A Study of the Initial Stages of Spark Discharges in Gases

HARRY J. WHITE, *University of California*

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The electro-optical shutter is used to study spark breakdown in nitrogen, hydrogen, oxygen, carbon dioxide, helium and argon at atmospheric pressure and for gap lengths up to about 1 cm. Four distinct types of breakdown, as characterized by the appearance and growth of the luminous streamers, are recognizable in these gases. The velocities of the streamers emanating from the cathode in the cases of hydrogen and nitrogen have been measured and have been found to be about 10^7 cm per sec. which is of the order of magnitude of the calculated velocities of electrons in these gases under breakdown conditions. Pencil drawings representing the course of the breakdown in hydrogen, nitrogen, helium and argon are reproduced. Photographs of single sparks in early stages are shown for nitrogen, oxygen, air and carbon dioxide, the exposure time for some of these being as short as 5×10^{-9} sec. The experiments indicate that the major portion of the current passing during breakdown is carried by electrons, and that these, for the most part, come from the cathode rather than from ionization in the gas. The shortness of the spark lag, and the breakdown times of the sparks, show that the phenomenon is essentially due to the motion of electrons, and that the space charges which cause breakdown result from the large difference in the mobility velocities of electrons and positive ions. A theory is formulated to explain the appearance and growth of the streamers observed in certain gases, such as nitrogen.

INTRODUCTION

A GREAT deal of work has been done on spark breakdown in gases, but until the last few years very little has been known about the exact evolution of the spark. That the time required for breakdown is very brief has been shown by oscillograms due to Rogowski and Klemper.[1] The theoretical treatment of the spark mechanism has been largely due to Townsend and his school. Recently these theories have been modified by Loeb[2] and Schumann[3] to take account of the important effect of space charges which develop just before a breakdown occurs.

The occurrence of a spark is the manifestation of an unstable condition of the gas, and this instability is evidenced by the extreme rapidity of the breakdown. Until the last few years the shortness of the times involved, which are of the order of magnitude of 10^{-8} sec., has prevented any study of the exact evolution of the spark. The electro-optical shutter is an apparatus capable of acting with the required speed. It was originally devised by Abraham and Lemoine[4] in 1899 and has been used since then by Beams,[5] Lawrence and Dunnington,[6] Dunnington,[7] and others to study spark phenomena, but for several reasons failed to give results when used to study the very earliest stages of spark breakdown. These difficulties have been largely overcome by Dunnington[8] who has made a detailed analysis of the shutter action and has applied it to the study of the early stages of breakdown in air. Washburn[9] has given a more general solution of the differential equation governing the operation of the shutter and has applied it to the study of the breakdown of liquids.[10]

APPARATUS

A schematic diagram of the apparatus is shown in Fig. 1. The apparatus is essentially the same as that used by Dunnington[8] and reference should be made to his paper for a detailed description of it and its operation. The high voltage is supplied by a transformer and Kenotron with a condenser resistance filter. The spark

[1] Rogowski and Klemper, Archiv f. Elektrotechnik **24**, 129 (1930).
[2] Loeb, J. Frank. Inst. **210**, 15 (1930).
[3] Schumann, Zeits. f. tech. Physik **11**, 58 (1930).
[4] Abraham and Lemoine, Comptes Rendus **129**, 206 (1899).
[5] Beams, Phys. Rev. **28**, 475 (1926).
[6] Lawrence and Dunnington, Phys. Rev. **35**, 396 (1930).
[7] Dunnington, Phys. Rev. **38**, 1535 (1931).
[8] Dunnington, Phys. Rev. **38**, 1506 (1931).
[9] Washburn, Phys. Rev. **39**, 688 (1932).
[10] Washburn, Physics **4**, 29 (1933).

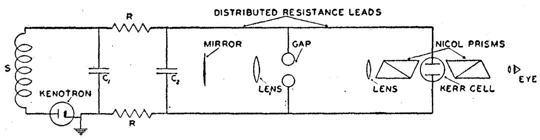

FIG. 1. Schematic diagram of the apparatus.

gap consists of two brass spheres 4 cm in diameter, mounted in a glass chamber which is part of a vacuum system. The gap length is made variable by screw feeds, and the spheres are readily removable for cleaning. The electro-optical shutter consists of the two crossed nicol prisms with the Kerr cell placed between them. A transmission line of variable length and resistance joins the spark gap to the Kerr cell. The optical system consists of two parts; the first a lens and eyepiece for viewing the gap directly through the shutter, the second a lens and plane mirror which forms a second image of the spark close to the original one. This latter system provides the means for varying the length of the light path to the shutter, the plane mirror being movable in a direction perpendicular to its plane. The cathode of the spark gap is illuminated by ultraviolet light from a quartz mercury arc, a large quartz prism being used to separate out the visible light.

The most important part of the apparatus is the Kerr cell[11] used in the electro-optical shutter, for the success of the research depends upon its proper functioning. The liquid used in the cell was nitrobenzene, this being chosen because of its relatively large Kerr constant. The sharpness of cut-off of a cell is very sensitive to small amounts of impurity in the Kerr substance, so that a cell which is to be used with a brilliant source, such as a spark, should contain only very pure liquid.

EXPERIMENTAL

In the experimental work several time concepts are used and these will be defined and described briefly.

$$\textit{Path time} = t_p = (L_w - L_1)/(3\times 10^{10}), \qquad (1)$$

where L_w = length of the wire path from the gap to the Kerr cell in cm; L_1 = length of the direct light path from the gap to the Kerr cell in cm. The path time is simply a means of expressing the length of the wire path to the cell. As defined, it is the time the shutter would be open if the gap voltage dropped instantaneously and the Kerr cell had an infinitesimal capacity.

$$\textit{Light time} = t_L. \qquad (2)$$

The light time is the time the shutter is open after the first visible light from the spark passes through it. This is susceptible to measurement by means of the movable mirror (Fig. 1). For a given value of t_p the mirror may, in some cases, be moved far enough away so that the reflected image entirely disappears, that is, the shutter closes before the light from the mirror reaches it. This extra or increased light path is then the time which the direct image of the spark has been in existence and is the value of t_L.

$$\textit{Effective time} = t_e. \qquad (3)$$

This is the time the shutter is open after the voltage across the gap begins to drop rapidly. Its value can be measured by a method due to Dunnington.[8]

VISUAL STUDIES

The results of some visual studies of spark breakdown at atmospheric pressure in hydrogen, nitrogen, helium and argon are shown by the pencil drawings in Fig. 2. These must be considered as only approximate representations, especially in the case of helium. The lower lines represent the limit of the cathode sphere, and the upper lines that of the anode sphere. The values of t_L or t_p are given along the lower lines. It was not found possible to measure the value of t_L for argon and helium, hence only the values of t_p are given. The numbers along the upper lines indicate the gap lengths.

In hydrogen the breakdown begins at the cathode with a streamer which progresses across the gap with approximately uniform velocity,

[11] A description of the Kerr cell and of some improvements in its technique is being submitted for publication elsewhere.

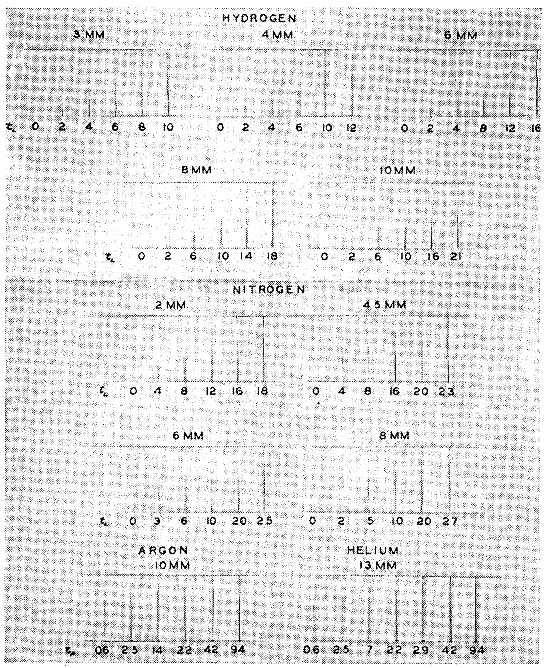

FIG. 2. Pencil drawings of the initial stages of sparks.

and joins a similar streamer from the anode at a point about three-fourths of the distance across the gap from the cathode. The spark is comparatively faint in this gas.

The breakdown in nitrogen may be one of two forms, depending on the gap length and pressure. For atmospheric pressure and gap lengths of less than about 3.5 mm, the breakdown is quite similar to that in hydrogen. For the longer gaps the breakdown starts in a region out in the gap as well as at the cathode, the two appearing simultaneously as nearly as can be determined. They grow together and the breakdown is completed in a manner similar to that for shorter gaps.

The earliest observable discharge in helium is a broad diffuse glow similar to a Geissler discharge and extending the length of the gap. An isolated streamer then appears in the gap and grows toward both the anode and the cathode. Later a spot forms at the surface of the cathode and a streamer appears at the anode. These different portions grow together and the breakdown region broadens and increases in intensity.

The breakdown in argon is similar to that in helium except that no glow discharge is observed and no anode streamer forms. Loeb has suggested that the glow would probably be present in this gas also if it were pure enough. The time required for the completion of the bright filament across the gap for both helium and argon is several times that for hydrogen and nitrogen. This quantity cannot be accurately determined but is larger than that indicated by t_p.

The velocity of the cathode streamers in hydrogen and nitrogen can be measured with considerable accuracy. This was done by observing the length of the streamer in the reflected image as a function of the increased light path for a series of values of t_p. A typical set of curves plotted from these data is shown for nitrogen with a 3 mm gap in Fig. 3. The value of t_p is indicated along each curve and the length of the streamer is expressed as a percentage of the distance across the gap. These curves are approximately parallel straight lines showing that the cathode streamer has, approximately, a uniform velocity. The time plotted is that taken by light in travelling the extra path to the mirror and back, thus an increase in this time means that

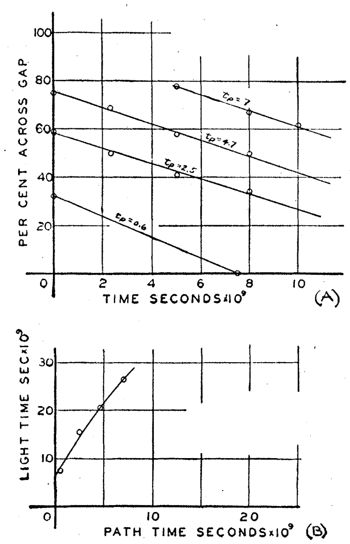

FIG. 3. (A) Growth of cathode pencil as a function of increased light path, nitrogen, 3 mm gap; (B) path time correction curve.

an earlier stage of breakdown is being observed.

The lower curve in Fig. 3 is designated as the "path time correction curve." It gives the value of t_L as a function of t_p and is obtained from the upper set of curves. The positions of these points serve as a partial check on the accuracy of the data, for they should lie on a continuous curve. A consideration of the electric circuit of which the Kerr cell is a part shows this curve to have the correct form.

The cathode streamer velocity was measured for several gap lengths in hydrogen and nitrogen and the results are shown in Figs. 4 and 5. For an 8 mm gap in hydrogen this velocity is 3.2×10^7 cm per sec. and the corresponding value in nitrogen is 1.4×10^7 cm per sec.

The time required for the bright filament to develop across the gap was also measured for these gases; the results are shown in Figs. 6 and 7. For an 8 mm gap in hydrogen this time is about 18×10^{-9} sec., while in nitrogen it is about 27×10^{-9} sec. The form of the curve obtained for nitrogen is similar to that obtained by Dunnington[8] for air. The knee of this curve corresponds to the appearance of the isolated streamer.

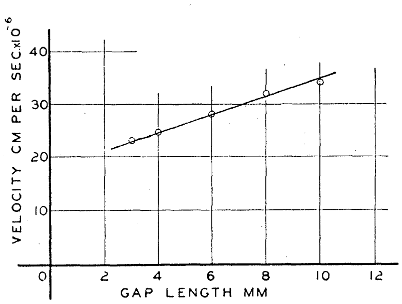

FIG. 4. Velocity of the cathode pencil as a function of gap length, hydrogen.

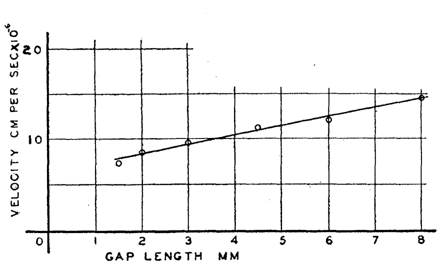

FIG. 5. Velocity of the cathode pencil as a function of gap length, nitrogen.

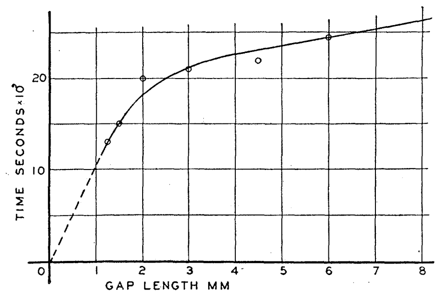

FIG. 6. Development time of the conducting filament in nitrogen.

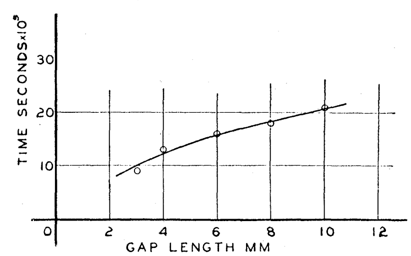

FIG. 7. Development time of the conducting filament in hydrogen.

The time interval between the beginning of the rapid drop in voltage across the gap and the appearance of light of visible intensity can be measured, being simply (t_e-t_L). Dunnington has measured the effective time t_e for certain gaps and pressures in air. He finds for a gap of 5 mm, atmospheric pressure, and $t_p=0.7\times10^{-9}$ sec., a value $t_e=8\times10^{-9}$ sec. The corresponding value of t_L is about 6×10^{-9} sec. These values show that visible light is emitted very soon after the voltage across the gap begins to drop rapidly, the time being, for this case, about 2×10^{-9} sec.

PHOTOGRAPHS

The photography of the early stages of spark breakdown presents considerable difficulty because of the extreme briefness of the exposure times, these being of the order of 10^{-8} sec. or less. The photographs in this paper were obtained by taking full advantage of the available light and using supersensitive panchromatic film with contrast developers.

In order to increase the intensity of the image, the photographic lens, previously placed behind

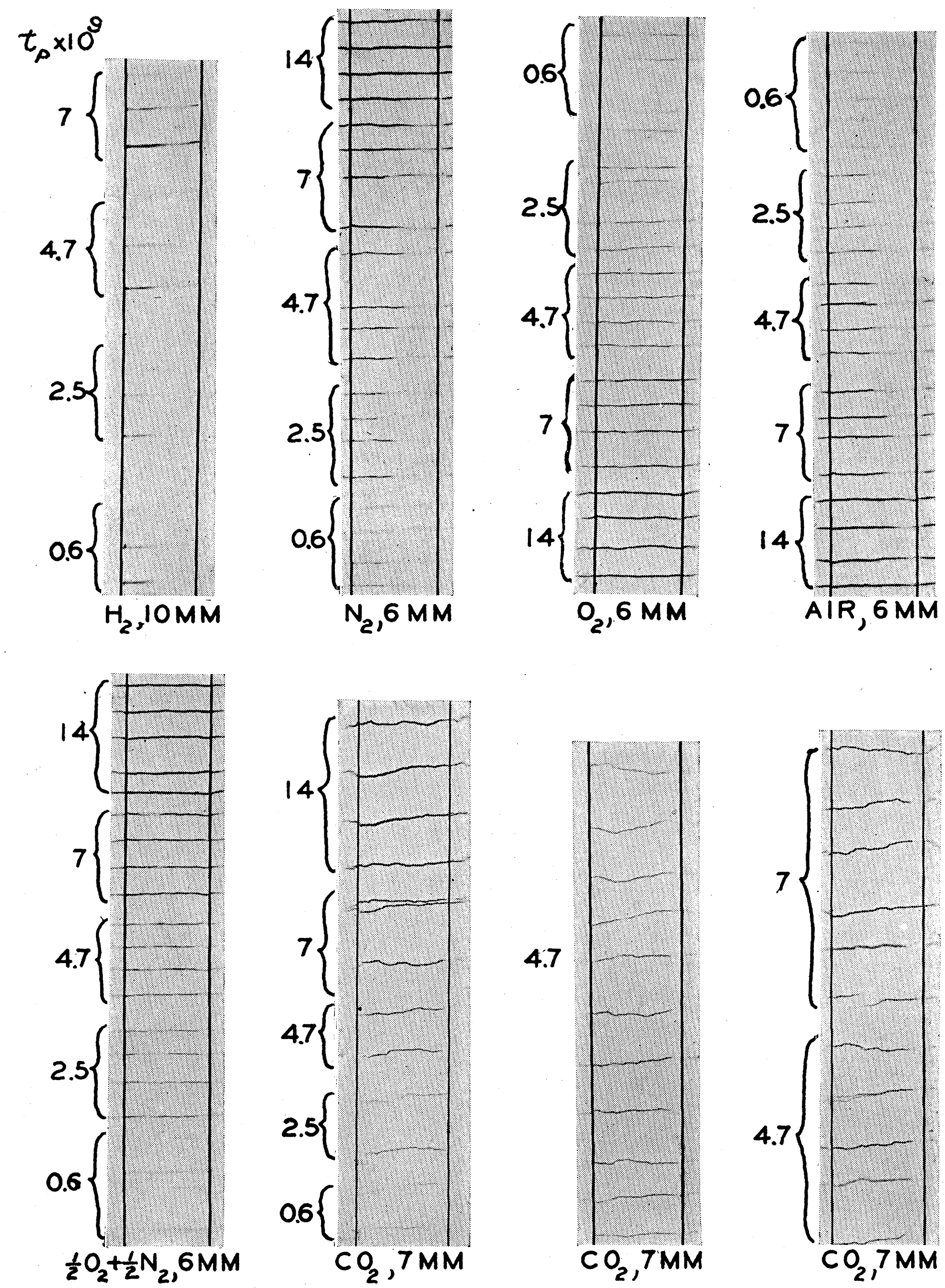

FIG. 8. Photographs of the initial stages of sparks.

the shutter, was placed in front of it as shown in Fig. 1. This greatly increases the effective aperture of the lens which was previously limited by the opening of the Kerr cell. Calculation shows that the image intensity is increased about 15 times over that of the best previous arrangements, the image size being doubled.

Examples of the photographs are shown in Fig. 8. The limits of the electrodes are represented by the lines, the cathode being on the left, the anode on the right. The values of t_p are given outside the brackets which enclose sparks taken under the same conditions. The photographs are all of single sparks, except in the case of hydrogen for which it was necessary to use multiple exposures on account of the faintness of the single sparks. The blackening beyond the lines is due to reflection from the electrodes and is to be disregarded. The faint haze extending across the gap in some of the pictures is due to the Kerr cell background.

There are several features of the breakdown to be noted in the various gases. The multiple filament effect, or the appearance of a multiple filament in the region where the cathode streamer and the isolated central streamer join, occurs in the cases of nitrogen, oxygen, and mixtures of these gases. It is especially noticeable in the mixture of half oxygen and half nitrogen. Double anode streamers appear also for these gases and are especially prominent in the case of air. The isolated region is clearly shown in air and the mixture of half oxygen and half nitrogen, in the brackets marked $t_p=0.6$, and is less clearly shown in the other two cases. For carbon dioxide the extremely tortuous path of the breakdown is to be noted. Several cases of branching towards the cathode also appear in this gas for which this is a rather frequent phenomenon.

The exposure time for a given photograph is equal to the light time t_L as can be seen from the definition of the latter quantity. t_L can be obtained from a set of curves such as shown in Fig. 4, so that the exposure times are known for those cases in which it is possible to measure t_L. As an example of the extreme shortness of the exposures, the exposure time for nitrogen with a 6 mm gap and a value of $t_p=0.6\times10^{-9}$ sec. is about 5×10^{-9} sec., while for the same gap length and $t_p=14\times10^{-9}$ sec., the exposure time is about 24×10^{-9} sec.

Types of Breakdown Observed

Four distinct types of breakdown, as characterized by the appearance and development of the streamers, are recognizable in the gases thus far studied. In hydrogen, and in nitrogen with gaps shorter than about 3.5 mm, the initial streamer appears at the cathode and grows towards the anode with an approximately uniform velocity. When it is about halfway across the gap, a streamer appears at the anode and grows towards the cathode streamer, meeting the latter at a point about one-fourth of the gap length from the anode. For an 8 mm gap, the cathode streamer velocity in nitrogen is 1.4×10^7 cm per sec. and in hydrogen it is 3.2×10^7 cm per sec. The calculated velocity of electrons[12] under breakdown conditions is 1.5×10^7 cm per sec. for nitrogen and 1.0×10^7 cm per sec. for hydrogen, these values depending on the average energy assumed for the electrons. The fact that the observed velocities of the streamers equals in order of magnitude the calculated velocities of electrons in the breakdown electric field, leads to the important conclusion that the breakdown is due to the motion of electrons.

For gap lengths greater than about 3.5 mm in nitrogen, two distinct streamers appear initially, one being at the cathode as above, the other in a detached region out in the gap. These two grow together, mainly by the advance of the central streamer, and the breakdown is completed in a manner similar to that for short gaps.

In helium, at the earliest time for which it is possible to observe, the discharge is a glow about 1 mm in diameter and extending the length of the gap. Then a spot forms at the surface of the cathode and an indistinct streamer appears in the gap, after which the breakdown is completed in a way similar to that for long gaps in nitrogen. The streamer velocities are smaller than those in nitrogen by a factor of about 3.

The distinguishing features of the breakdown in carbon dioxide are the tortuousness of the

[12] Langevin, Ann. Chim. Phys. **5**, 245 (1905).

streamers and the branching which occurs at the cathode. The position and growth of the streamers are otherwise similar to those occurring in the long gaps of nitrogen.

Discussion

The material presented in this paper is confined to the results of a study of the position and growth of the visible streamers which appear in the initial stages of spark breakdown. The complete understanding of a spark discharge involves a knowledge of the preceding or dark current stage, particularly of the distribution of ions in the gap just before the visible streamers appear. The fact that streamers are formed in localized regions shows that the phenomenon is primarily one of space charge effects. By correlating the emission of visible light with intense ionization, a knowledge of the streamers occurring in a spark breakdown shows in what region or regions the space charge fields are important.

Previous experimenters[1, 13] have shown that, in the case of static breakdown with the cathode illuminated with ultraviolet light, both the spark lag and the time of breakdown are of the order of 10^{-7} sec. Now the velocity of electrons, under breakdown conditions in gases, is so much greater than that of positive ions, that the latter may be considered as remaining practically stationary during such a short time interval. Thus the space charges which result in breakdown arise because of this great difference in velocity and are almost entirely built up by the motion of electrons. The large velocity of the initial streamers and the rapidity of breakdown show that the major portion of the charge transported during breakdown is carried by electrons. A simple calculation shows that these must come mostly from the cathode, for if any appreciable number of them came from ionization in the gap, the positive charge remaining after the removal of the electrons would raise some region of the gap to an impossibly high potential.

The results of this experiment together with those just mentioned, lead to a plausible explanation of breakdown as it occurs in a gas such as nitrogen. Suppose that a spark gap is at the sparking potential corresponding to a given set of conditions and that ultraviolet light is allowed to shine on the cathode beginning at a given instant. This initiates a stream of electrons moving to the anode with a velocity which is of the order of magnitude of 10^7 cm per sec. Each of these electrons produces ion pairs according to the Townsend equation, $n = \exp^{\int \alpha dx}$, where α is the Townsend coefficient and x the distance moved in the direction of the field. There results an excess of positive charge in the gap immediately after the first burst of electrons reaches the anode, which, because of the exponential nature of the Townsend equation, lies for the most part very close to the anode. The presence of the excess positive charge disturbs the originally uniform field, decreasing it in a region close to the anode and increasing it in the rest of the gap.

Subsequent electrons produce more ions in the region of greater field and fewer in the region of lesser field, the net effect being to cause the region of large excess positive charge to advance towards the cathode. The most intense field lies directly in front of this advancing charge and its magnitude increases as it advances because the total amount of excess charge is being increased. If the ionization becomes sufficiently large and light of visible intensity is emitted, it will occur in this region, so that a streamer appears there first. The idea of an electron avalanche, and the resultant concentration of the field in the region of the cathode is due to von Hippel and Franck[14] and was developed quantitatively by Schumann.[15] A somewhat similar theory was proposed by Loeb[16] at about the same time.

The image, in the cathode, of the positive charge produces a field which becomes important as the head of this charge approaches the cathode. Owing to this, the field is still further increased in the region near the cathode. Thus for gap lengths short enough, the initial streamer is formed at this electrode, but increasing the gap length sufficiently, results in the formation of a

[13] Snoddy, Phys. Rev. **40**, 409 (1932).

[14] von Hippel and Franck, Zeits. f. Physik **57**, 696 (1929).
[15] Schumann, Zeits. f. tech. Physik **11**, 194 (1930).
[16] Loeb, Science **69**, 509 (1929).

detached streamer. Experimentally this is found to be true, but in addition, a streamer always appears at the cathode at about the same time that the central streamer appears, indicating that some other process is effective in building up positive space charge close to the cathode. This may be due to positive ion impact or to photoelectrons ejected from the cathode by radiation from the discharge.

Suppose that a short gap is being considered, so that initially the only streamer that appears is at the cathode. This streamer is semiconducting and the field is strongest at its tip, causing it to grow towards the anode. A previous discussion shows that most of the current is carried by electrons coming from the cathode. A considerable proportion of these leave the tip of the streamer and advance ahead of it, eventually annulling the positive space charge previously present, and building up a negative space charge which is concentrated near the anode. As a result, the field there in time becomes strong enough to cause a streamer to form.

For a long gap, a central streamer appears in addition to the one at the cathode. The field between these two is comparatively large, as shown by the above discussion, and the central streamer grows faster towards the cathode than towards the anode. Experimentally the ratio of these two velocities is found to be about three or four. After the two streamers join, the breakdown is completed in a manner similar to that for short gaps.

It follows from the above considerations that the spark lag is very nearly the time required for the space charge to build up a field of strength sufficient to cause a streamer to form, and is therefore dependent on the intensity of the ultraviolet illumination. For illumination of very high intensity, the lag will be of the order of magnitude of the time it takes electrons to traverse the gap, that is, about 10^{-7} sec.

Snoddy observed time lags of this magnitude when illuminating spark gaps with an intense ultraviolet light source. No doubt experimental investigations of the dependence of the spark lag on the intensity of illumination of the cathode will contribute to a more complete understanding of the breakdown process.

In conclusion, I wish to express my appreciation to Professor E. O. Lawrence, under whose direction this research is being carried on, for many helpful suggestions and discussions. I also wish to thank Dr. F. G. Dunnington for his help in the experimental work, and Professor L. B. Loeb and Dr. A. M. Cravath for their assistance in the interpretation of the results.

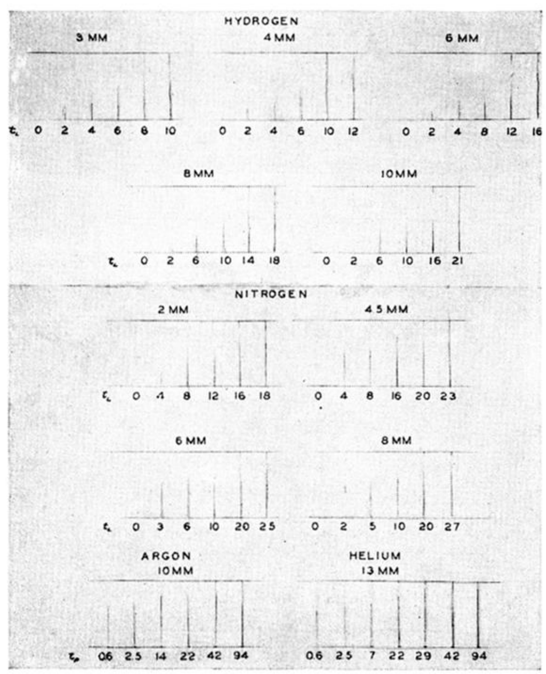

FIG. 2. Pencil drawings of the initial stages of sparks.

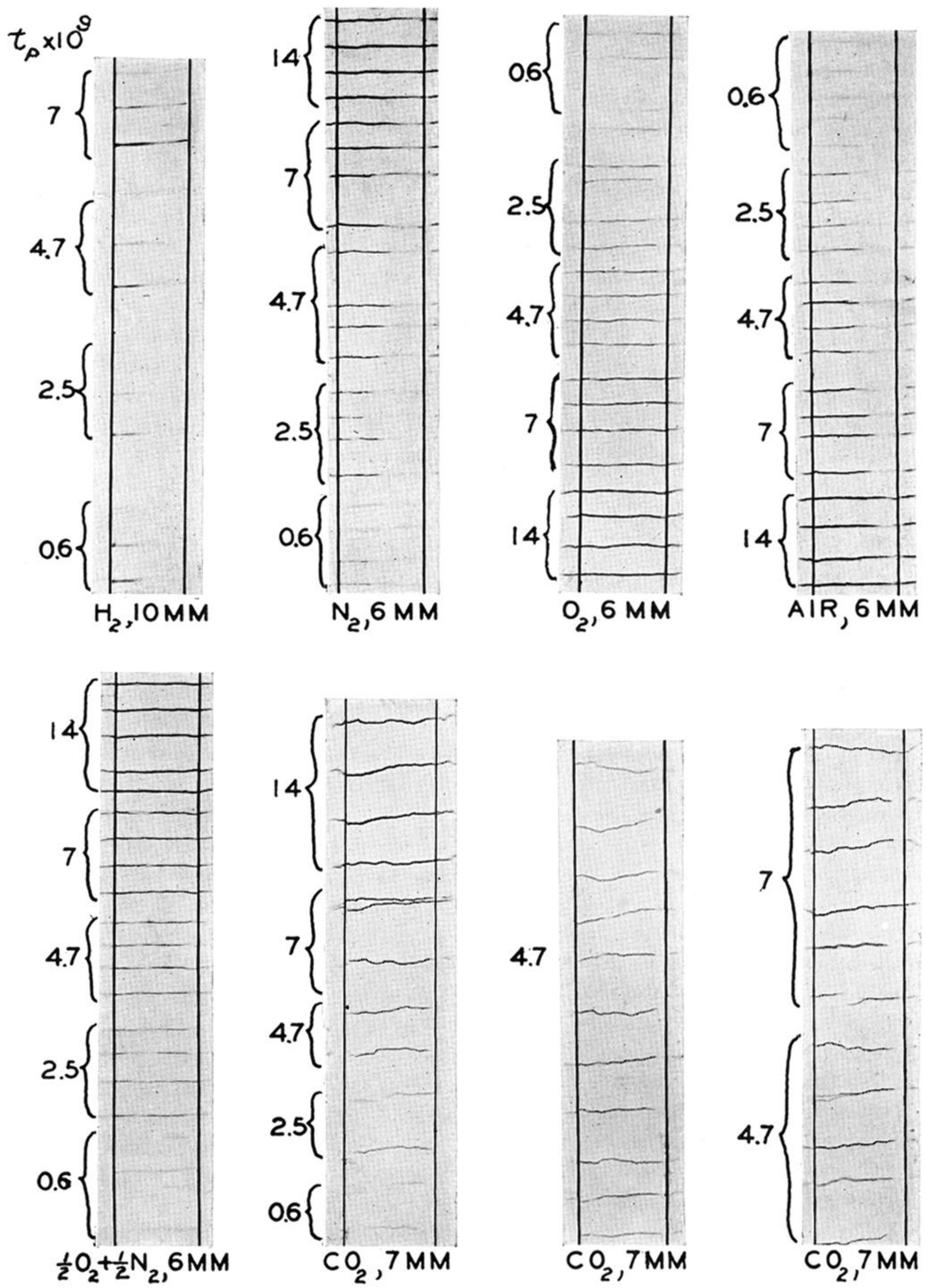

FIG. 8. Photographs of the initial stages of sparks.