The development of the spark discharge. II

By T. E. Allibone, D.Sc., Ph.D. and J. M. Meek, M.Eng.

(*Communicated by S. R. Milner, F.R.S.—Received* 26 *August* 1938)

[Plates 10–16]

1. Introduction

An account has already been given of observations made with a rotating-film camera in the study of the electric spark in air at atmospheric pressure (Allibone and Meek 1938; Allibone 1938). The object of the present paper is to extend the previous results, and in particular to describe the development of the spark in air at reduced pressures, viz. from 76 to 0·3 cm. Hg. The high-speed cathode-ray oscillograph has been used in conjunction with the rotating camera to enable voltage and current oscillograms to be made. Various phenomena, previously observed by oscillographic methods only, have now been shown to be associated with definite processes in the discharge mechanism.

2. Apparatus and technique

The general features of the apparatus used in the present work are no different from those previously described (Allibone and Meek 1938;* referred to later as (I)). The same 2000 kV impulse generator has been used throughout the experiments, though for the low-pressure work only two of the twelve stages of condensers were used; these had a series capacitance of 0·06μF and gave a maximum output voltage of 330 kV. One terminal of the generator was connected to the discharge gap through series resistances of different values; the other terminal, together with one electrode of the discharge gap, were earthed.

The high-voltage electrode used in the experiments at atmospheric pressure consisted of a brass rod 1 cm. in diameter with a point tapered to a cone of 30°. This electrode was suspended vertically over a plane earthed electrode at heights varying from 25 to 200 cm. The plane electrode (240 × 240 cm.) was of sufficient extent to prevent discharges terminating at its edge.

---

* Erratum in Paper I: page 123, Table I, column 2. Time-lags for gap lengths of a above 25 cm. should be $\times 10^{-6}$ sec.

In the experiments at reduced pressures the discharge gap was mounted in a glass cylinder 37 cm. internal diameter and 100 cm. in length. One end was sealed by a bakelite board, 1 in. thick, the other end by a steel plate; the chamber was evacuated by a rotary oil pump and the pressure was recorded on a mercury manometer. The high-voltage electrode consisted of a brass rod, $\frac{3}{4}$ in. in diameter, with a steel tip in the form of a 30° cone; this electrode, suspended from the bakelite board, projected 28 cm. into the cylinder coaxially, so that the development of the discharge from the electrode tip is unlikely to have been influenced by any discharge over the surface of the bakelite. With regard to the earthed electrode, it had been the authors' intention to use a plane in order to obtain complete dissimilarity between the electrodes. It was found, however, that for the selected gap of 50 cm. the negative discharge frequently terminated on the edge of the plane and also took place over the inner surface of the glass cylinder in the vicinity of the plane even though the edge of the plane was turned to a radius of 5 cm. A short pointed steel rod 1 cm. long placed in the centre of the earthed electrode had the effect of concentrating the negative discharges on to its tip and almost eliminated sparkover on the surface of the glass, whilst it had no appreciable effect on the behaviour of the positive discharge. One half of the inside surface of the glass cylinder was covered with black paper in order to prevent confusion of the photographs of the discharge due to reflexion from this surface. The air in the chamber was frequently changed, so that the character of the discharge would not be affected by change in gas composition.

The rotating-film camera described in the previous paper (I) was again used in the experiments; the only alteration was the introduction of a new quartz-rocksalt lens ($f/4{\cdot}5$: focal length 12 cm.) which considerably enhanced the quality of the photographs. The special value of the transmission of the far ultra-violet radiations by this lens was of course lost in the low-pressure experiments as a glass tank had to be used.

Records of the voltage applied to the discharge gap, and also of the current in the discharge, were obtained by means of a high-speed cathode-ray oscillograph. In some cases a capacitance potential divider was connected in parallel with the discharge gap and coupled to the oscillograph. In other cases the voltage applied to the oscillograph was derived from an antenna arranged close to the high-voltage electrode. This antenna was carefully shielded from the earthed electrode to reduce the influence of upward-developing streamers on the recorded voltage. The latter method is admittedly less accurate than the former method so far as the voltage ordinate is concerned, but the use of a condenser potential divider considerably modifies the wave-front of the applied voltage when the series resistance is large and is therefore undesirable. The current in the discharge was measured by connecting the lower electrode to earth through a non-inductive resistance, the value of which was sufficient to enable the voltage developed across it to be applied directly to the oscillograph.

3. General description of records

The nomenclature described in the previous paper (I) has again been adopted to describe the different processes in the development of the discharge. The stepped leader process already observed has been found to be accentuated when the discharge takes place in air at less than atmospheric pressure, with a resultant decrease in the speed at which the envelope of the tips of the individual leaders progresses. Neither the speed of the main stroke, nor that of the leader stroke traversing a pre-ionized path, has yet been measured but is known to be in excess of 3×10^8 cm./sec. (I). Thus in the analysis of the photographs the main stroke is again used as the basis for the measurement of leader stroke velocity.

In all the illustrations of the discharges the high-voltage electrode is at the top, and the earthed electrode at the bottom, the leader stroke appears on the left, the main stroke on the right. The oscillograms given in the text are printed with their time axes from left to right to correspond to the photographs of the sparks: a zero line is given for reference, and the natural period of the timing wave is given on each record. The spacing d in cm. between the electrodes, the circuit resistance R in ohms, the pressure P in cm. Hg. and, where relevant, the height p of the earthed point above the earthed plane are given on each photograph. In all the records the minimum voltage required to cause sparkover was used (unless otherwise stated).

As there is such a very marked difference between the discharges when the polarity of the high-voltage electrode is changed, detailed description of the results will be separated into two categories, positive and negative discharges, each being subdivided into sections, atmospheric and sub-atmospheric pressures.

4. The positive discharge

(a) *Atmospheric pressure*

Considerable attention has already been given to the positive discharge (I) and relatively little can be added to the previous details. However, as the technique of voltage measurement involved the use of a condenser voltage divider placed across the gap, the effect of the presence of this divider on the development of the discharge has been investigated. It will be realized that the capacitance C in parallel with the gap cannot be altered without at the same time altering the rate of rise of applied voltage unless the series resistance is also altered by a proportionate amount. Experiments were therefore made with varying values of C with the same value of R, and then with different values of R keeping CR approximately constant. The results can be expressed in the following manner:

(A) Addition of capacitance increases the thickness of the photographic record of the main stroke, i.e. the current in the stroke is greater.

(B) Addition of capacitance in so far as it is accompanied by a greater value of CR increases the number of stepped leader strokes—these steps begin to occur on the rising front of the voltage wave.

(C) Addition of resistance in so far as it is accompanied by a greater value of CR increases the number of stepped leader strokes as in (*b*) above: note when C is very small and R is large the current in the leader stroke causes a drop in the terminal voltage and the voltage waveform takes on a "saw-tooth" appearance.

(D) Addition of capacitance, keeping CR constant, increases the current flowing in the final stepped leader stroke, and the current is maintained at that higher value until the main stroke occurs. In the limit as R reaches low values the whole picture is too blurred by halation from the main stroke to enable deductions to be made.

Records illustrating the above are given in fig. 1, Plate 10, for a gap of 100 cm. (*a*) with a resistance of 100,000 ohms, and capacitances of 10, 200 and 5000 $\mu\mu$F, and (*b*) with a capacitance of 10 $\mu\mu$F, and resistances of 10,000, 100,000 and 1,000,000 ohms. In fig. 1 (*a*) series, the wave-front of the applied voltage was approximately 2 μsec. for the first record (i), and it will be observed that a single leader stroke traverses the whole gap in 46 μsec., and is then followed by the main stroke: no partial discharges precede this leader stroke, which has a final velocity of $2\cdot5\times10^6$ cm./sec. In the second record (ii) the wave-front was approximately 50 μsec., and during this time several stepped leader strokes develop before the final leader stroke traverses the gap. This leader stroke, which is initiated 13 μsec. before the main stroke occurs, has a final velocity of $3\cdot6\times10^6$ cm./sec. In the third record (iii) there are stepped leader strokes (not visible in the printed record) for 140 μsec. before the final leader stroke develops (this is blurred by the main stroke). The main stroke is very heavy and is followed by multiple strokes which occur after a further 100 and 210 μsec.

respectively. These multiple strokes are similar to those examined by Malan and Collens (1937) in the case of the lightning flash.

In the fig. 1 (*b*) series, the first record (i) shows a weak initial leader stroke followed by a strong leader the intensity of which is maintained until the main stroke occurs after 12 μsec. This latter leader stroke is strongly branched and the subsequent retracing of these branches by the main stroke is most evident. The "final" velocity of the leader after it has traversed 75 % of the gap is $8 \cdot 10^6$ cm./sec. The second record (ii) is of course comparable with (i) of the first series: the leader traverses the whole

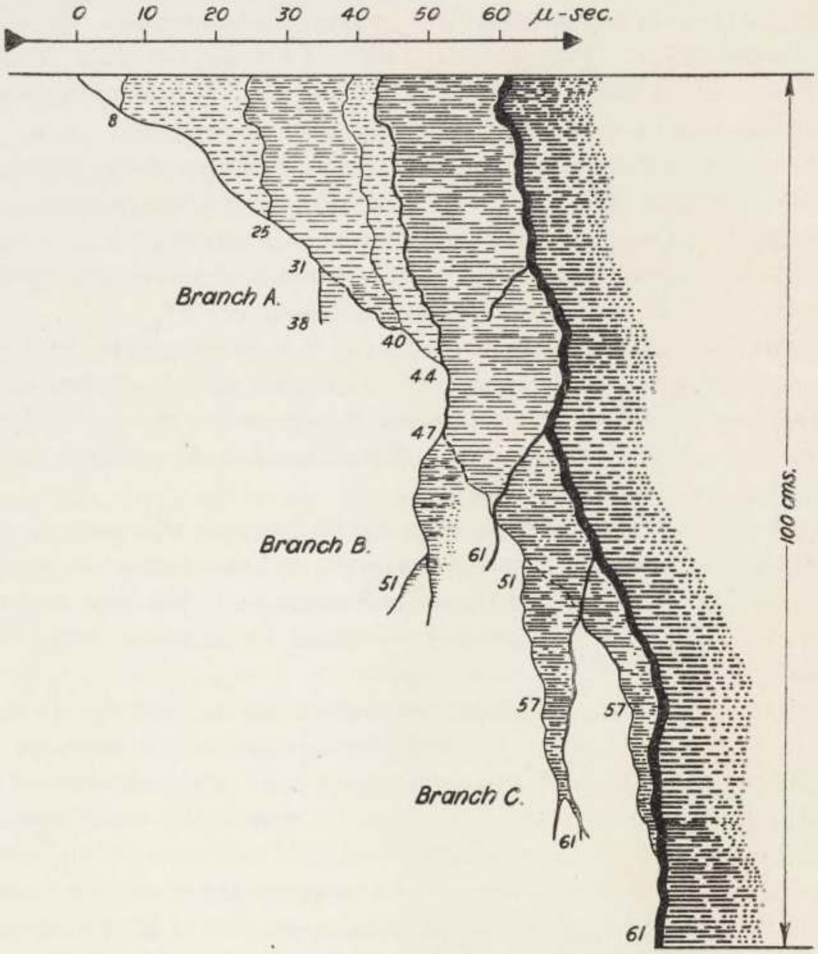

Fig. 2. Positive point electode: earthed plane electrode. Drawing based on an original photograph of a discharge over a 100 cm. gap. $R = 100{,}000$; $C = 300$. (A photograph of a similar discharge is given in fig. 1 (*a*) (ii).)

gap in 46 μsec. with a final velocity of $2{\cdot}5 \times 10^6$ cm./sec. In the third record (iii) four well-defined stepped leaders occur at intervals of 14, 22 and 41 μsec., the last develops nearly to the opposite electrode with a final velocity of $2{\cdot}4 \times 10^6$ cm./sec. and meets a short negative leader 7 cm. above the earthed plane. The occurrence of this type of discharge was mentioned in (I) (p. 101), but no record was then available from which the speed of the negative leader stroke could be measured: in this record the speed is 2×10^6 cm./sec. This upward developing leader is also branched.

It will be seen from the above that the detailed formation of the leader stroke can be altered by changing the circuit constants; their effect on the speed of formation of the leader stroke has already been studied in (I).

As mentioned above, the addition of capacitance increases the current and luminosity of the stepped leader stroke and details of the branching of the leader stroke are thereby enhanced. A number of records of discharges under these conditions exhibit the type of branching described by Schonland, Malan and Collens (1935, p. 598). These are illustrated in fig. 2, a drawing of a discharge 100 cm. long, $R = 100{,}000$, $C = 200$ μμF. The numbers to the left of the leader stroke and its branches denote the times in microseconds subsequent to the initiation of the discharge. The branches *A* and *B* have ceased to develop, whereas the branch *C* is still developing when the main stroke occurs and follows the paths of each of the branches exactly as described for the lightning flash.

(*b*) *Subatmospheric pressures*

Records of spark propagation have been taken with three different values of series resistance and at pressures from 76 cm. to 0·3 cm. Hg. The description of records will be made in order of increasing resistance. Fig. 3, Plate 11, gives representative records: *a*, $R = 700$ ohms; *b*, $R = 10{,}000$ ohms; *c*, $R = 100{,}000$ ohms: and in each group, (i) is at 40 cm. pressure, (ii) at 20 cm. pressure, (iii) at 10 cm. pressure, and (iv) at 5 cm. pressure.

With low resistance, halation due to the main stroke obliterates the leader stroke at atmospheric pressure: at 40 cm. pressure (fig. 3 (*a*) (i)) the leader stroke can just be distinguished; at 20 cm. pressure (fig. 3 (*a*) (ii)) stepped leader strokes become very pronounced on the principal channel and on the branches; at 10 cm. pressure (fig. 3 (*a*) (iii)) an ill-defined brush discharge from the anode is followed after very long time intervals (50–70 μsec.) by isolated stepped leader strokes and finally, after about 100 μsec. the main discharge occurs; at 5 cm. pressure (fig. 3 (*a*) (iv)) the brush discharge from the anode becomes even more diffuse, and extends further towards the opposite electrode; its speed of development cannot be measured on account of its lack of definition. It is accompanied by a small discharge at the cathode which may occur almost at the same instant as the start of the anode brush. A slow speed leader stroke then develops from the anode along the core of the diffuse brush discharge; the speed is estimated to be 2×10^5 cm./sec. near the anode but increases as it meets the ascending brush discharge. The main stroke then follows. With series resistance of 10,000 ohms (fig. 3 (*b*)) the leader stroke and stepped leader strokes are well developed at 76, 40, 20, 10 and 5 cm. pressure. Record fig. 3 (*b*) (ii) very clearly shows the development of nine stepped leader strokes, each branched at their tips. The discharge paths at 5 cm. Hg (fig. 3 (*b*) (iv)) are not so diffuse as in fig. 3 (*a*) (iv), though each step becomes ill-defined at its tip. With series resistance of 100,000 ohms (fig. 3 (*c*)) the stepped leader strokes are very clearly defined at all pressures.

At pressures lower than 5 cm. Hg records could only be taken for $R = 700$ ohms, fig. 4 (*a*), Plate 12: and for $R = 10{,}000$, fig. 4 (*b*), Plate 12. For $R = 100{,}000$ ohms the discharge paths were too weak to be identified. Rotating camera records were taken at 2·5 and 1·0 cm. Hg and stationary camera records at 0·9, 0·6 and 0·35 cm. Hg. The discharge paths are always diffuse at these pressures and the leader stroke travels apparently in a continuous and not a step-by-step method with a speed of about 2×10^5 cm./sec.: it is not branched. Rotating camera records of discharges at less than 1 cm. Hg were unintelligible on account of the diffuseness of the discharge. Three stationary camera records are given in fig. 5, for $R = 700$ ohms. At 0·35 cm. Hg a diffuse pink glow discharge spreads out from the anode to fill the chamber as shown in fig. 5 (*a*), Plate 12. A cathode dark space is evident, and also patches of light on the cathode due to positive-ion bombardment. With increase in pressure to 0·6 cm. Hg a certain concentration of the discharge into a central core is apparent as shown in fig. 5 (*b*), Plate 12, and this core is terminated at the anode by an intense streamer 5–10 cm. in length, whilst at the cathode the core appears to concentrate on several small tufts of discharge. The discharge at 0·9 cm. Hg as illustrated in fig. 5 (*c*), Plate 12, shows a streamer developing from the cathode in conjunction with the streamer from the anode; the whole chamber is filled with a pink glow, and a more concentrated column of glow discharge is seen to join the two streamers. For discharges at pressures lower than 1 cm. Hg complete sparkover in the accepted sense did not occur with this polarity: an increase of applied voltage does not cause an increase in the length of the streamers beyond a certain value but only an increase in their intensity and in the intensity of the column of glow discharge joining their tips.

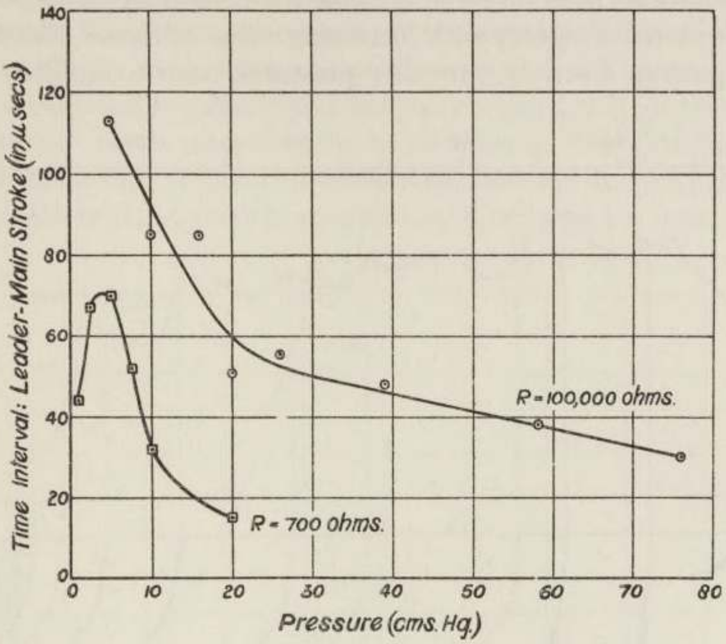

FIG. 6. Positive point electrode: earthed plane ($p = 1$ cm.) electrode. Curves relating the time interval between the initial positive leader and main stroke with pressure for a 50 cm. discharge gap.

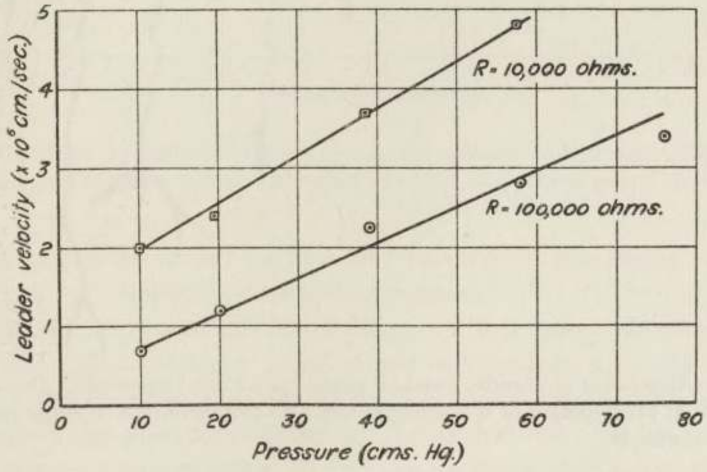

FIG. 7. Positive point electrode: earthed plane ($p = 1$ cm.) electrode. Curves relating leader stroke velocity at 70 % gap length with pressure for a 50 cm. discharge gap.

It has already been noted in (I) that the time interval between leader and main stroke increases with increasing value of circuit resistance: this feature persists down to very low pressures, and in addition the time intervals increase with diminishing pressure for any one value of series resistance. Curves for these time intervals are given in fig. 6 for two values of series resistance, 700 and 100,000 ohms. As the pressure is diminished the deviation of results from the mean values increases and may reach

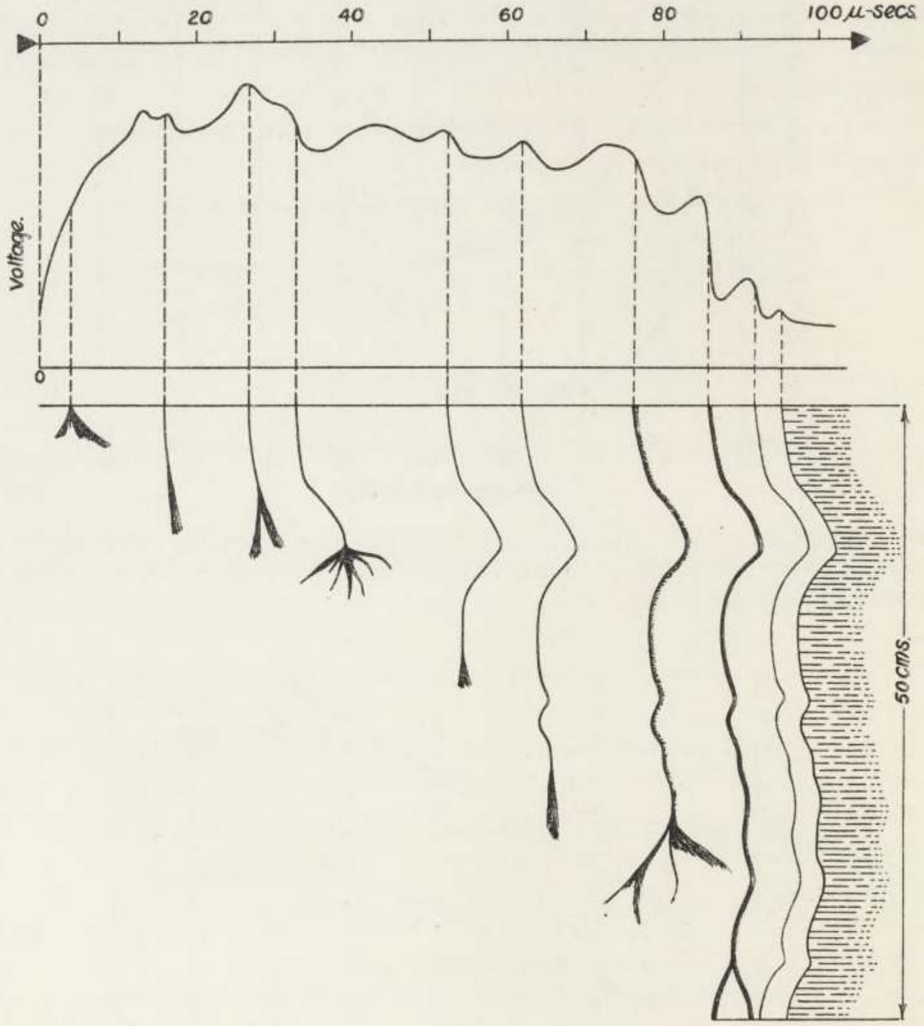

FIG. 9. Positive point electrode: earthed plane ($p = 1$ cm.) electrode. Drawing based on an original photograph of a discharge and the synchronized voltage oscillogram. $R = 100{,}000$: $P = 10$.

50 % at pressures of a few cm. Hg. Very many photographic and oscillographic records were taken therefore to obtain representative values of the leader/main stroke time interval and there can be no doubt as to the reality of the maximum value of this interval as recorded in the lower curve: no explanation can be advanced for its occurrence. The variation of the velocity of the leader stroke with series resistance and gap length has also been discussed in (I). A further variation with pressure has been observed and curves are given in fig. 7 which show a more or less linear increase of leader stroke velocity with increasing pressure.

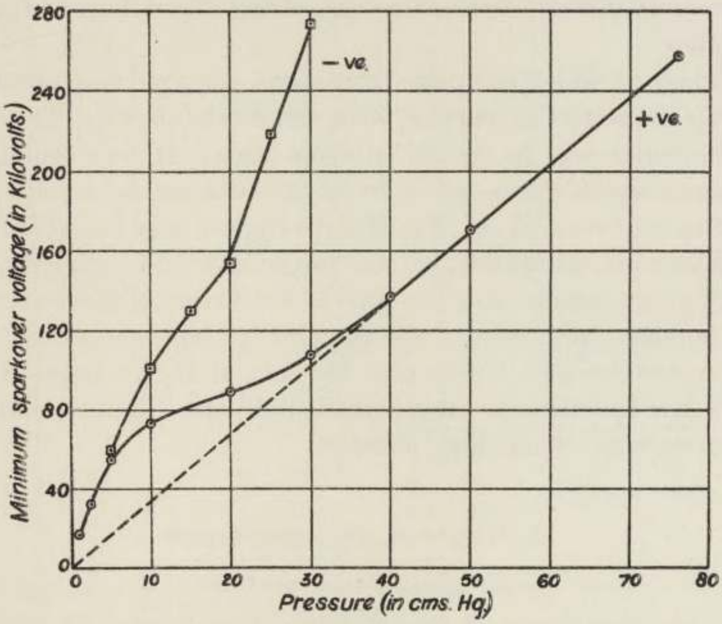

FIG. 10. Relation between minimum sparkover voltage and pressure for a 50 cm. discharge gap between a high-voltage point and an earthed plane ($p = 1$ cm.).

The method of recording the voltage at the upper electrode by an antenna and an oscillograph is of course comparable with that used by Appleton and Chapman (1937) and by Schonland (1937). The sensitivity of the method has been increased since it was first used, (I), and with high series resistance the variations of voltage at the terminal are seen to be quite large: they may amount to 20 % for strong leader strokes. An example of such an oscillogram is shown in fig. 8, Plate 13. The time intervals between successive stepped leader strokes are found to correspond with the times between voltage variations picked up on the antenna; a comparison between one of these oscillograms and the synchronized photograph of the discharge is shown in fig. 9 for a series resistance of 100,000 ohms and a pressure of 10 cm. Under these conditions of resistance and pressure no continuous streamer can be observed to join the tips of the individual leader strokes. Calculations based on the observed voltage drop indicate that the current in the leader stroke is of the order of $\frac{1}{4}$ amp.; the value increases with increasing pressure, and this is also confirmed by the increased intensity of the leader stroke at higher pressures. With series resistance of 10,000 and 1000 ohms the voltage variations are proportionately smaller.

The voltage at which complete breakdown occurred was measured by a sphere gap connected in parallel with the discharge gap. The condenser potential divider was in circuit in these tests. It was found that the breakdown/pressure curve—given in fig. 10—did not agree with Paschen's law at pressures below 40 cm. Hg. This divergence may be explained by the long time-lags of breakdown of the gap at low pressures, the lags (see fig. 6) being comparable with the time-to-half-value of the wavetail of the applied impulse (400 μsec.); the impulse voltages necessary to cause breakdown are therefore higher than the A.C. or D.C. voltages with which Paschen's law has hitherto been investigated, the "impulse ratio" therefore increases with diminishing pressure.

5. The negative discharge

(a) *Atmospheric pressure*

In the previous paper (I) the discharge from a negative high-voltage point to an earthed plane has been studied for gaps no larger than 70 cm. It was however decided to study the point/plane discharge over as large an electrode spacing as possible to see whether the height of the junction point of the negative and positive leaders varied with gap length and series resistance. The resistance was varied down to a value at which the leader stroke was rendered invisible by halation of the main stroke.

It was found that the height of the junction point above the earthed plane expressed as a percentage of the electrode spacing decreased with increase of gap length for otherwise identical conditions. The height of the junction point varied from 56% of the gap length for a 25 cm. gap to 32% of the gap length for a 150 cm. gap for $R = 100,000$. The height of the junction point was also found to decrease with a decrease in series resistance. For a 50 cm. gap it varied from 53% of the gap length for $R = 250,000$ to 44% of the gap length for $R = 13,000$. The fact that the height of the junction point of the positive and negative leader strokes expressed as a percentage of the gap length diminishes with increasing gap length and decreasing circuit resistance offers a possible explanation of the observed fact that photographs of the negative lightning flash to ground seldom show an upward directed positive leader stroke rising to meet the negative leader stroke.

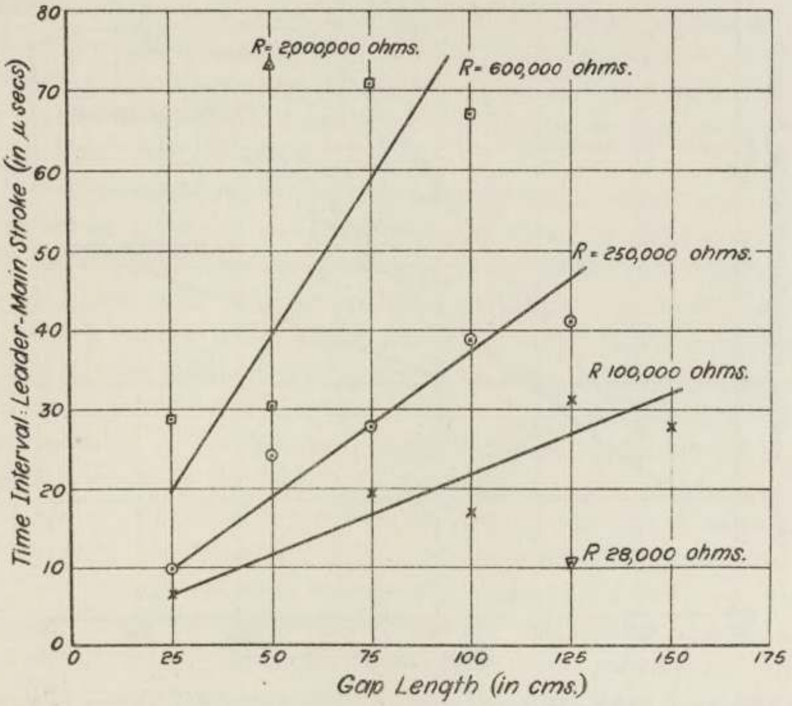

FIG. 11. Negative point electrode: earthed plane electrode. Curves relating the time interval between the initial negative leader and main stroke with gap length for different series resistances.

Further study of the negative discharge over the point/plane gap has confirmed the work previously reported and now curves for different resistances can be given showing the variation with gap length of the time interval between the initiation of the first negative leader stroke and the occurrence of the main stroke. Average values of these time-intervals derived from a number of photographs are given in fig. 11. The curves show an increase of the time interval with gap length and with resistance. The fact that the points do not lie on a uniform curve is due to the wide variation in time interval which may occur, even under identical conditions. The variation may be as great as 50 %, but it is offset to some extent by plotting average values only. The increase of the time interval between the first negative discharge and the main stroke with increasing series resistance can be ascribed—as in the foregoing section on the positive discharge—to the increased time to maximum value of the voltage wave, and to the variation of terminal voltage due to current in the discharge when the resistance is very high.

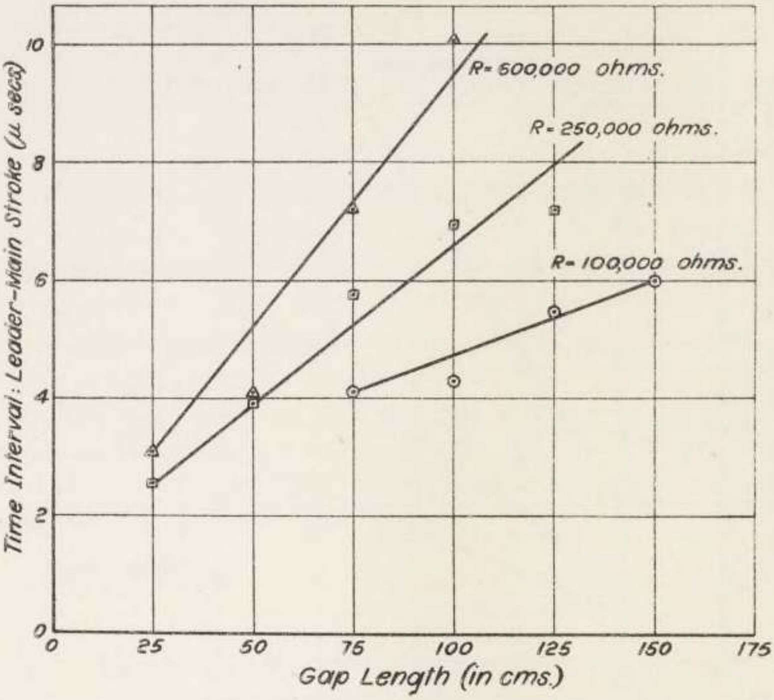

Fig. 12. Negative point electrode: earthed plane electrode. Curves relating the time interval between the initiation of the positive upward-developing leader and the main stroke with gap length for different series resistances.

As previously stated the upward-growing positive leader is generally initiated at the same instant as the final negative leader. Variation of the time interval between the positive leader and the main stroke with gap length and series resistance is shown in fig. 12.

A number of interesting new features of the negative discharge have been observed. In the vicinity of the cathode the discharge often takes the form of thin concentrated filaments some inches in length branched in either direction. Such streamers may be clearly seen on the left of the main spark shown in fig. 13 (*a*), Plate 13, where they sometimes intermingle with branches from the upward-developing positive leader stroke. They may be likened to the mid-gap streamers described by Dunnington

(1931) and to the concentrated filaments which frequently appear in the negative Lichtenberg figures. In fig. 13 (*b*), Plate 13, a diffuse discharge at the cathode becomes concentrated into one of these filaments a few inches away from the cathode and 7 μsec. later a second negative leader stroke follows over the track of the concentrated filament but its connexion to the cathode is over an irregular track.

A photograph of a discharge in which corona and not a complete spark took place is shown in fig. 13 (*c*), Plate 13. The stepped leader process is present at the cathode, while two mid-gap streamers can be clearly seen with their axes collinear and branched in the direction of the cathode. A long branch also extends from the lower mid-gap streamer towards the anode for about 80 % of the gap length.

Another interesting though infrequent phenomenon associated with the negative leader stroke is the appearance of an upward-growing positive type leader in the downward-growing negative leader mechanism. A discharge in which such a leader stroke formation is present is shown in fig. 14 (drawn from a photograph) where a positive leader branching upwards can be seen although the general branching of the discharge in this vicinity is downwards. The path traced out by the positive leader is followed in detail by a subsequent negative leader. Although the speed of the positive leader is too fast to be measured by the present camera for the first few cm. of its path, yet over the last 5 cm. it travels at a speed of 3×10^6 cm./sec. No explanation can yet be provided for the appearance of this positive type leader in the vicinity where it is found.

Variation of series resistance causes an interesting change in the mechanism of the discharge for short point-plane gaps of the order of 25 cm. For resistances up to about 500,000 ohms there is no change in the normal leader mechanism, i.e. negative and positive leaders meet in mid-gap. However, with higher values of resistance the normal positive leader does not develop directly from the plane. A small brush discharge from the cathode is accompanied by a long upward-growing brush discharge from the earthed plane, while from out of this latter discharge, at about 8 cm. above the plane, a leader stroke of the normal positive type develops to meet a negative leader stroke near the cathode, after which the main stroke occurs. Such a discharge is shown in fig. 15 (*a*), Plate 14, for a circuit resistance of 600,000 ohms and the time-interval between the brush discharge and the main stroke is 2·5 μsec. Further increase in the series resistance, to 2 megohms, causes an increase in the height at which the normal positive leader develops from the brush discharge, and in some cases no such positive leader is evident, but the main stroke takes place in a line parallel to the axes of the original brush discharges, as seen in fig. 15 (*b*), Plate 14. This long brush discharge is a feature of the positive discharge from plane-type electrodes: it was referred to in the previous paper (I) for sphere/sphere electrodes but it was not then appreciated that the extent of the brush discharge was a function of the circuit resistance. Recently this same type of positive discharge was seen from the spherical terminal of a very low powered van de Graaff-type electrostatic generator.

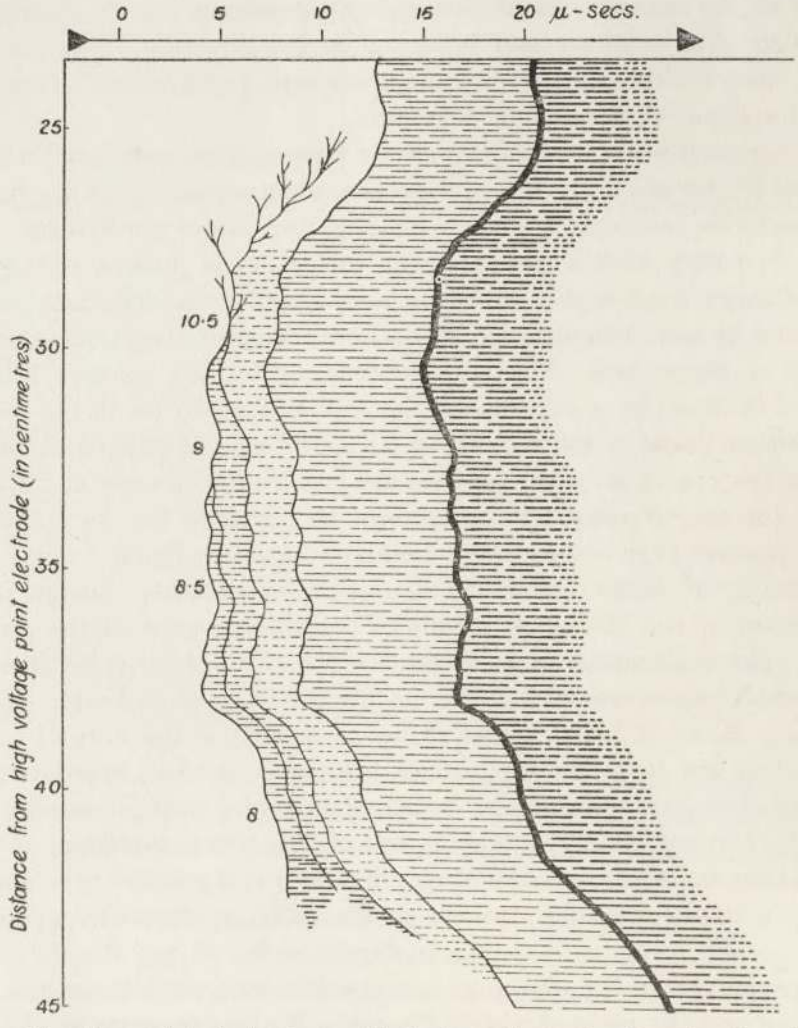

FIG. 14. Negative point electrode: earthed plane electrode. Drawing based on an original photograph to illustrate an upward-developing positive leader in the downward-developing negative leader-stroke mechanism. (The junction point of the negative leader and the main positive leader from the earthed plane is at 70 cm. from the high-voltage point. Total gap-length is 125 cm.)

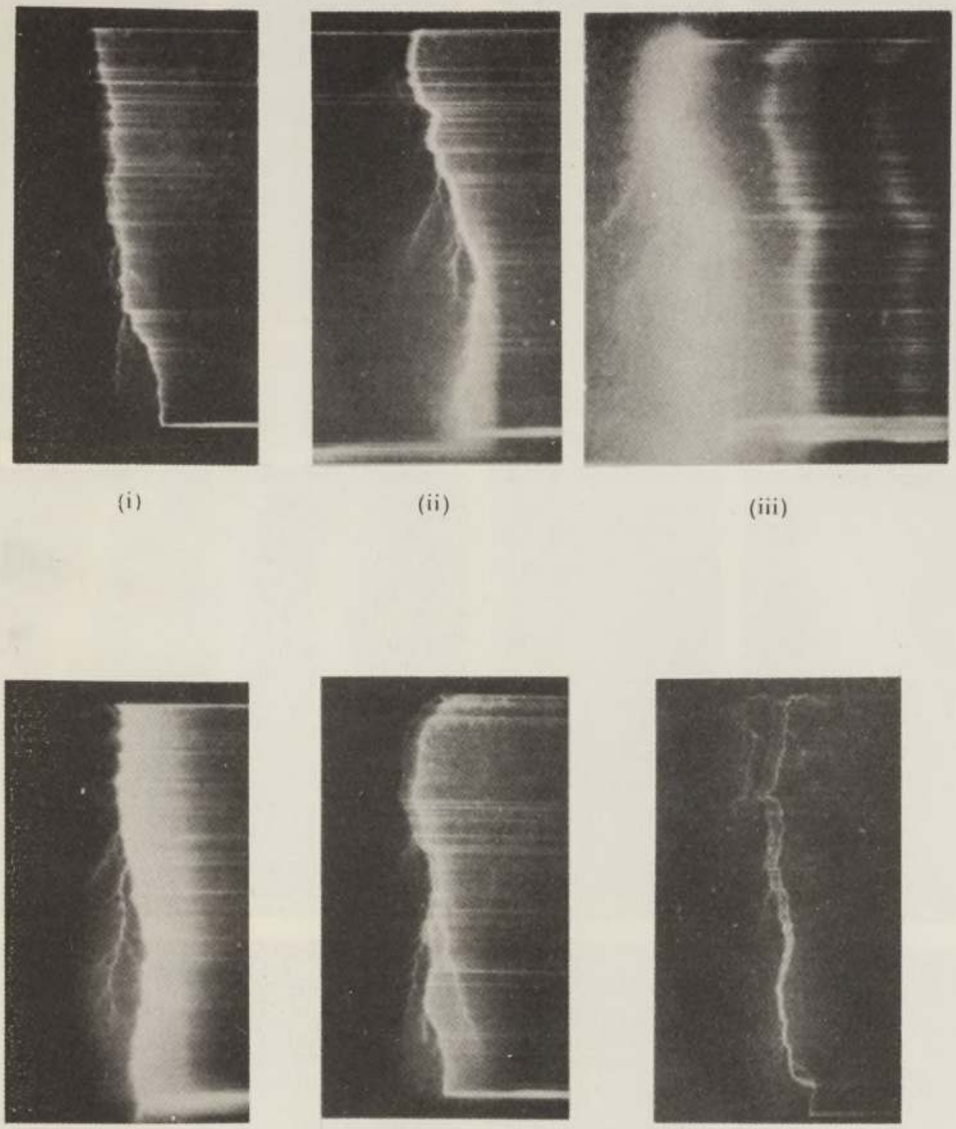

FIG. 1. Positive point electrode: earthed plane electrode. (*a*) $R = 100,000$: (i) $C = 10$; (ii) $C = 200$; (iii) $C = 5000$. (*b*) $C = 10$: (i) $R = 10,000$; (ii) $R = 100,000$; (iii) $R = 1,000,00$.

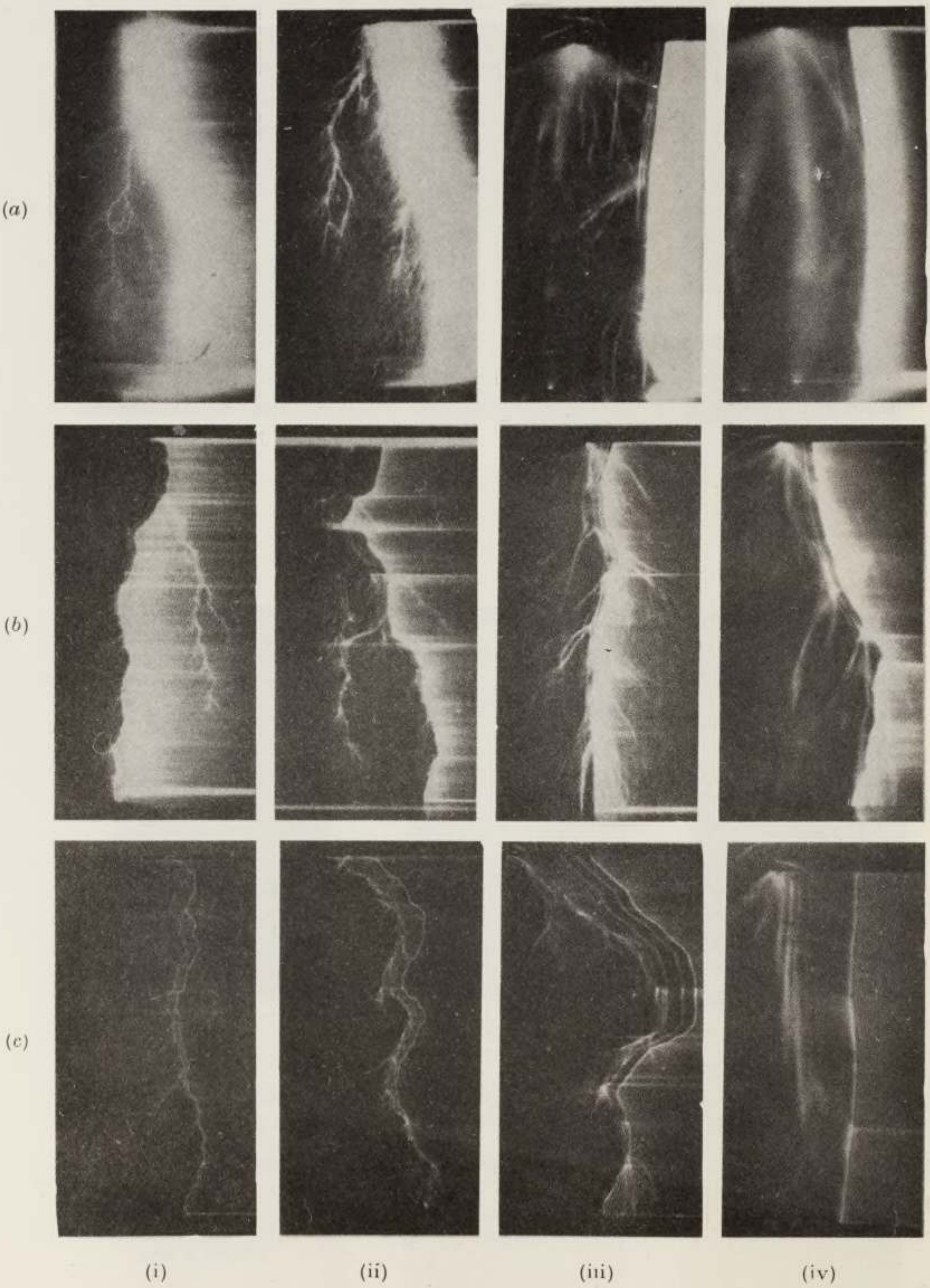

FIG. 3. Positive point electrode: earthed plane ($p = 1$ cm.) electrode. (a) $R = 700$; (b) $R = 10{,}000$; (c) $R = 100{,}000$. (i) $P = 40$; (ii) $P = 20$; (iii) $P = 10$; (iv) $P = 5$.

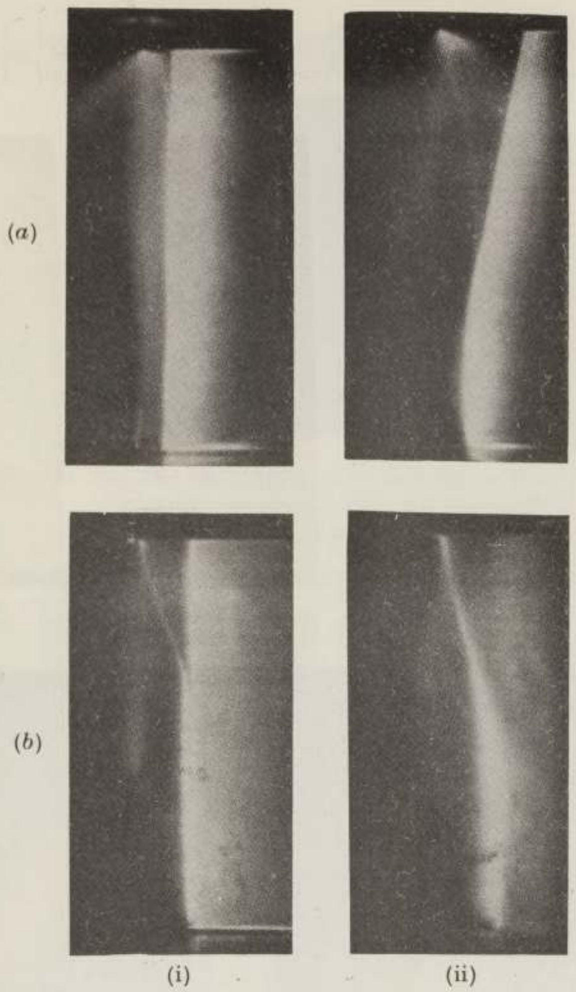

FIG. 4. Positive point electrode: earthed plane ($p=1$ cm.) electrode. (*a*) $R=700$; (*b*) $R=10{,}000$. (i) $P=2{\cdot}5$; (ii) $P=1{\cdot}0$.

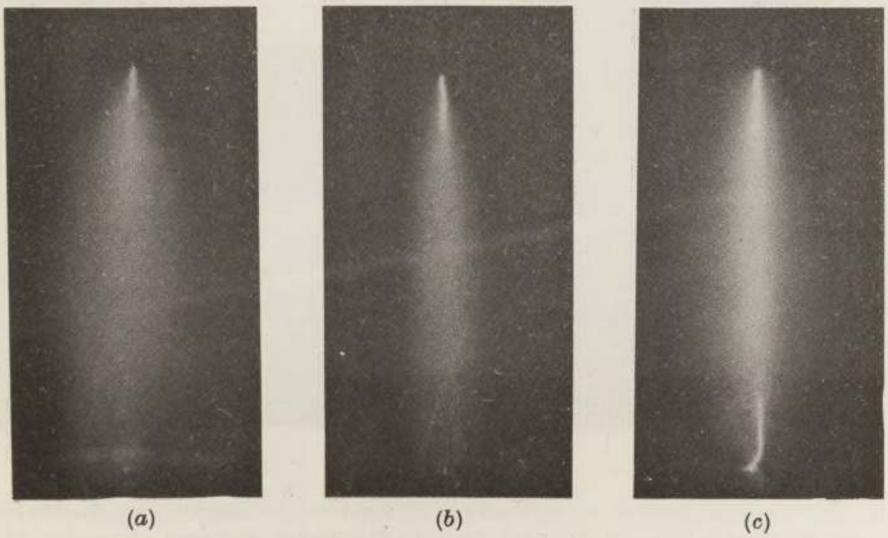

FIG. 5. Positive point electrode: earthed plane ($p=1$ cm.) electrode. "Still" photographs. $R=700$. (*a*) $P=0{\cdot}35$; (*b*) $P=0{\cdot}6$; (*c*) $P=0{\cdot}9$.

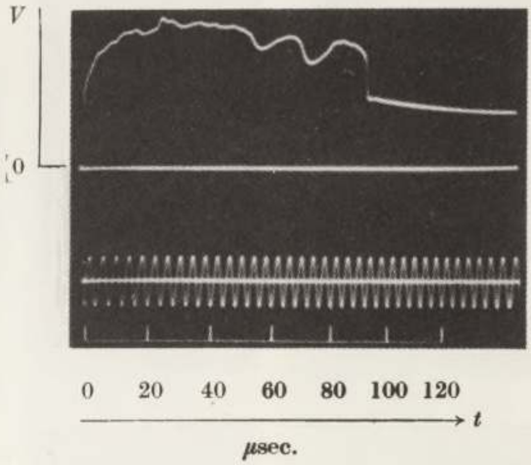

FIG. 8. **Positive point electrode:** earthed plane ($p = 1$ cm.) electrode. Voltage oscillogram. $R = 100{,}000$; $P = 10$. (Timing oscillation—1 cycle per 4 μsec.)

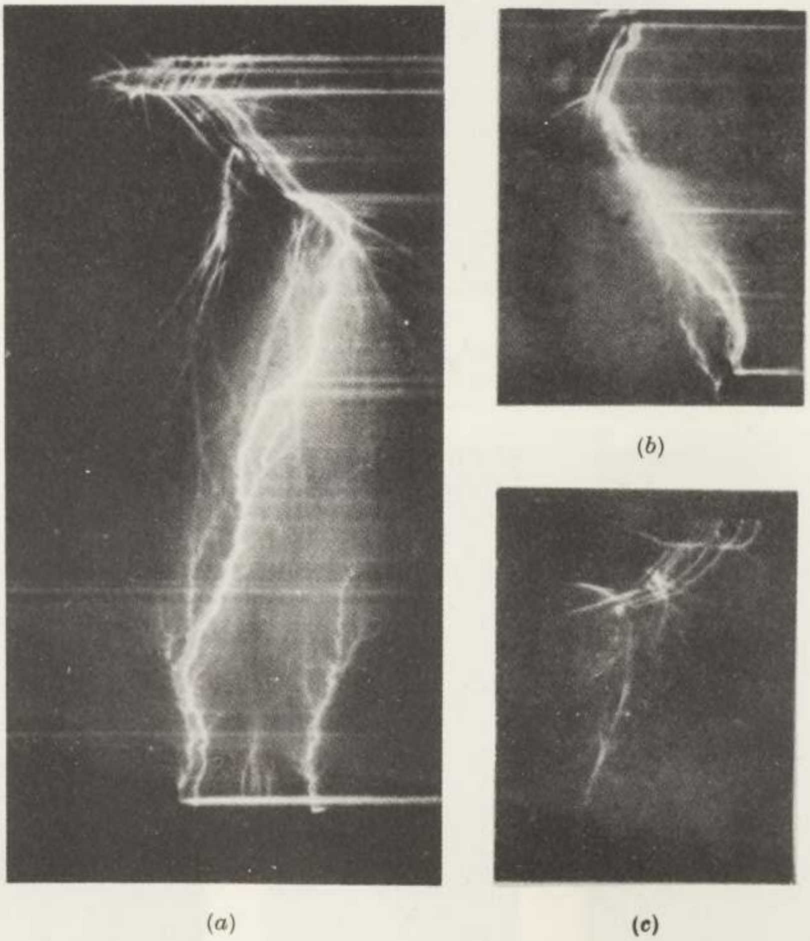

FIG. 13. Negative point electrode: earthed plane electrode. (*a*) $d = 100$; $R = 600{,}000$. (*b*) $d = 50$; $R = 600{,}000$. (*c*) $d = 100$; $R = 450{,}000$ (corona discharge shown for 40% gap).

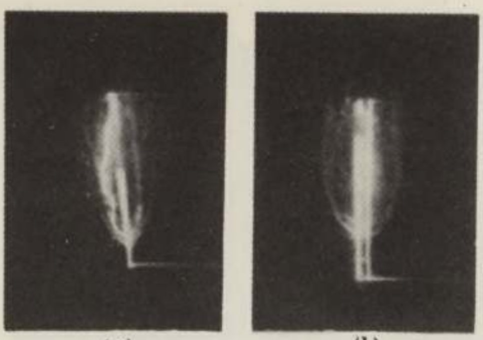
(*a*) (*b*)

FIG. 15. Negative point electrode: earthed plane electrode.
(*a*) $d=25$; $R=600{,}000$. (*b*) $d=25$; $R=2{,}000{,}000$.

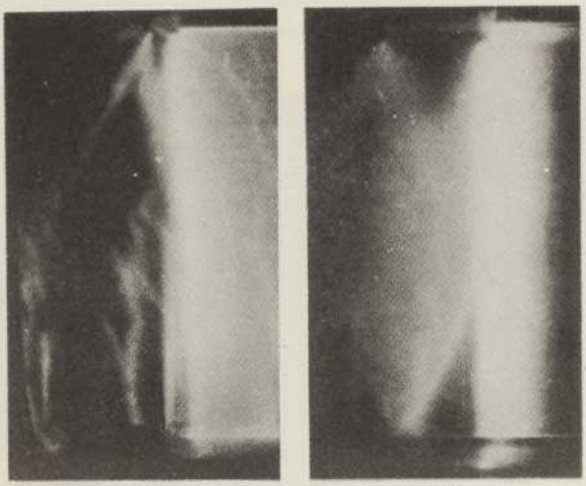
(*a*) (*b*)

FIG. 17. Negative point electrode: earthed plane ($p=1$ cm.) electrode.
(*a*) $R=10{,}000$; $P=2{\cdot}5$. (*b*) $R=700$; $P=1$.

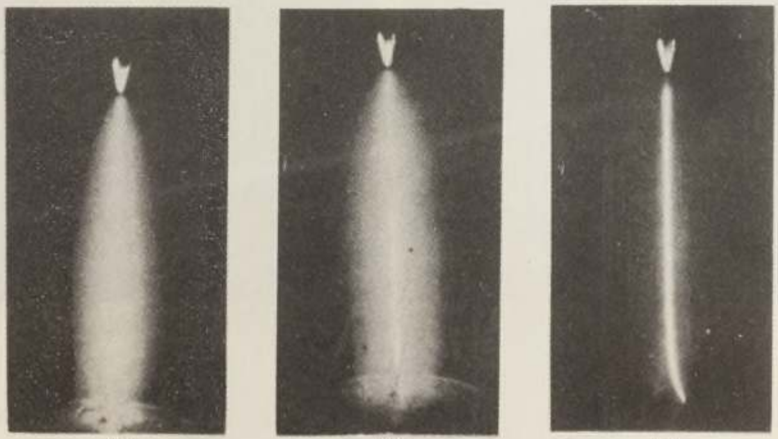
(*a*) (*b*) (*c*)

FIG. 18. Negative point electrode: earthed plane ($p=1$ cm.) electrode.
"Still" photographs. $P=0{\cdot}35$.

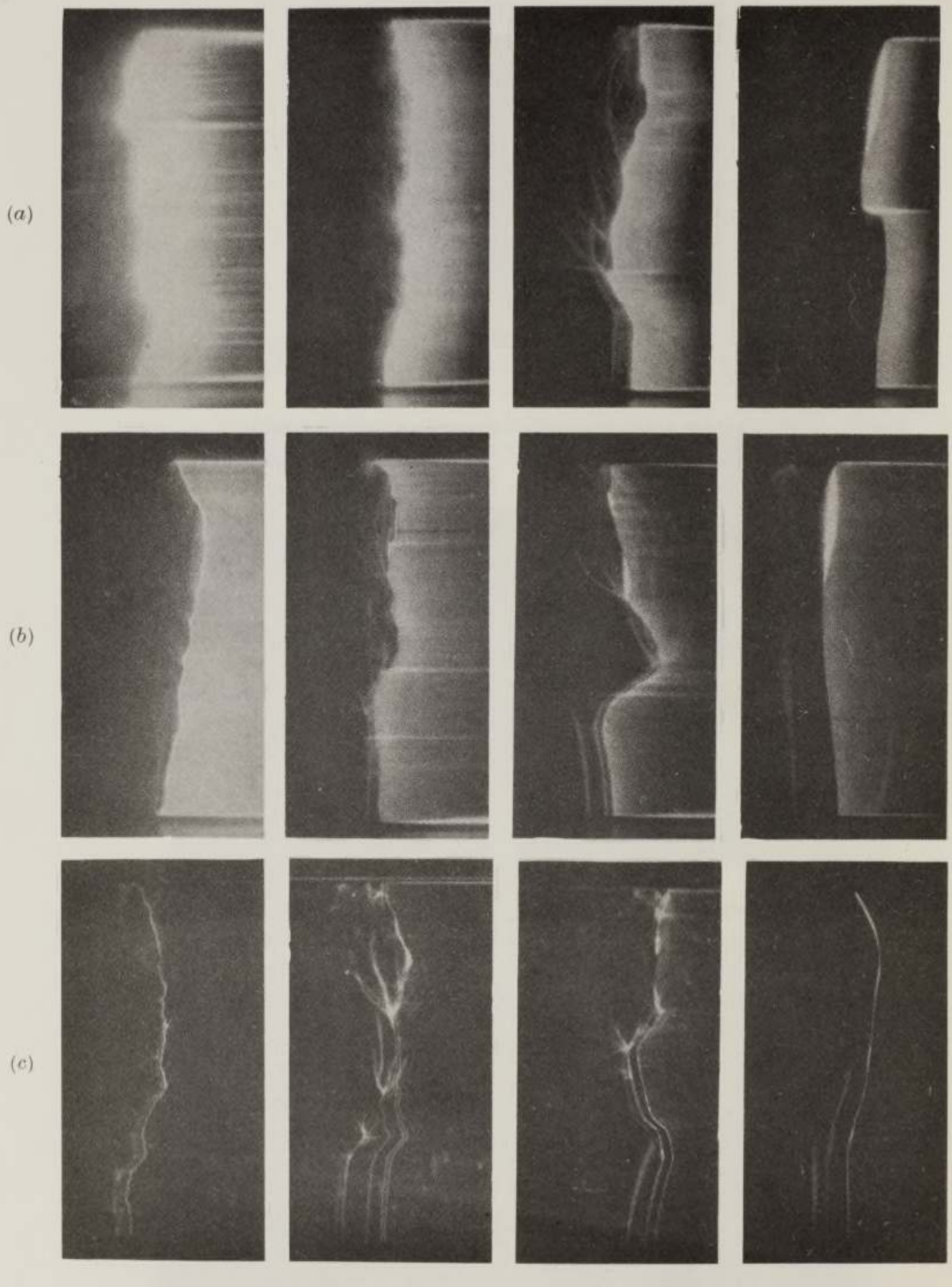

FIG. 16. Negative point electrode: earthed plane ($p = 1$ cm.) electrode. (a) $R = 700$; (b) $R = 10{,}000$; (c) $R = 100{,}000$. (i) $P = 30$; (ii) $P = 20$; (iii) $P = 10$; (iv) $P = 5$.

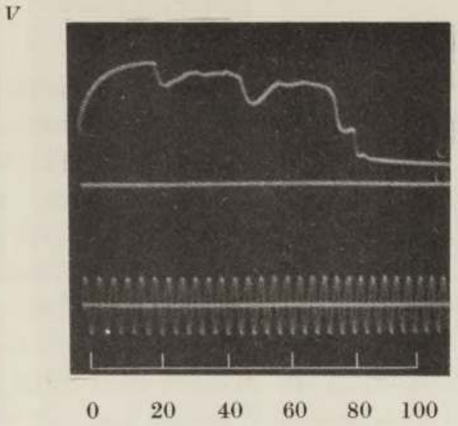

FIG. 20. Negative point electrode: earthed plane ($p = 1$ cm.) electrode. Voltage oscillogram. $R = 100{,}000$: $P = 10$. (Timing oscillation—1 cycle per 4 μsec.)

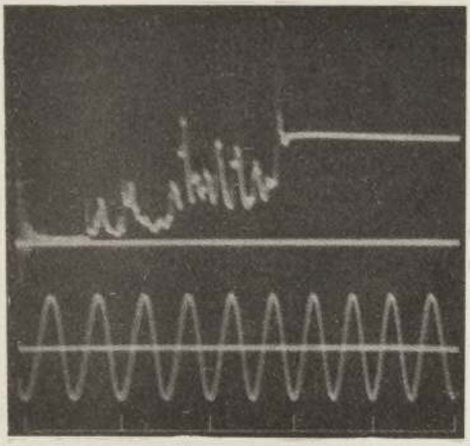

FIG. 22. Negative point electrode: earthed plane ($p = 1$ cm.) electrode. Current oscillogram. $R = 100{,}000$: $P = 19$. (Timing oscillation—1 cycle per 8 μsec.)

FIG. 23. Positive point electrode: earthed plane electrode. $R = 100{,}000$; $P = 5$.

(*b*) *Subatmospheric pressures*

The negative discharge has been investigated at pressures from 76 to 0·3 cm. Hg. Representative records for three different resistances are grouped in fig. 16, Plate 15: *a*, $R = 700$ ohms; *b*, $R = 10{,}000$ ohms; *c*, $R = 100{,}000$ ohms; while each group is divided into four pressures: (i) 30 cm. Hg; (ii) 20 cm. Hg; (iii) 10 cm. Hg; (iv) 5 cm. Hg.

With low resistance, as in the case of the positive discharge, leader strokes cannot be distinguished at atmospheric pressure due to halation caused by the main stroke. However, they are clearly visible at pressures below 30 cm. Hg, when both positive and negative leaders can be seen to meet in the upper mid-gap region. The height of the junction point increases with decrease in pressure. With the two higher resistances the stepped development of leader strokes is well defined, but there appears to be no fundamental difference in the mechanism of the discharge for all three pressures. The method of development of the leader strokes is most clearly seen in fig. 16 (*c*) (ii), Plate 15. Four brush discharges at the cathode are accompanied by four upgrowing positive leader strokes from the anode. No difference can be observed in the times of occurrence of these positive leader strokes and the corresponding negative discharges. A camera of higher resolving power might reveal such a difference, but at present it cannot be stated whether the positive leader is a consequence of the brush discharge appearing at the cathode, or whether the latter is produced as a result of the field distortion caused by the development of the positive leader. The last of the negative brush discharges takes the form of a leader stroke some 2 cm. in length: the lengths of the positive leaders are approximately 11, 16, 32 and 40 cm.—no continuous streamer can be observed to join their tips. Each of the positive leader strokes follows the track ionized by the previous leader, after which it develops into virgin air; each leader is strongly branched at its tip. The discontinuous nature of the development—seen at 10 cm. pressure—is not so apparent when the pressure is raised to 40 cm. Here the successive steps are so close that their tips appear to form a continuous streamer, but with a camera of higher resolving power it is probable that a discontinuous development would be observed.

At 5 cm. pressure the stepped development of the positive leader stroke becomes less apparent for all three resistances; however, in all cases the first long brush discharge is seen to accompany a short brush discharge at the cathode. An elongated column of discharge, apparently the junction-point of the positive and negative leaders, can be seen near the cathode; this column becomes more pronounced at still lower pressures. At 2·5 cm.

Hg the discharge—shown in fig. 17 (*a*), Plate 14—becomes much more diffuse and at 1 cm. Hg, fig. 17 (*b*), Plate 14, the upward developing leader is almost identical with the positive leader shown in fig. 4 (*a*) (ii): its speed is about 2×10^5 cm./sec., and it is continuous and not stepped. It merges into a very elongated column of discharge from the cathode. The stationary camera records given in fig. 18, Plate 14, for a pressure of 0·34 cm. Hg and for a range of applied voltages show that as the voltage is increased the central bright core to the diffuse glow discharge increases in length from the anode upwards. There is intense luminosity around the cathode point, and there is a dark space adjacent to it. With further increase of voltage sparkover can take place, unlike the positive discharge at the corresponding pressure. Further study with the rotating camera will be necessary to elucidate the progress of the discharge at very low pressures.

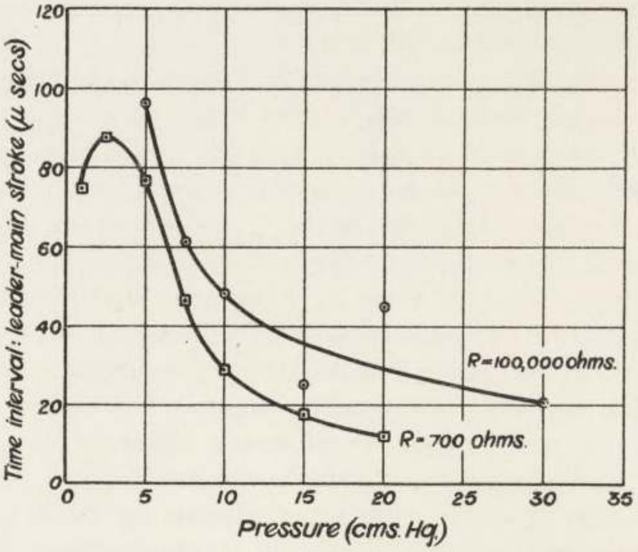

FIG. 19. Negative point electrode: earthed plane ($p=1$ cm.) electrode. Curves relating the time interval between the initiation of the negative leader stroke and the main stroke with pressure for different series resistances.

The variation with pressure and resistance of the time interval between the initiation of the negative leader and the main stroke is shown in fig. 19, the curves are generally similar to those in fig. 6 for the positive discharge. At all pressures up to atmospheric the time intervals for the negative discharge are smaller than those for the positive discharge; a probable reason for this is that the negative discharge never traverses the whole gap but is met by an ascending positive leader from the earthed electrode.

A wide variation in voltage at the cathode occurs for high resistances when the pressure is low; a typical oscillogram of the voltage recorded on an antenna is shown in fig. 20, Plate 16. The variation in voltage is more pronounced than for the positive discharge, a fact which has previously been observed at atmospheric pressure (I). Calculations based on the measured voltage drop show that the current which flows on the occurrence of the second step in the oscillogram must be of the order of $\frac{1}{2}$ amp. The

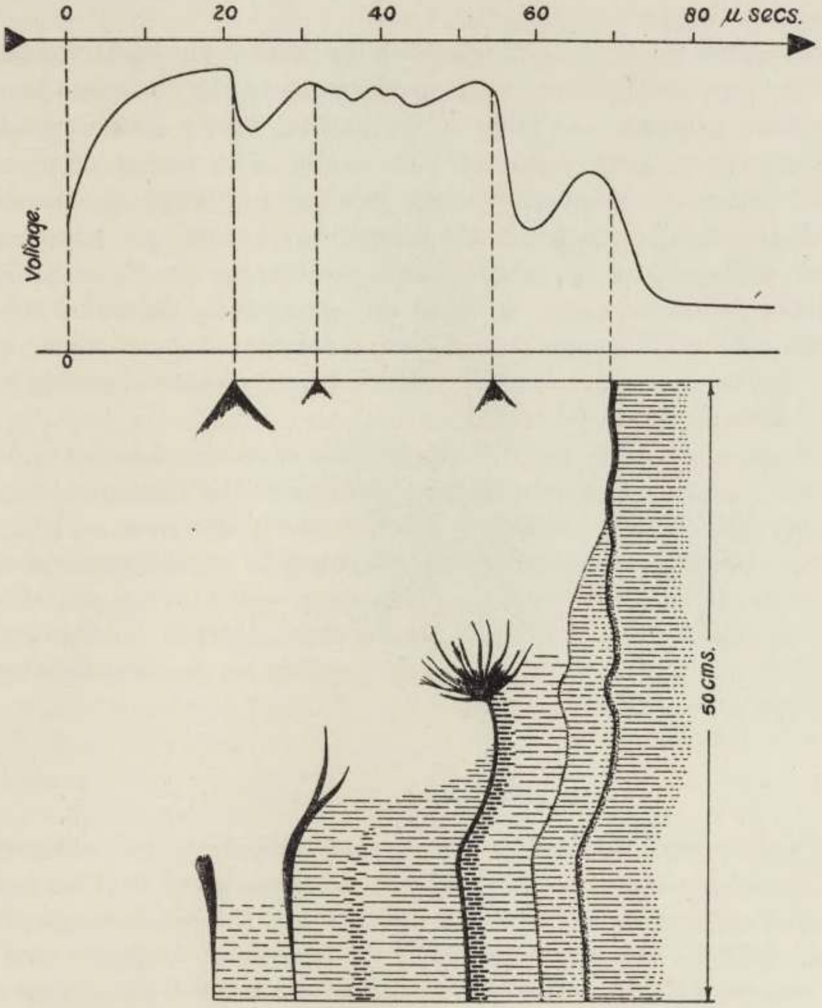

Fig. 21. Negative point electrode: earthed plane ($p = 1$ cm.) electrode. Drawing based on an original photograph of a discharge and the synchronized voltage oscillogram. $R = 100,000$; $P = 10$.

voltage fluctuations with series resistance of 10,000 and 1000 ohms are correspondingly smaller. An analysis of a photograph of a discharge together with the synchronized voltage oscillogram is given in fig. 21. The sudden drops in voltage are seen to correspond closely with the steps in the leader stroke development.

In the earlier paper (I) oscillograms of the current flowing to the earthed electrode were synchronized with photographs of the discharge in air at atmospheric pressure, and steps in the positive leader stroke were found to correspond to peak values of the current. The accentuation of the stepped nature of the positive leader development when the pressure is reduced causes the variation in the current to be more pronounced, and a current oscillogram at 18 cm. pressure is given in fig. 22, Plate 16. Subsequent to a period of 11 μsec. in which no current flows the leader stroke is initiated; the main stroke occurs after a further 35 μsec. during which time there are a number of peak values of current corresponding to the various steps in the leader stroke.

As in the case of the positive discharge a curve has been obtained to show the variation in the breakdown voltage of the discharge gap with pressure. Due to the frequent sparkover along the glass surface, particularly at higher pressures, the curve cannot be considered as accurate as that for the positive discharge. The curve—given in fig. 10—shows a similar deviation from Paschen's law to that observed for the positive discharge; this deviation may again be ascribed to the long time-lags to breakdown at the lower pressures.

6. Discussion of results

The further work reported in this paper on the development of the spark at atmospheric pressures confirms the observations given in (I) as regards the major differences between the positive and the negative spark discharge. Even for the longest gap (150 cm. breakdown voltage = 1600 kV) for which records are available the negative discharge from a point electrode is always met by an ascending positive leader stroke from the earthed plane and the length of this leader is not less than 30 % of the gap. In the case of the positive discharge the positive leader stroke is only infrequently met by an ascending negative leader stroke: the leader stroke of the positive discharge often splits into two main branches as it approaches the earthed plane but this branching is not necessarily caused by an ascending negative leader. The "root-branching" of the lightning flash referred to by Schonland and others (1935) and Schonland (1938) does not appear therefore to afford proof of the existence, before the main flash, of an upward-developing leader stroke.

The subatmospheric discharges afford assistance in the interpretation of the discharges at atmospheric pressure. The leader-stroke/main-stroke mechanism persists at least down to 5 cm. Hg with the same general distinction between positive and negative types of discharge. The individual stepped leader strokes become more sharply defined and more widely separated in time as the pressure is reduced (down to 10 cm. Hg). The positive leader strokes (whether downward or upward directed) at low pressures are seen to consist of a number of individual stepped leader strokes disconnected from one another; each stroke travels rapidly over a pre-ionized track and then more slowly through virgin air. A good example of this is given in fig. 23, Plate 16, where each step terminates as a fine tuft. At higher pressures the close proximity in time of the stepped leader strokes gives the impression of the pilot streamer referred to in (I) but, as stated previously, a camera of higher resolving power might show that the development of the discharge at atmospheric pressure was also discontinuous. The negative leader strokes at low pressures are shorter than at atmospheric pressure: at 10 cm. Hg they are little more than tufts of discharge 1 or 2 cm. in length disconnected from each other as at atmospheric pressure. At low pressures therefore the positive leader predominates to an even greater extent than at atmospheric pressure.

The mechanism of the spark has been investigated oscillographically by Rogowski, Flegler and Tamm (1927); Tamm (1928); Rogowski and Tamm (1928); Krug (1932) and Köhler (1936), using impulse voltages. Rogowski and others (1927) showed that the breakdown process between parallel plate electrodes took place in two stages, the voltage first collapsed from maximum value to about half that value, remained at about that value for a short time (some tenths of a microsecond) and then collapsed to zero. Tamm (1928) showed that this effect occurred at all pressures from 76 to 18 cm. Hg between parallel plate electrodes 1–4 mm. spacing. At very low pressures (0·7 cm.) the second stage of the breakdown process did not occur and it was noted that only a glow discharge took place, not a sharply defined spark. In air the step in the voltage collapse was not observed for breakdown in inhomogeneous fields. Rogowski and Tamm (1928) showed photographs of the glow discharge at various stages of development (at 4 cm. Hg between parallel plate electrodes) and they identified the start of the glow discharge with the first step in the voltage collapse: they noted that the next stage in the spark development started at the anode with the formation of a concentrated spark and this finally resulted in the complete voltage collapse. Krug (1932) observed the voltage step for breakdown in inhomogeneous fields, viz. between point/plane and sphere/plane electrodes. These experiments were made with electrode spacings of up to 10 cm., 80 kV. Köhler (1936) showed how the duration of the voltage step in the breakdown process varied with pressure and took oscillograms of the current in the discharge as well as of the voltage between electrodes: he obtained steps only with homogeneous fields, not with inhomogeneous fields.

No previous observations seem to have been made with the rotating camera in combination with the oscillograph, so that no definite correlation between the voltage steps and the development of the luminous discharge has been made. It appears from the present work that all the sudden discontinuities in the oscillograms of the voltage across the gap may be ascribed to the development of stepped leader strokes, i.e. the momentary voltage drop at the onset of each leader is the product of the circuit resistance and the leader-stroke current. Where the resistance in circuit is small the voltage steps may not be perceptible on the oscillograms: conversely they may be greatly accentuated by increasing the series resistance to high values as in fig. 8. The magnitude of the leader stroke currents appears to be of the order of one ampere in the present series of tests and also in the records of Rogowski and others where voltages of only 1–5 kV were used; to obtain good oscillograms of the step in the voltage collapse therefore the optimum value of circuit resistance should be increased linearly with the applied voltage.* The early predischarges carry smaller currents than the leader strokes which just precede the main stroke but they can be observed in the current oscillograms, and, with adequate series resistance, their occurrence can be identified in the voltage oscillograms. The duration of the voltage steps increases as the pressure is reduced to 5 cm. Hg, thereafter, for lower pressures, the duration diminishes as shown in figs. 6 and 19. The curves down to 5 cm. Hg are similar to those of Köhler (1936) for very small gaps and homogeneous fields. Below 5 cm. pressure the sharply defined positive and negative leader strokes become more diffuse, and at 1 cm. pressure the discharge corresponds to the glow discharge described by Tamm (1928). It is important to note that for large gaps, the discharge at low pressures develops from the positive

---

* In impulse voltage circuits it is customary to introduce sufficient resistance to make the circuits aperiodic, the value of this resistance is frequently of the order of some hundreds of ohms irrespective of the voltage of the circuit in which it is used. Whilst this value may be sufficient to accentuate the voltage steps on oscillograms of breakdown of very small gaps (as employed by Rogowski and others) a much higher value is in general necessary for large gaps.

electrode exactly as Rogowski and Tamm (1928) had described for very small gaps.

Flegler (1937) has studied the development of the discharge at low pressures by means of the cloud chamber, and determined three main stages in the breakdown process: (*a*) preliminary stage of very weak illumination, generally only detectable as a fog in the chamber and sometimes by small irregularities of the voltage wave; (*b*) appearance of bright luminosity in a few channels, accompanied by the Rogowski "step" in the voltage wave; (*c*) complete sparkover and collapse of voltage. These three stages are confirmed in the present work, but the first stage is shown to be essentially similar to the second stage, and differs from it only as regards the magnitude of the current carried by the various predischarges.

The deviation from Paschen's law is not considered to be important. Köhler (1936) showed that Paschen's law held for power-frequency voltages and impulse voltages of a variety of waveshapes for pressures down to 10 cm. Hg, between spheres. The time to breakdown was small compared with the duration of the wave-tail of the impulse voltage. For point/plane electrodes the time to breakdown becomes so large at low pressures that impulse voltages higher than the static breakdown voltage have naturally to be applied.

Although the cause of the steps in the oscillogram of the breakdown process are now fully explained there is as yet no explanation of the variation of the duration of these with pressure. Since the critical breakdown field varies with pressure, and the mean free path varies inversely as pressure, the leader stroke velocity should not depend on pressure. A possible explanation for the slower velocity of the leader is that the density of photoelectrons ahead of the streamer diminishes with pressure, and, as Cravath and Loeb (1935) have shown, the velocity may depend on the density of primary electrons ahead of the streamer.

At low pressures the discharge develops almost entirely from the anode. A suggested explanation of this is that as the pressure is reduced the voltage gradient at the electrodes diminishes and, since the leader stroke current does not vary greatly with pressure, the cloud of positive ions formed at the cathode when a leader develops has a proportionately greater influence on the gradient ahead of this leader: this restricts the development of the negative leader as discussed in (I) (p. 125), and the completion of the breakdown process is left to the positive leader stroke.

The further study of the effect of resistance on the velocity of propagation of leader strokes reported here indicates the importance of this as a factor in discharge development. It is difficult to see how to make full use of this in studying the lightning flash but inasmuch as clouds have not the properties of metallic conductors it is reasonable to ascribe different leader-stroke velocities to differently charged clouds as previously suggested (Allibone 1938).

The authors with to express their thanks to Mr G. J. Scoles, M.Eng., for checking some of the oscillographic observations, and to Dr A. P. M. Fleming, C.B.E., Director and Manager of Research and Education Departments, Metropolitan-Vickers Electrical Co., Ltd., for permission to publish this paper.

REFERENCES

Allibone, T. E. 1938 *J. Instn Elect. Engrs.* **82**, 513.
Allibone, T. E. and Meek, J. M. 1938 *Proc. Roy. Soc.* A, **166**, 97. Referred to as (I).
Appleton, E. V. and Chapman, F. 1937 *Proc. Roy. Soc.* A, **158**, 1.
Cravath, A. and Loeb, L. B. 1935 *Physics*, **6**, 125.
Dunnington, F. G. 1931 *Phys. Rev.* **38**, 1535.
Flegler, E. 1937 *Elektrotech. Z.* **47**, 58.
Köhler, A. 1936 *Arch. Elect.* **30**, 528.
Krug, W. 1932 *Z. Tech. Phys.* **13**, 377.
Malan, D. J. and Collens, H. 1937 *Proc. Roy. Soc.* A, **162**, 175.
Rogowski, W., Flegler, E. and Tamm, R. 1927 *Arch. Elect.* **18**, 506.
Rogowski, W. and Tamm, R. 1928 *Arch. Elect.* **20**, 625.
Schonland, B. F. J. 1937 *Trans. S. Afr. Inst. Elect. Engrs.* **28**, 204.
— 1938 *Proc. Roy. Soc.* A, **164**, 132.
Schonland, B. F. J., Malan, D. J. and Collens, H. 1935 *Proc. Roy. Soc.* A, **152**, 595.
Tamm, R. 1928 *Arch. Elect.* **19**, 235.