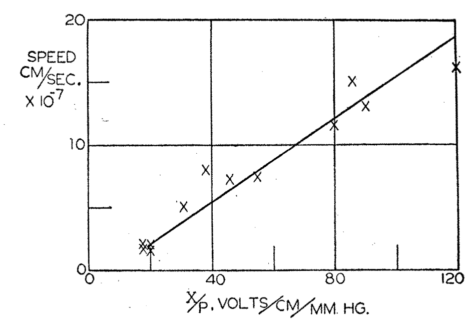



FIG. 8. Speed of low potential discharge in air as function of $X/p$ for pressures of 0.20 mm to 0.50 mm Hg and for positive potential. Lowest speed $1.7\times10^7$ cm/sec at $X/p$ about 20.

[9] F. H. Sanders, Phys. Rev. **41**, 667 (1932).

[10] A. M. Cravath, Phys. Rev. **47**, 254 (1935).

By assuming $n_0$ constant over the range of pressures of the experiments, and substituting the experimental values of $S$, $r$, $p$, and $V$ for one set of conditions, one finds that $n_0 \cong 10^2$ ions per cubic cm, and Eq. (5) becomes

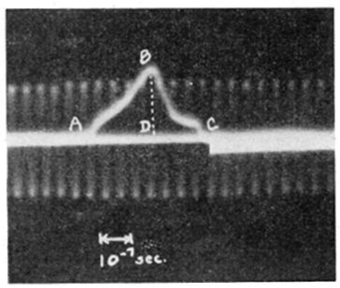
$$S = 1.5 \times 10^8 (rV/80p)^{\frac{1}{2}} \times \exp[-(prV)^{\frac{1}{2}}/228(80)^{\frac{1}{2}}]. \quad (6)$$

This equation cannot be expected to hold at low pressure, since loss by diffusion to the walls has not been taken into account. The agreement at the higher pressures is shown in Table III, in which the observed values are taken from Fig. 3.

The value of $n_0$ is of the order of one-tenth the magnitude assigned to the corresponding $N$ in the lightning leader, so that the pre-ionization in the two cases may not be greatly different in its effect on the speed. However, a direct comparison of the speeds in the tube with those of the lightning leader is open to criticism. While the values of $X/p$ are approximately the same in both cases, the low pressures prevailing in the tube cause a marked difference in the discharge characteristics. Diffusion to the walls becomes important, and recombination is practically negligible. The latter point might be expected to rule out the existence of a stepped leader such as that discussed by Meek, in which the stepping is a result of lowered conductivity in the column due to recombination. However, oscillograms showed that at certain pressures and potentials there was a lowering of conductivity in the tube, and thereby a limitation of the energy fed into the discharge until a fresh breakdown occurred. This effect, shown in Fig. 4, seems somewhat analogous to the stepped leader mechanism of Meek, except that in this case the loss of conductivity might be better attributed to diffusion to the tube walls than to recombination. The disappearance of the stepped leader in long sparks in air at low pressures has been noted by Allibone and Meek.[5]

The higher speed in hydrogen may be due partly to the greater drift speed resulting from the longer free path compared with air at the same conditions.

We wish to express our appreciation to Professor J. W. Beams for his continued interest and assistance in this work.

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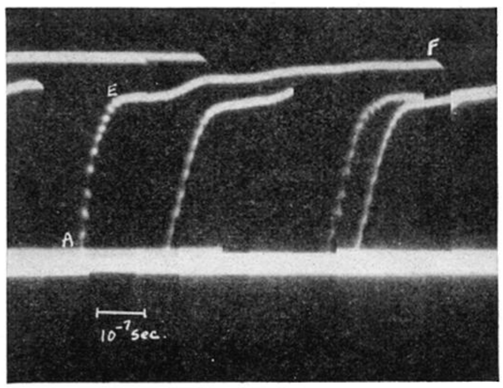


FIG. 4. Several oscillograms of potential from $E$-4 to ground. The maximum of the initial rise is at $E$ and the final maximum at $F$. Hydrogen at 2.5 mm Hg pressure, −85 kv applied potential.