IONS AND BARRIERS IN ELECTRIC DISCHARGES

BY DR. G. K. M. PFESTORF AND R. S. N. RAU

Received July 13, 1953

SUMMARY

It is well known that electrons and positive ions are responsible in the case of the electric spark. Investigations have been undertaken in the High Voltage Laboratory to study the effect of injecting ions (both positive and negative) into the spark gap.

Also the effect of paper screens in blocking the ions is being investigated.

§ 1. INTRODUCTION

Though the electric spark has been known to man since time immemorial, its mechanism has been but little understood. Prof. J. S. Townsend was the first to clarify the mechanisms involved.

TOWNSEND'S THEORY

The basis of the theory is the "Ionisation by collision" by positive ions and electrons. Townsend derived an equation for the current 'i' in a gap between two parallel plane electrodes as a function of the photo-electric current 'i_0'[1] *

The equation reads,

$$i = i_0 \frac{(\alpha - \beta)\, \epsilon^{(\alpha-\beta)x}}{\alpha - \beta \epsilon^{(\alpha-\beta)x}} \tag{1}$$

where α is the Townsend's first coefficient of ionisation, *i.e.*, the number of pairs of ions produced by one electron in one cm of advance ; β is the Townsend's second coefficient of ionisation, *i.e.*, the number of pairs of ions produced by one positive ion in one cm of advance ; x is the distance in cm from the point—at which the current i is obtained—to the cathode.

From the above equation Townsend interpreted the criterion for the electric spark.

* For references see end of paper.

The criterion being, coming to existence of a very large number of ions per second or in other words, infinite current. Thus from Equation (1) we have,

$$\alpha = \beta \epsilon^{(\alpha-\beta)x}$$

$$\alpha \epsilon^{-\alpha x} = \beta \epsilon^{-\beta x} \qquad (2)$$

§ 2. Limitations of Townsend's Theory[2]

The initial success of the theory as applied to low gap lengths and pressures led to its being extended to higher gap lengths and pressures, in general to higher $p\delta$, where p is the pressure (mm of mercury) and δ is the gap length (cm). But however it was found to be seriously inadequate. (1) Townsend's theory holds for $p\delta < 200$ mm cm only. (2) Formative time lags at 760 mm pressure have been measured to be of the order of 10^{-7} second or less for a one cm gap, the gap being moderately overvolted.[3] But however mobility measurements show that these time intervals are a small fraction of the time necessary for the positive ions to cross the gap. Hence the sole cause of the spark is due to the movement of electrons alone. The positive ions are more or less immobile during the formation of the spark. Hence ionisation by positive ions is definitely ruled out. (3) At atmospheric pressure, the breakdown voltage of a given gap is found to be practically independent of the material of the cathode while the Townsend's theory does depend on it. (4) The development of the spark requires intense ionisation, which is only possible by photons. The photons are far more effective in producing ionisation than high energy particles. This necessitates a different mechanism. (5) In certain gaseous discharges as positive point corona and lightning discharge there is no cathode action at all. A correct theory must take into account all types of discharges. In the mean time substantial developments were taking place in the field of Atomic Physics. To make the theory consistent with modern ideas it was necessary to alter the mechanism due to Prof. Townsend.

§ 3. Conditions for Correct Theory for $p\delta > 200$ mm cm

(1) The mechanism must depend entirely on the movement of the electrons, the positive ions being practically immobile as was made clear in § 2.

(2) The materialisation of the spark must depend on the movement of electrons in a narrow filamentary channel.

(3) The spark-over voltage must be independent of the cathode material and depend on the ionisation process in the mass of gas. Such intense ionisation as exists just preceding the spark can only be due to the photons.

(4) The mechanism should be such as to be applicable for $p\delta > 200$ mm/cm and must take into account the space charge processes occurring in the spark gap.

(5) The intense ionisation must start from the anode and proceed towards the cathode or from middle of the gap to the cathode.

§ 4. Streamer Theory of the Electric Spark

This is the modern concept of the electric spark. The development of this theory is due to H. Raether in Germany and L. B. Loeb in America.

But Raether and Loeb independently arrived at the same mechanism almost simultaneously, the former from cloud chamber studies[4] and the latter, in collaboration with G. W. Trichel and A. F. Kip from corona studies.[5]

Assume a plane parallel gap spaced δ cm and say one electron leaves the cathode per sec. This electron in its travel of a distance x cm from the cathode will produce ϵ^{ax} electrons which forms an " electron avalanche". In an avalanche as the electrons move ahead they leave behind relatively heavy hence immobile positive ions of an equal number.

Thus accompanying the cumulative ionisation a number of atoms of the gas are excited due to impact from electrons. The state of excitation depends on the energy of the impinging electron and on the energy absorbed by the atom. These atoms give rise to radiations of short wavelength as they fall back to ground level. This radiation is absorbed by the mass of the gas and will give rise to intense photo-ionisation. Actually the gas, as well as the cathode are irradiated by photons of various energies, travelling with the velocity of light (see Fig. 1).

As stated before positive ions are left behind as the electron avalanche proceeds. Such of the photoelectrons created in or in the immediate vicinity of the positive space charge channel will be drawn into the space charge. If the space charge field is of about the same order as the applied field the action becomes very effective.

Thus the electrons due to cumulative photoionisation are drawn into the positive space charge making it a highly conducting plasma, starting from the anode. The positive ions left behind together with those due to photo-ionisation will further extend the space charge to the cathode. Thus the space charge develops into a positive ion streamer starting from the anode.

Raether first observed and photographed these streamers in the cloud chamber.[6] Raether estimated the velocity of propagation of the space charge streamer as 2×10^7 to $1 \cdot 3 \times 10^8$ cm/sec.

b3

As the space charge streamer approaches the cathode an intense field is set up at the surface of the cathode, a rush of electrons is produced therefrom, to annul the positive space charge. In short a cathode spot develops which is a copious source of electrons. Thus the gap is rendered highly conducting and the result is the spark. The velocity of propagation of the returning wave of ionisation due to the electrons is exceedingly large and is of the order of 10^8 to 10^9 cm/sec.[7]

§ 5. Experimental Study

(1) *Injection of ions.*—The following experimental study was conducted in the High Voltage Laboratory.

Point and plane electrodes were chosen for the study. In the case of point to plane discharge, for a given spacing, the breakdown voltage depends on the polarity of the point electrode. The breakdown voltage when the point is negative is roughly double that when the point is positive. This is because of the fact that when the point is positive, the field strength in the neighbourhood of the point is high and adequate for streamer formation as was outlined in § 4.

In the case of negative point to plane discharge an attempt was made to artificially produce the streamer by injecting positive ions into the gap. The arrangement for shooting the ions into the spark gap is as follows: (Fig. 2).

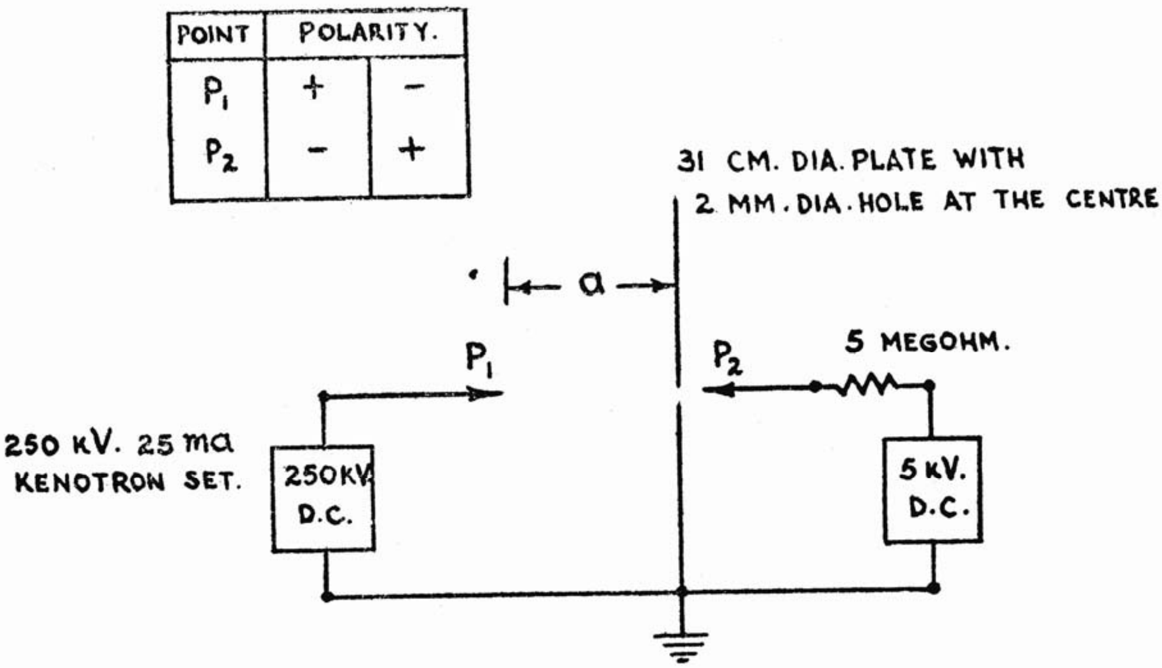

Fig. 2. Arrangement for shooting the ions

A small 5 kV d.c. supply feeds a sharp point P_2 facing an aperture of 2 mm diameter at the centre of circular plate electrode. The plate electrode is made out of sheet aluminium and is 31 cm in diameter. The spacing of P_2 was so adjusted to produce corona on P_2*. The voltage of the point P_1 was raised to breakdown the gap between P_1 and the plate. The breakdown voltage with positive ion injection is reduced by about 40 per cent. as compared to the case with no ion injection, that is bringing down the breakdown voltage very near to the case when the point electrode is positive (Fig. 3). From this it is seen that the streamer has been built up successfully by the injected positive ions.

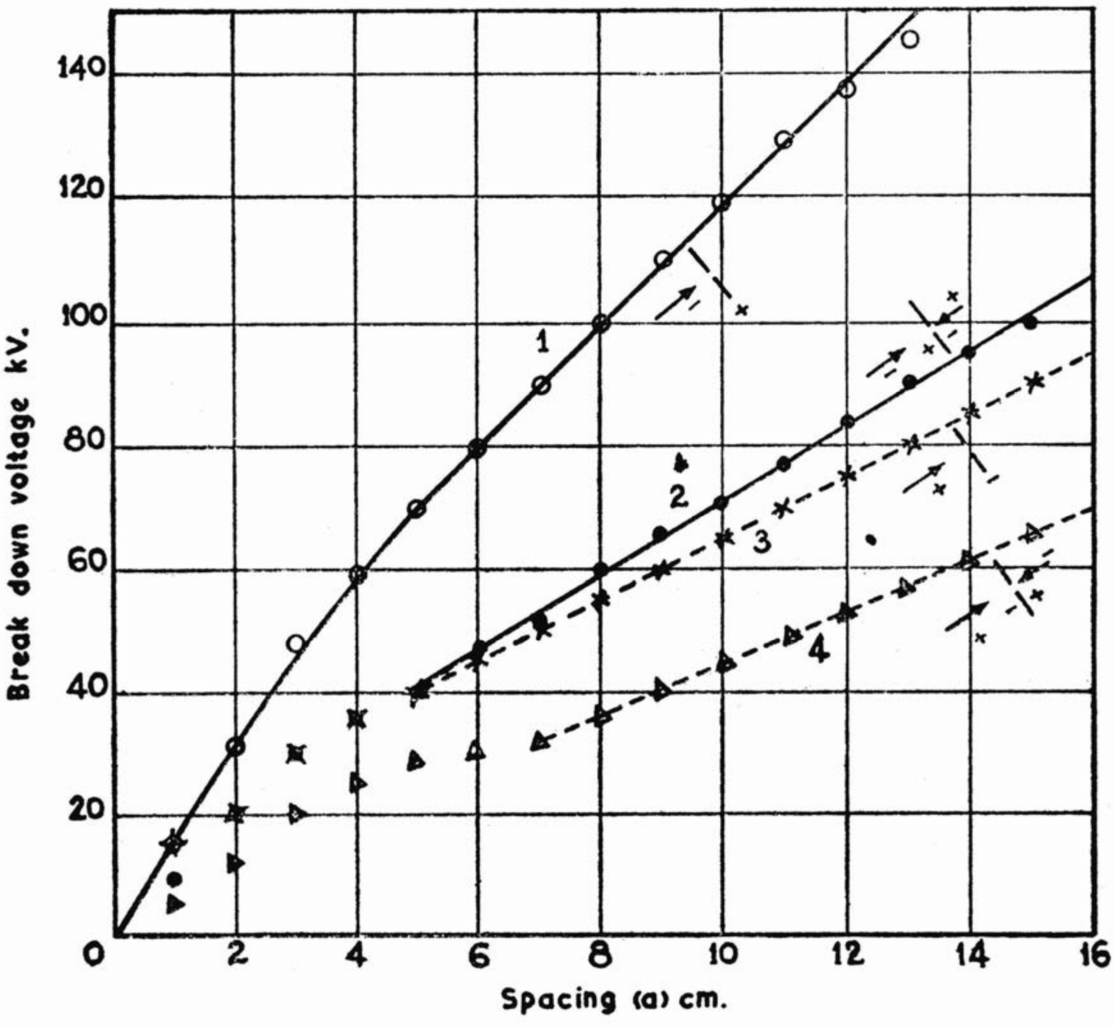

FIG. 3. Effect of initial ions

1. No ion injection.
2. Positive ion injection.
3. No ion injection.
4. Electron injection.

* It was later on found that to obtain consistent results it was necessary to maintain a small arc.

Figure 3 shows the results obtained with positive injection and electron injection. With electron injection the reduction in breakdown voltage for a given spacing is about 30 per cent. This is due to the increase of the density of ionisation as a result of the injection of electrons.

(2) *Effect of screens.*—It is well known that even very thin screens of insulating materials increase the breakdown strength of a gap considerably. A drawing paper screen 0·1 mm thick was inserted between the point electrode P_1 and the plate electrode (Fig. 4). The breakdown voltage for various

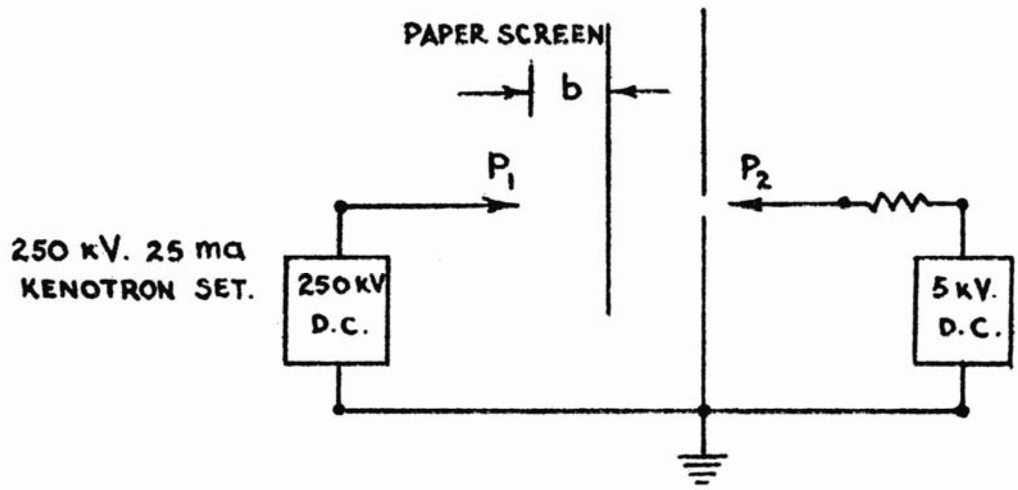

FIG. 4. Arrangement of paper screen with ion injection

positions of the screen was measured, with and without ion injection. The results are shown in Fig. 5.

It will be seen from Fig. 5, that the breakdown voltage increases as the spacing of the screen is increased to about 2 cm from the point electrode P_1 and the breakdown strength is a maximum. Then the breakdown voltage slowly decreases till the neighbourhood of the plate electrode is reached, where the breakdown strength increases rather sharply. The change of slope in the neighbourhood of the maximum voltage obtained near the point electrode is small. Hence the best protection of the gap is obtained when the screen is placed near the point electrode whereas it is not so in the neighbourhood of the plate electrode.

With ion injection the breakdown voltage gradually increases, becoming constant till a short distance from the plate after which the breakdown voltage curve joins that with no ion injection at the point where the slope changes sign. From this it appears that the positive ions are completely blocked by the screen when the screen is inserted in the neighbourhood of the plate electrode.

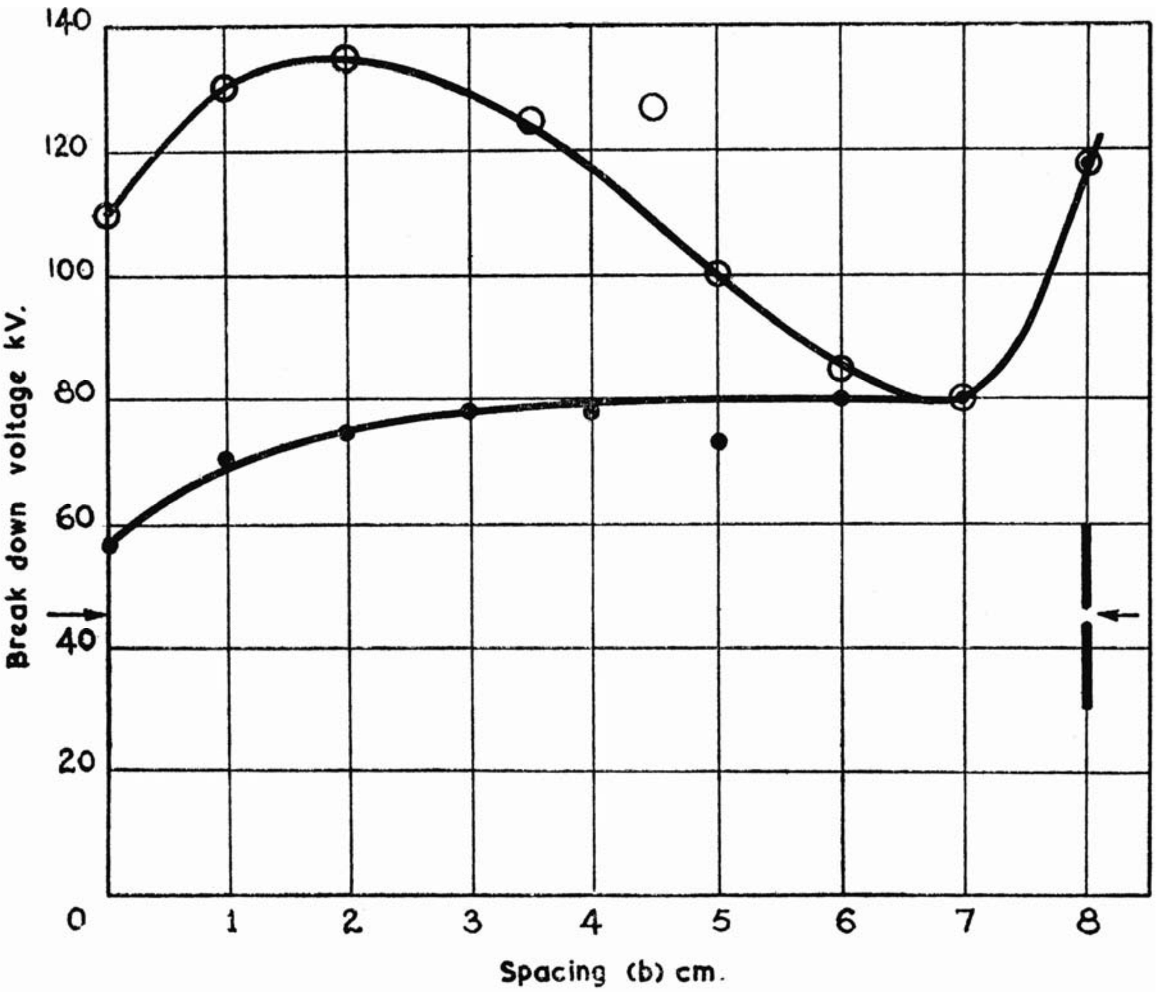

FIG. 5. Effect of paper screen

1. No ion injection. ooo 2. Positive ion injection. ●●●

There is a particular application of the screens[8] in High Voltage Engineering. Since the screen enables the beakdown voltage of a given gap to be raised, it becomes possible to design and build compact High Voltage Equipment.

REFERENCES

1. J. S. Townsend .. *Electrons in Gases* (Hutchinson's Scientific and Technical Publications), 1947, 98.

L. B. Loeb .. *Fundamental Processes of Electrical Discharge in Gases*, (Wiley & Sons. NY), 1939, 372.

2. ——— and J. M. Meek .. *The Mechanism of the Electric Spark* (Stanford Univ. Press, Calif., U.S.A., 1941), 28.

3. P. O. Pedersen .. *Ann. d. Physik.*, 1923, **71**, 371.

J. W. Beams .. *Jour. Franklin Inst.*, 1928, **206**, 809.

4. A. F. Kip .. *Phy. Rev.*, 1938, **54**, p. 139; 1939, **55**, 382,

5. H. Raether .. *Zeits. f. Physik.*, 1939, **112**, 464,

6. ——— .. *Ibid.*, 1937, **107**, 91,

7. B. F. J. Schonland., D. J. Malan and H. Collens — *Proc. Roy. Soc.*, London, 1935, **152 A**, 595.

T. E. Allibone and J. M. Meek .. *Ibid.*, London, 1938, **166 A**, 97; 1938, **169 A**, 246.

8. A. Roth .. *Hochspannungstechnik* (Wien-Springer-Verlag), **1950**, 224.

Roser .. *Schirme zur Erhöhung der Durchschlagsspannung in Luft.* Zusammenfassung der Ergebnisse aus Arbeiten von Holzkamp, Krüger, Kurscheff, Meier, H. Müller, *ETZ.*, 1932, **53**, 411.

E. Marx .. *Hochspannungs Praktikum.* (Springer Verlag), 1952, 166.