The Dark Current Time in Condensed Discharges in Air at Atmospheric Pressure

By L. B. Snoddy
General Electric Company

(Received February 29, 1932)

The time of current flow prior to the appearance of luminosity in a condensed discharge was measured by means of the high speed rotating mirror developed by Henriot and Hunguenard. The discharge was initiated by ultraviolet light from another spark gap. This light was focussed on the cathode of the gap under investigation. The light from the two gaps after reflection by the mirror was focussed on a photographic plate. The separation of the images on the plate was a measure of the dark current time. This time was found to be a function of the electrode geometry. For symmetrical hemispherical electrodes, 6.5 mm in diameter, 4 mm apart, it was not greater than 2×10^{-7} sec. It increased to 3×10^{-5} sec. for a gap with two spherical electrodes, the anode 25.4 mm and the cathode 1 mm in diameter. As near as this method could determine, in all cases the luminosity appeared at the same time throughout the gap.

SINCE the publication of the theory of spark breakdown developed by v. Hippel and Franck,[1] the dark current time, i.e., the time during which current flows prior to the appearance of luminosity in condensed discharges, has been of considerable importance. In the theory outlined by them the discharge is initiated by photoelectrons liberated at the cathode. The gap space is assumed to be initially without either ions or electrons and the field intensity that necessary for static breakdown. Since the speed of the electrons is of the order of 10^7 cm/sec. at breakdown potentials, there must of necessity be an interval of at least 10^{-7} sec. (for a one cm gap with no overvoltage) between the liberation of the first electron and the complete breakdown.

This time must not be confused with the time lag of breakdown as it is ordinarily considered. Most of the time lag measurements of Pedersen,[2] Beams,[3] and others are concerned with highly overvolted gaps or with gaps to which a steep wave front is applied and the voltage allowed to build up until discharge occurs. The conditions in these experiments are not at all those postulated by v. Hippel and Franck. The field strength is much more than the minimum necessary for breakdown with consequent higher electron speeds and greatly increased rate of ionization. There are also ions initially present in the gap space before the impulse is applied. This probably acounts for the short times observed (order of magnitude 10^{-8} sec.).

Street and Beams[4] have shown that with gaps swept free of ions the lag may be 10^{-6} sec. or longer, even with very high overvoltage. In this case the initial supply of electrons is probably furnished by auto-electronic emission

[1] v. Hippel and Franck, Zeits. f. Physik **57**, 696 (1929).
[2] P. O. Pedersen, Ann. d. Physik **71**, 317 (1923).
[3] J. W. Beams, Jr. Franklin Inst. **206**, 809 (1928).
[4] J. C. Street and J. W. Beams, Phys. Rev. **38**, 416 (1931).

from the cathode. With the gap initially free of ions but supplied with electrons by photoelectric emission from the cathode, the breakdown again becomes very short. In this case it is not possible to apply much over-voltage.

For non-irradiated gaps to which just the minimum potential is applied the time lag may be several seconds in length.[5]

These experiments in most cases, except those initiated by ultraviolet light, do not fix the actual time at which the discharge is initiated as the interval measured is the total time taken by the voltage wave to rise to its final value. The methods usually do not indicate the time from the first flow of current to the appearance of luminosity which indicates the final complete breakdown. It was thought worthwhile to investigate the magnitude of this time interval by using the high speed rotating mirror developed by Henriot and Hunguenard[6] and improved by Beams.[7] Instead of the constant intensity irradiation postulated by v. Hippel and Franck, a second spark gap was used as the source of ultraviolet light.

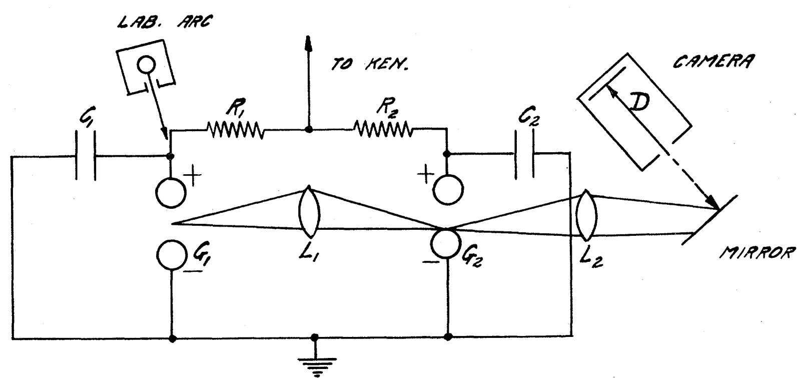

Fig. 1. Diagram of apparatus. $R_1 = 2.5 \times 10^5$ ohms; $R_2 = 5 \times 10^5$ ohms; $C_1 = 0.01$ mfd; $C_2 = 0.01$ mfd.

The experimental arrangement is shown in Fig. 1. The spark gaps G_1 (the light source) and G_2 (the gap under investigation) with the condensers C_1 and C_2 were charged in parallel from the same Kenotron tube through the resistances R_1 and R_2. The light from G_1 was brought to focus on the cathode of G_2 by the quartz lens L_1 (simple double convex lens). The combined light from the two gaps was brought to focus by a second lens (glass achromat) on the plate of the camera at D after reflection by the rotating mirror. A quartz mercury arc was arranged in such a way that gap G_1 was constantly irradiated. This caused G_1 to break down at very constant potential and prevented much overvolting of G_2. Care was of course taken to prevent any light from the mercury arc striking G_2. Gap G_1 was adjusted in such a way that G_2 never discharged unless irradiated by light from G_1. The gaps were carefully lined up so that with the mirror stationary the images were exactly superimposed on the ground glass screen of the camera at D.

[5] K. Zuber, Ann. d. Physik **76,** 231 (1925).
[6] Henriot and Hunguenard, Jour. d. Phys. et Radium **8,** 443 (1927).
[7] J. W. Beams, Rev. of Sc. Inst. **1,** 667 (1930).

To make sure that the ultraviolet light from G_1 was properly focussed on G_2, the following procedure was adopted. With G_1 tripping G_2 each time, the potential of G_1 was lowered by decreasing the gap spacing and the position of the quartz lens adjusted until the minimum potential at which constant tripping of G_2 would take place was obtained. This evidently corresponded to the position of maximum ultraviolet illumination.

The glass lens L_2 was adjusted so that the top of the cathode of G_2 was sharply outlined on the camera screen. Since the quartz lens was uncorrected and since the position of maximum ultraviolet illumination did not quite bring the visual image of G_1 to a sharp focus on the tip of G_2, the image of G_1 on the camera plate is not as well defined as that of G_2. This is not a source of great error, however, for the spark does not strike at precisely the same point of the gap surface in consecutive discharges. It was found that with the gaps irradiated this wandering was much less pronounced than is ordinarily the case.

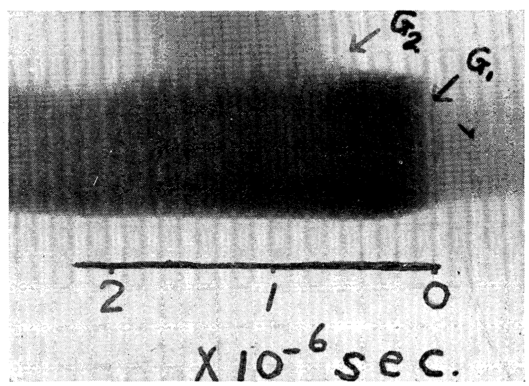

Fig. 2. Photograph of discharge. Electrodes of G_2 brass spheres, 6.5 mm in diameter.

The Kenotron system was adjusted to charge the condensers to breakdown potential in from 2 to 3 seconds. With this slow charging rate the gap space was swept practically free of ions between discharges, allowing breakdown to take place at the minimum potential in a field undistorted by the presence of a large number of ions.

It is evident that with the mirror rotating there will be a separation of the images of the two discharges if the time between the irradiation and the appearance of luminosity in G_2 is greater than the resolving power of the rotating mirror. In this work the mirror was used at speeds from 160 r.p.s. to 2100 r.p.s., corresponding to linear image speeds of 1.64×10^5 to 2.14×10^6 cm/sec. With the last speed it should be possible to detect easily a difference of 10^{-7} sec. in image separation.

This resolving power was, however, decreased by the wandering of the spark on the electrode surfaces. In each case the amount of the variation was determined from measurements made with the mirror stationary and allowance made for it in computing the time separation. With cathodes of small diameter (1 mm), the wandering was practically eliminated.

The time measured here is evidently made up of two intervals; the first, that required to liberate an electron from the surface of the electrode, and second, that between the liberation of electrons and the actual breakdown. The first interval was shown by Lawrence and Beams[8] to be approximately 3×10^{-9} sec., much smaller than this method could detect. The separation measured here can consequently be considered as a true dark current time.

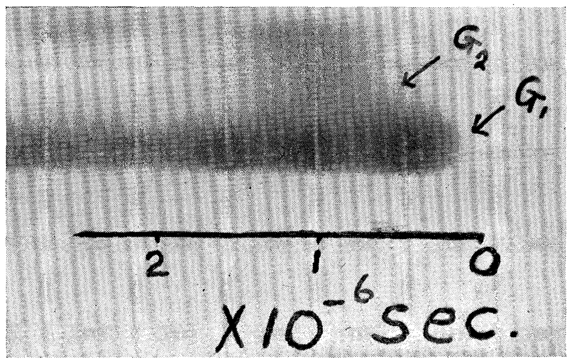

Fig. 3. Photograph of discharge. G_2 electrodes, 1 mm spheres.

It is assumed here that the ultraviolet illumination of G_2 coincides with the visible illumination. Although the ultraviolet and visible light probably do appear at slightly different times, the separation can hardly be greater than 1 or 2×10^{-8} secs.

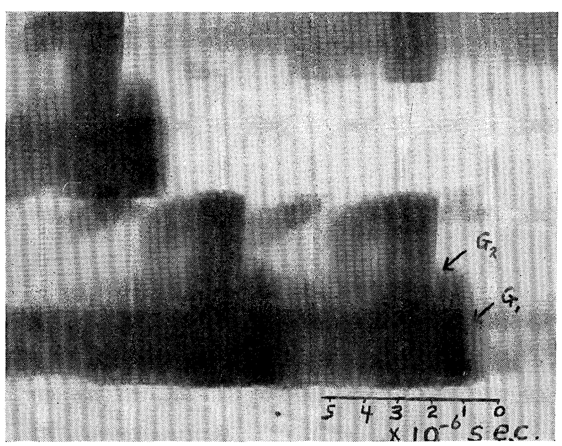

Fig. 4. Photograph of discharge. G_2 anode, 6.5 mm in diameter. Cathode 1 mm in diameter.

For the photograph shown in Fig. 2, the electrodes of G_2 are brass hemispheres, 6.5 mm in diameter. The variation in point of starting on the electrode surface is quite noticeable for spheres of this diameter. Allowing for this variation the dark current time is found not to exceed 2×10^{-7} sec. In the

[8] E. O. Lawrence and J. W. Beams, Phys. Rev. **32**, 478 (1928).

photograph of Fig. 3 the electrodes of G_2 are 1 mm in diameter. For this case the time does not exceed 3×10^{-7} sec.

The slight increase in image separation with this change to 1 mm spheres made it of interest to try the experiment with very unsymmetrical fields, since it is well known that the time lags with point-plane and point-sphere gaps are much longer than with the ordinary symmetrical sphere gap.

In Fig. 4 are shown three photographs taken with an anode 6.5 mm in diameter and a cathode 1 mm in diameter. The average time separation is 12×10^{-7} sec. with an image speed of 1.48×10^6 cm/sec.

Two photographs with anode 23 mm and cathode 3.17 mm in diameter are shown in Fig. 5. The average separation is 2.1×10^{-6} sec.

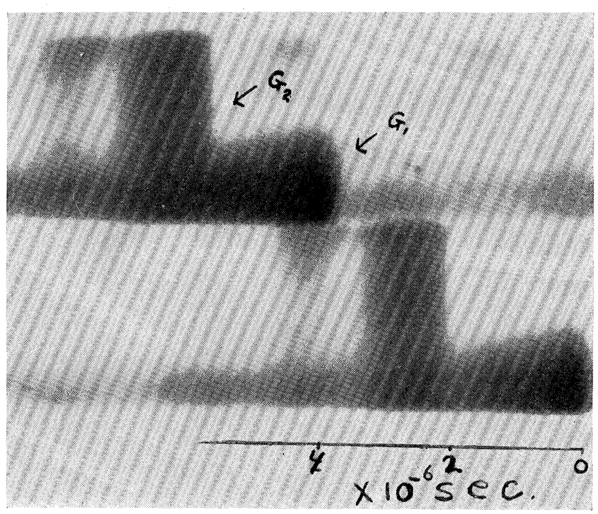

Fig. 5. Photograph of discharge. G_2 anode, 23 mm in diameter. Cathode 3.17 mm in diameter.

The results are tabulated in Table I. The anode and cathodes were brass except for the last result; for this a steel ball was used as anode. No photographs were obtained in this last case with 25.4 mm anode and 1 mm cathode.

TABLE I. *Time lag of spark breakdown for electrodes of various sizes.*

Electrode Characteristics Anode (dia. in mm)	Cathode (dia. in mm)	Gap Spacing (mm)	Image Speed (cm/sec.)	Time Separation (sec.)
6.5	6.5	4	2.14×10^6	Not greater than 2×10^{-7}
1.0	1.0	4	2.14×10^6	Not greater than 3×10^{-7}
6.5	1.0	5.3	7.6×10^5 1.48×10^6	$11(\pm 1) \times 10^{-7}$
23.0	3.17	5.3	1.48×10^6	$21(\pm 3) \times 10^{-7}$
25.4 (steel)	1.0	5.3	1.64×10^5	3×10^{-5}

The separation was so great that the images appeared together on the plate only once or twice in two or three hundred discharges. The separation was, however, measured on the screen with a reasonable degree of accuracy.

The potential difference and gap spacings were adjusted so that no corona or brush discharge was visible at the small electrode of G_2. Since this experiment was carried out with all apparatus in a small dark room any discharge could be easily detected.

As a check against errors due to improper focussing, etc., the process of tripping was reversed. Without changing the gap arrangement in any way, the light from the quartz mercury vapor arc was focussed on G_2 instead of on G_1. This caused G_2 to discharge first, initiating G_1 in turn and thus reversing

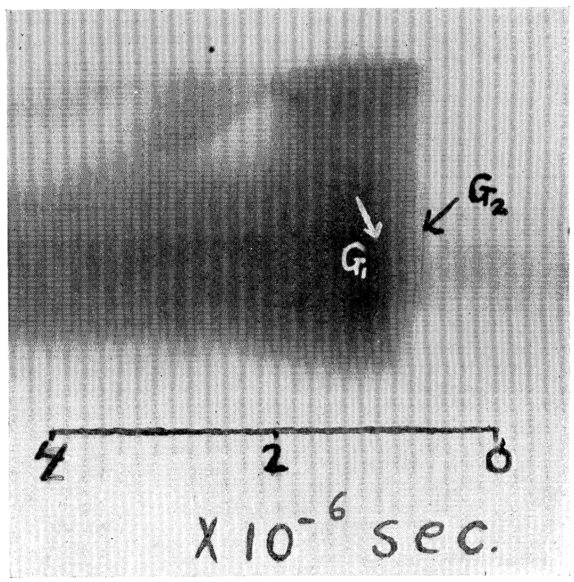

Fig. 6. Photograph showing G_2 tripping G_1.

the original process. This reversed effect is shown in Fig. 6. The experimental conditions are exactly the same as in Fig. 4, except for the position of the quartz arc. It is evident that the order of the images is reversed. The image of G_2 appears before that of G_1.

These results are in accordance with the known time lags of point-plane and point-sphere gaps. They are, however, remarkably constant when compared to the results obtained with point-plane electrodes. For example, McEachron and Wade[9] obtained time lags ranging from 9×10^{-6} to 380×10^{-6} sec. for a point to plane discharge of a 12 mm non-irradiated gap (polarity the same as in this work).

Another interesting feature is that the appearance of luminosity in the irradiated gap is instantaneous as near as this method is capable of determin-

[9] McEachron and Wade, A.I.E.E. **44,** 832 (1925).

ing. In the case of the longest lags investigated here, the luminosity from the first gap G_1 becomes very faint before the second gap G_2 breaks down. Even for lags of this length the effect of the ultraviolet light was real as the second discharge could be entirely eliminated by placing a glass screen between the two gaps.

For lags not over 1×10^{-6} sec. in length, G_2 was illuminated by light of high intensity. For the long lags of 3×10^{-5} sec. the light was intermittent and rapidly decreasing in intensity, due to the damping of the oscillations of the G_1 circuit, brought about by the resistance of wires and contacts and the energy loss in the spark itself. Introducing enough resistance in the G_1 circuit to prolong the discharge for 3×10^{-5} sec. decreases the light intensity so much that consistent tripping is difficult to obtain. More capacity could of course be used, but in that case the electrodes would be badly pitted, again making good tripping difficult.

An attempt was made to trip G_2 with the polarity reversed, i.e., the large sphere as cathode with the anode of small diameter. This was unsuccessful, no consistent tripping could be obtained. The difficulty seemed to be in the formation of a corona or brush discharge from the small anode before the field intensity at the cathode was sufficiently high for the electrons liberated to produce breakdown. It is known that breakdown occurs with a point sphere or point-plane arrangement at a much lower voltage with the point positive than with it negative.[10]

[10] Wolcott, Phys. Rev. **12,** (1918).

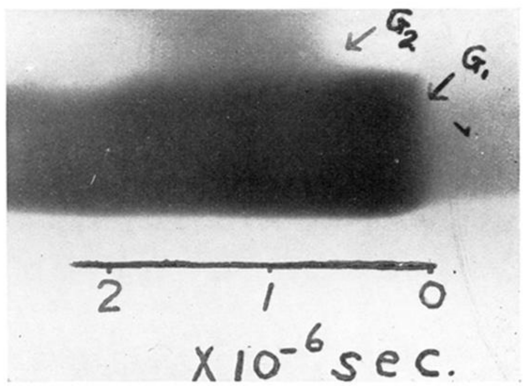

Fig. 2. Photograph of discharge. Electrodes of G_2 brass spheres, 6.5 mm in diameter.

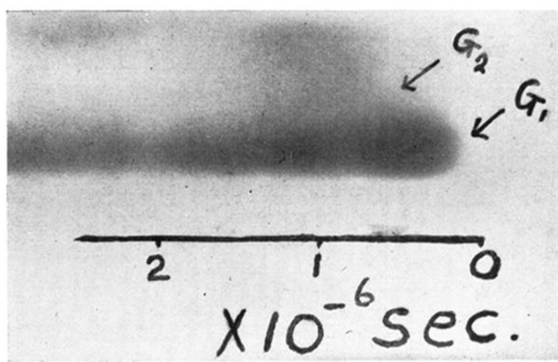

Fig. 3. Photograph of discharge. G_2 electrodes, 1 mm spheres.

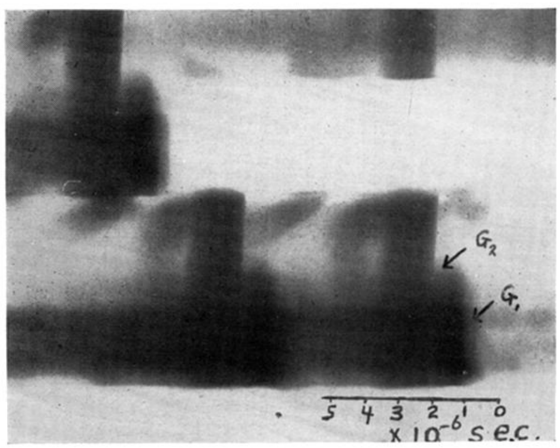

Fig. 4. Photograph of discharge. G_2 anode, 6.5 mm in diameter. Cathode 1 mm in diameter.

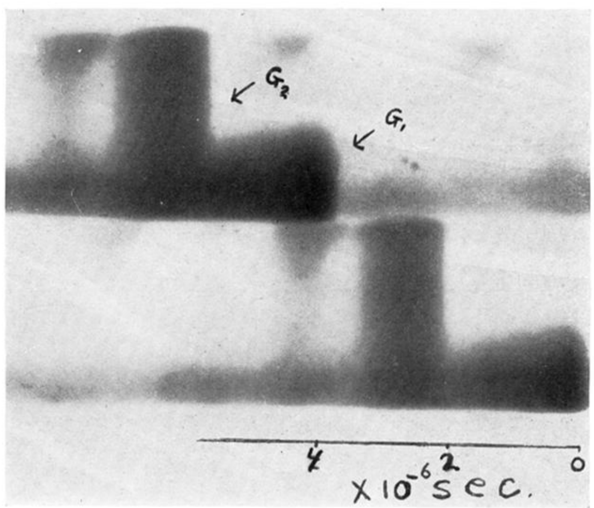

Fig. 5. Photograph of discharge. G_2 anode, 23 mm in diameter. Cathode 3.17 mm in diameter.

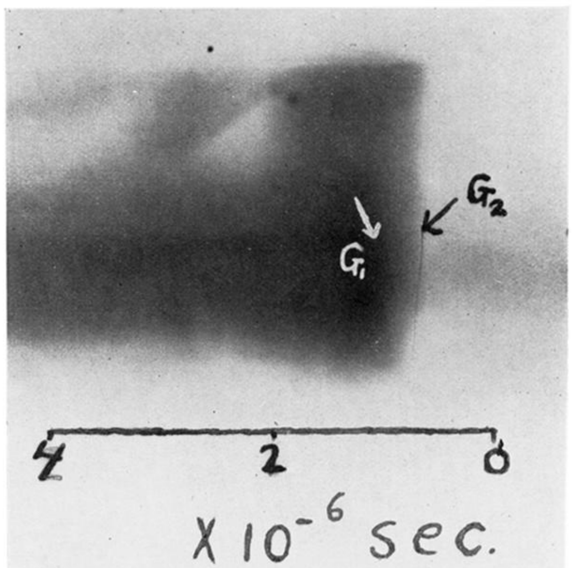

Fig. 6. Photograph showing G_2 tripping G_1.