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Formative Time Lags of Uniform Field Breakdown in N_2†

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Formative time lags of spark breakdown in N_2 have been measured in uniform fields as a function of percent overvoltage, pressure (150 to 700 mm Hg) and electrode separation (0.3 to 1.4 cm). For the range of variables studied the formative time lags are almost identical with values previously observed in air; the time lags vary from 100 μsec close to threshold to 1 μsec at a few percent overvoltage. The present data as well as the earlier measurements in air indicate a secondary mechanism of photoemission of electrons either from the cathode or from the gas near the cathode. This mechanism requires a large number of successive electron crossings. The dependence of the sparking potential on the number of initiating electrons has been determined; the sparking potential of pure N_2 shows an enormous dependence on the value of the primary current.

I. INTRODUCTION

THE present experiments are an extension of earlier work carried out in air.[1] The experiments of FB examined the nature of the threshold setting mechanism of the uniform field spark in air, and showed that formative time lags of breakdown in air near threshold are of the order of 100 μsec. FB state: "It is believed . . . that two processes acting together produce the observed long time lags at low overvoltages. These are (1) a suitable secondary mechanism (most probably photoemission at the cathode) . . . and (2) space charge distortion due to the large number of positive ions in the gap." Calculations show that space charge distortion alone cannot satisfactorily account for the observed time lag dependence on overvoltage in air.[2] It thus appears that a Townsend-like discharge sets the threshold for uniform field breakdown in air rather than a streamer-like process.[3] It seemed important to determine the generality of the results in air by investigating other gases.

II. APPARATUS AND EXPERIMENTAL PROCEDURE

Unless otherwise noted, the apparatus and experimental procedure are as described by FB. The chamber was evacuated to a pressure (p) of about 10^{-5} mm,[4] and then filled with N_2 to a low pressure; a glow discharge was then maintained between the electrodes while the chamber was again evacuated. The process was repeated several times and fresh gas was then admitted.

Values of the first Townsend coefficient, α, as determined by Masch[5] were used to evaluate the initial cathode photoelectric current i_0. The value of i_0 was adjusted so as to avoid statistical lags and yet was never so large as to introduce space charge effects. All time lag measurements were made with the approach voltage V_0 exactly 2 kv below the sparking potential V_s (except for one set of measurements in which V_0 was set at 4 kv below V_s).

About four observations of the time lag were made at each overvoltage studied; the actual number of measurements taken at any given overvoltage was determined by the internal consistency of the observations. The average of these observations was taken as the formative time lag. Justification for using the average will be given later. About eight different overvoltages were studied for a given pressure and electrode separation (δ); such measurements were taken at various values of p and δ. The dependence of the time lags on i_0 was also studied.

To determine the significance of the observed scatter in the time lag measurements, an extensive study of the time lag distribution was made for one particular overvoltage (with $\delta = 1$ cm and a pressure near atmospheric). A statistical distribution of time lags superimposed on a formative time lag τ is given by[6]

$$n = n_0 e^{-(t-\tau)/\sigma}, \tag{1}$$

where n is the number of lags out of n_0 observations which exceed t, and σ is the mean statistical scatter time. If a straight line results when the data are plotted semilogarithmically according to Eq. (1), then the distribution is statistical; such a graph is referred to as a Laue plot.

The absolute values of all voltages are correct to within 0.5 percent since this is the accuracy of the voltage measuring resistors (all other errors are negligible compared to this). However, since the error in the resistors remains constant (except for small variations

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† Supported by ONR and the Research Corporation. For preliminary reports of this work, see G. A. Kachickas and L. H. Fisher, Phys. Rev. **82**, 318, 569 (1951). Also see L. B. Loeb, Phys. Rev. **81**, 287 (1951).

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[1] L. H. Fisher and B. Bederson, Phys. Rev. **81**, 109 (1951). This paper will be referred to as FB.

[2] B. Bederson, Ph.D. thesis, New York University (1949) (unpublished).

[3] For a description of the streamer process, see J. M. Meek, Phys. Rev. **57**, 722 (1940); L. B. Loeb and J. M. Meek, *The Mechanism of the Electric Spark* (Stanford University Press, Stanford, 1941); H. Raether, Arch. Elektrotech. **34**, 49 (1940); Z. Physik **117**, 375, 524 (1941); Ergeb. exakt. Naturwiss. **22**, 73 (1949).

[4] All pressures are given in mm, meaning mm of Hg.

[5] K. Masch, Arch. Elektrotech. **26**, 587 (1932).

[6] K. Zuber, Ann. Physik **76**, 231 (1925); M. von Laue, Ann. Physik **76**, 261 (1925); R. Strigel, *Elektrische Stossfestigkeit* (Julius Springer, Berlin, 1939), p. 67.

in temperature) relative voltages are correct to a much greater accuracy.

Voltage fluctuations usually prevent V_0 from being set closer than 3 v of the desired value at the instant the pulse voltage V_1 is applied. The value of V_1 may be set to within 0.5 v of the desired value, but the true pulse voltage is $V_1 - V'$ where V' is a correction due to the loss of part of V_1 in the circuit. It is estimated that $V_1 - V'$ is known to within 2 v, and that the uncertainty in the total voltage applied to the electrodes is of the order of 5 v.

All pressures have been corrected to 22°C.

III. EXPERIMENTAL RESULTS

Before presenting the time lag data, it is necessary to describe measurements of V_s as this quantity must be known in order to obtain the percent overvoltage (percent o.v.). Since it was found that the presence of a very small amount of impurity greatly alters the sparking potential of N_2, measurements of V_s were made in both "N_2" and "pure" N_2. By N_2 is meant Linde's high purity tank N_2 [7] which was passed directly from the tank through a liquid N_2 trap into the "outgassed" chamber. The term pure N_2 [8] refers to Linde's high purity tank N_2 which was passed over hot copper shot and then through a liquid N_2 trap.

The V_s values for N_2 and pure N_2 with no ultraviolet illumination of the cathode have about the same values and are in close agreement with the values given by Ehrenkranz.[9]

The sparking potential of N_2 with and without ultraviolet light is definite at any given time to within 2 v for a V_s of 30 kv. However, the actual value of V_s in N_2 depends on the value of i_0 to a small extent. For example, at electrode separations of 1.0 and 1.4 cm and with pressures of 460 and 730 mm an i_0 of about 200 electrons/μsec (ϵ/μ sec) lowers V_s of N_2 by about one percent. For any given filling of N_2, the decrease of V_s varies linearly with i_0 although the absolute variation changed somewhat from one filling to the next. Measurements of this decrease in V_s could not be made at a product of $p\delta$ less than about 400 mm×cm because ultraviolet illumination under these conditions at high enough potentials initiates a partial breakdown giving rise to a glow on the anode; only when the potential is raised further does a spark occur. This partial breakdown (which was not observed in air) has associated with it only a small change in the potential across the electrodes; in this respect, as well as in the localization of the luminosity, there is strong similarity to the corona discharge. Further study of these partial breakdowns seems worthwhile.

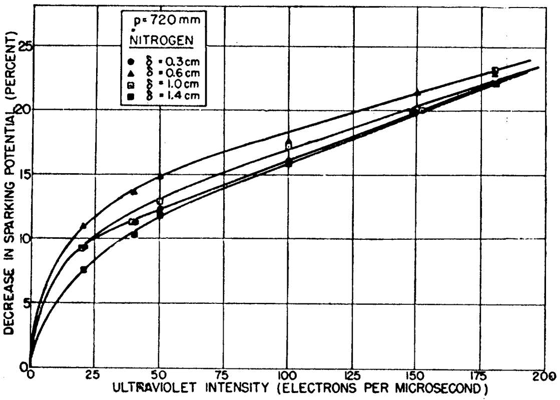

FIG. 1. Decrease in sparking potential *vs* primary current for pure N_2.

The sparking potential for pure N_2 without ultraviolet light varies at any given time within a range of 50 v in 30 kv, and the average value of about ten measurements was taken as the breakdown potential.[10] With ultraviolet illumination of the cathode, V_s for pure N_2 is lowered enormously and its value varies over a wide range at a given illumination level (about 100 v for $V_s \sim 30$ kv). This decrease in V_s is as great as 23 percent at atmospheric pressure with an i_0 of about 200 ϵ/μsec.[11] The variation of this decrease in V_s with i_0 for various electrode separations near atmospheric pressure is shown in Fig. 1. The only other measurements showing a large effect of i_0 on V_s were made by White[12] who found a ten percent decrease in V_s of air when i_0 was increased by a factor of a million. In fact, the variation of sparking potential with illumination in pure N_2 is so great that a spark can be induced to pass with an appropriate V_0 by shining the light from an ordinary flashlight through the quartz window of the chamber. This interesting effect merits further study.

Using the very definite sparking potentials obtained in N_2 (with no i_0) as V_s, formative time lags were measured with an i_0 of about 40 ϵ/μsec. The results are shown in Fig. 2 for $\delta = 1$ cm at three pressures along with the formative time lags for uniform field breakdown in air at atmospheric pressure as given by FB. As was the case in air, the time lags in N_2 are essentially independent of pressure over the range studied; this pressure independence allows the representation of the time lag data fairly well by a single curve at a given electrode separation. Figure 3 contains such a curve for the data of Fig. 2 with similar curve for $\delta = 1.4$, 0.6 and 0.3 cm over the same range of pressures given in Fig. 2. The time lag *vs* percent o.v. curves in N_2 are almost identical with those for air, and as in air, the

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[7] The Linde Company guarantees this N_2 to be 99.99 percent pure.

[8] A sample of pure N_2 was analyzed by mass spectrograph and found to contain by percentages N_2 99.89, CO_2 0.08, O_2 0.03. We are indebted to Dr. J. A. Hornbeck of the Bell Telephone Laboratories for this analysis.

[9] F. Ehrenkranz, Phys. Rev. **55**, 219 (1939).

[10] C. G. Miller and L. B. Loeb, J. Appl. Phys. **22**, 614 (1951) found that the exact breakdown potential in pure N_2 with negative wire coaxial geometry is difficult to determine.

[11] Ehrenkranz (reference 9) observed that for N_2 containing Hg and NO, V_s is lowered by 7 to 13 percent below V_s for pure N_2. Although Ehrenkranz employed an i_0, she gives no data for the variation of V_s with i_0.

[12] H. J. White, Phys. Rev. **48**, 113 (1935).

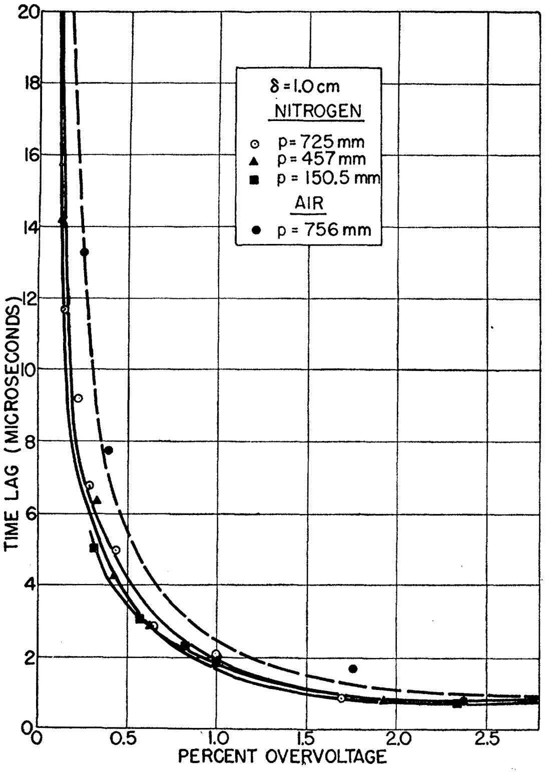

FIG. 2. Measured formative time lags *vs* percent overvoltage for N_2 and air at an electrode separation of one centimeter.

time lags at a given percent o.v. increase with increasing electrode separation.

Neither changing i_0 from 20 to 200 ϵ/μsec nor changing V_0 from 2 to 4 kv below V_s has any effect on the time lags in N_2. These statements are based on studies made primarily for an electrode separation of one centimeter at atmospheric pressure, although some measurements with varying i_0 and pulse voltage were made at other pressures and electrode separations.

To study the distribution of time lags for N_2, 50 observations were made at one overvoltage in the neighborhood of 0.2 percent for $\delta = 1$ cm and $p = 730$ mm. The results are shown as an ordinary distribution curve in Fig. 4 and as a Laue plot in Fig. 5. From the latter figure, it is seen that the time lag distribution is not statistical since the results plotted as described earlier do not form a straight line. Moreover, 80 percent of the time lag fluctuations may be accounted for by a voltage fluctuation of less than 5 v; the maximum fluctuation in the 50 observations may be ascribed to an error of about 10 v. Since an occasional error of 10 v out of 30 kv is not unreasonable, the entire distribution of time lags obtained in N_2 is attributed to voltage fluctuations. As was the case in air, the time lag distribution in N_2 at a given pressure and electrode separation broadens with decreasing percent o.v.; this broadening of the distribution with decreasing percent o.v. is associated with the steep slope of the time lag curves at low overvoltages. This discussion justifies the use of average values of the time lags in this gas as the significant values.

FB state that for air: "A part but not all of the fluctuations (in time lags) are due to the electronic errors. The other part of the fluctuation is probably inherent in the statistical nature of the spark." With the improved voltage regulation in the present experiment it was possible to investigate this conjecture. The distribution of time lags in air at $p = 757$ mm and $\delta = 1$ cm was studied by taking 100 observations at 0.285 percent o.v. The distribution obtained (shown in Figs. 4 and 5) is similar to that of N_2. Since the variation of time lags with percent o.v. is essentially the same for air and N_2, the time lag distribution in air may also be attributed to voltage fluctuations. Thus the conjecture of FB seems incorrect. Gänger[13] has observed statistical distributions of time lags of spark breakdown in air; however, the time lags measured were of the order of 5×10^{-8} sec and the illumination was inadequate for the prevention of statistical lags.

Formative time lags in pure N_2 are troublesome to measure. Figure 1 shows that V_s in pure N_2 with no i_0 is at least 12 percent higher than when i_0 is large enough to avoid statistical lags. In most cases it was found that in order to obtain time lags in pure N_2 that are shorter than 100 μsec (the maximum time measurable with the

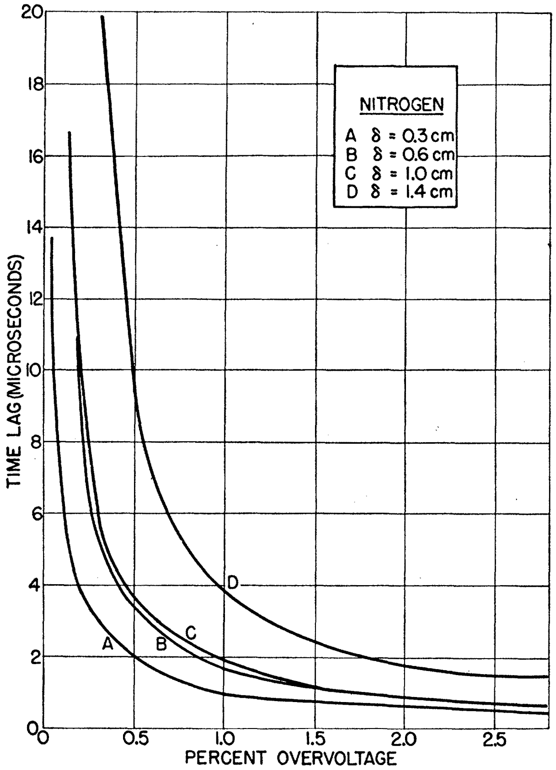

FIG. 3. Measured formative time lags *vs* percent overvoltage for N_2 at various electrode separations.

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[13] B. Gänger, Arch. Elektrotech. **39**, 508 (1949).

equipment used), a total voltage must be applied across the gap which is greater than the sparking potential obtained with no cathode illumination. V_0 must therefore be set below the sparking potential obtained with i_0, and to avoid possible effects of space charge distortion, it should be possible to set V_0 at least 2 kv below the lower sparking potential. Therefore, in order to make a complete study of the formative time lags in pure N_2, a pulse of about 10 kv is required. Because of this difficulty and because the results obtained would be valid only for a specific ultraviolet intensity, no detailed study of the formative time lags in pure N_2 was undertaken. However, to obtain some information about the time lags, measurements were made at one pressure (730 mm) for three values of δ, and the data are given in Fig. 6. The data to the right of the zero percent o.v. abscissa were taken with an i_0 of about 100 ϵ/μsec; the data to the left of zero percent were taken with no ultraviolet illumination. The points shown are averages except those with arrows; arrows on points indicate that at least one reading was obtained at the time plotted, but that other sparks occurred at the same percent o.v. with lags longer than 100 μsec. However, at some plotted points (with arrows) to the left of zero percent failures also occurred. The curves obtained are similar to those for N_2 providing the sparking potential with no i_0 is used as the static breakdown value; it is also clear that further study of pure N_2 will be very rewarding.

IV. DISCUSSION OF RESULTS

As was the case in air, the observed time lags in N_2 cannot be explained by secondary electron emission at the cathode by positive ion bombardment of the cathode. This mechanism leads to time lag *vs* percent o.v. curves lying way above the observed curves. The principal difficulty with fitting the data to such a mechanism is the low velocity of the positive ion. For example, the positive ion process requires time lags of microseconds at very high overvoltage whereas the experimental data yield time lags of the order of a microsecond at only a few percent o.v. As will be seen, the fit is no better for the data at overvoltages below a few percent.

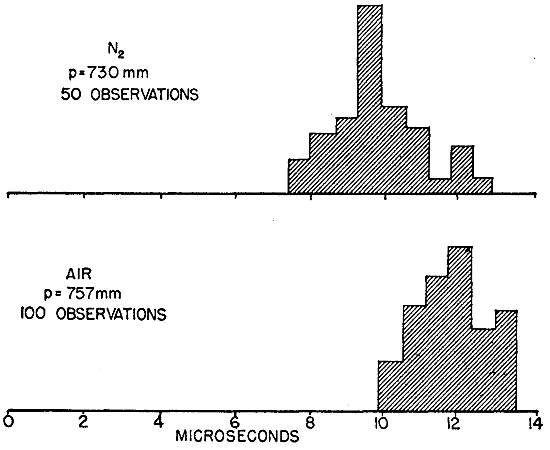

FIG. 4. Distribution of time lags at 0.2 percent overvoltage in N_2 and at 0.285 percent overvoltage in air.

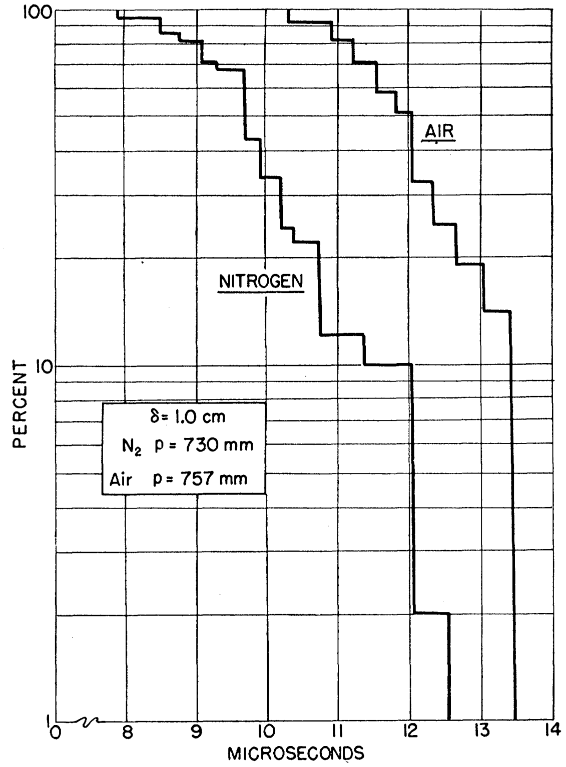

FIG. 5. Laue plots of data in Fig. 4.

The only remaining acceptable mechanisms for the production of secondary electrons are photoionization in the gas and photoemission of electrons from the cathode. The streamer theory considers that breakdown results from a single electron crossing either the entire gap or a fraction of the gap with photo-ionization in the gas close to the avalanche head as a secondary mechanism; the time required for a discharge to form on this basis is of the order of an electron transit time or less. Hence a streamer-like mechanism alone does not account for the long time lags observed at overvoltages below a few percent. Moreover, using either Masch's[5] or Posin's[14] values of α in N_2, the amplification factor $e^{\alpha\delta}$ was calculated at threshold as determined in this experiment; the average value of $e^{\alpha\delta}$ for all pressures and electrode separations studied is about 1000, a value much too low to give rise to a streamer as the result of a single avalanche. This small amplification factor at threshold indicates the unimportance of positive ion space charge distortion during all but the very latest phases of the build up.

In air, using FB's values of V_s and values of α as given by Sanders,[15] the amplification factor is calculated to be about 6×10^4 at atmospheric pressure for a gap

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[14] D. Q. Posin, Phys. Rev. **50**, 650 (1936).

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

of one centimeter; at lower pressures the factor is less by an order of magnitude. These amplification factors at threshold are still too small to give rise to a streamer as the result of a single avalanche.[16]

Hence we consider as valid secondary mechanisms photoemission of electrons from the cathode or from the gas near the cathode. These secondary mechanisms permit the space charge to build up to a critical value by successive electron avalanches, each avalanche starting at or near the cathode at about the same time that the preceding one reaches the anode. This means that for the longest lags observed perhaps one thousand or more successive avalanche crossings of the gap occur before breakdown. It is assumed that space charge distortion may be neglected until a critical space charge is built up in the gap; at this time breakdown may be completed by a streamer-like mechanism in an interval short compared to the build up time. For the purpose of calculation we consider the emission of electrons from the cathode only; essentially the same results would be obtained for photo-ionization in the gas near the cathode.

It may be assumed without appreciable error that all photons are created very near the anode and that the time for a photon to cross the gap is negligible.[17] Let γ be the number of electrons produced at the cathode photoelectrically per electron created in the gas (assumed constant). Then a single electron starting at the cathode at time zero gives rise to $\gamma(e^{\alpha\delta}-1)$ photoelectrons from the cathode at time t_e, the electron transit time, $\gamma^2(e^{\alpha\delta}-1)^2$ photoelectrons at time $2t_e$, and $\gamma^n(e^{\alpha\delta}-1)^n$ photoelectrons at time nt_e where n is the number of electron crossings. Assume that a spark occurs when the number of electrons liberated from the cathode as the result of a single electron being emitted at an earlier time reaches the value N. The calculated time lags are not very sensitive to the value of N chosen. It is to be expected that due to variations in diffusion, geometry and absorption of radiation the value of N for breakdown will be somewhat different at various pressures and electrode separations. In the calculations to follow, electrons liberated from the cathode by an external source at times later than zero are not taken into account. Experimental results showing the independence of the time lags on i_0 indicate that the procedure adopted is justified. Even if these succeeding primary electrons are taken into account, the calculated time lags are hardly affected but are modulated by a slowly varying logarithmic term as Schade[17] has shown.

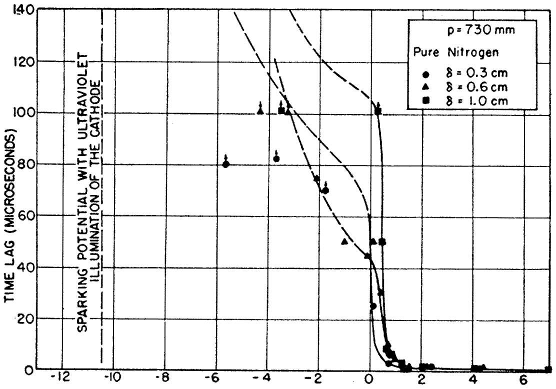

FIG. 6. Measured formative time lags *vs* percent overvoltage for pure N_2.

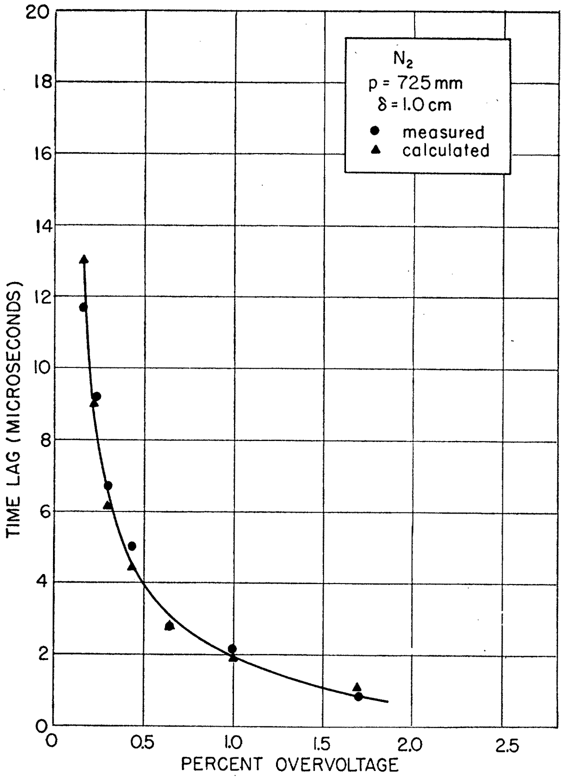

FIG. 7. Calculated and measured time lags *vs* percent overvoltage in N_2.

Then for a spark to occur after n electron transits the following condition must be satisfied

$$\gamma^n(e^{\alpha\delta}-1)^n=N. \tag{2}$$

Threshold is set by

$$\gamma(e^{\alpha_s\delta}-1)=1, \tag{3}$$

where α_s is the value of α at threshold. Since $e^{\alpha_s\delta}$ is of the order of 1000, Eqs. (2) and (3) may be written as

$$\gamma^n e^{\alpha\delta n}=N, \tag{4}$$

and

$$\gamma e^{\alpha_s\delta}=1. \tag{5}$$

Combining Eqs. (4) and (5) gives

$$e^{n\delta\Delta\alpha}=N, \tag{6}$$

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[16] See also the low values of the constant K in Meek's equation obtained by L. H. Fisher, Phys. Rev. **72**, 423 (1947).

[17] R. Schade, Z. Physik **104**, 487 (1937) has calculated time lags assuming positive ion bombardment of the cathode neglecting electron transit times.

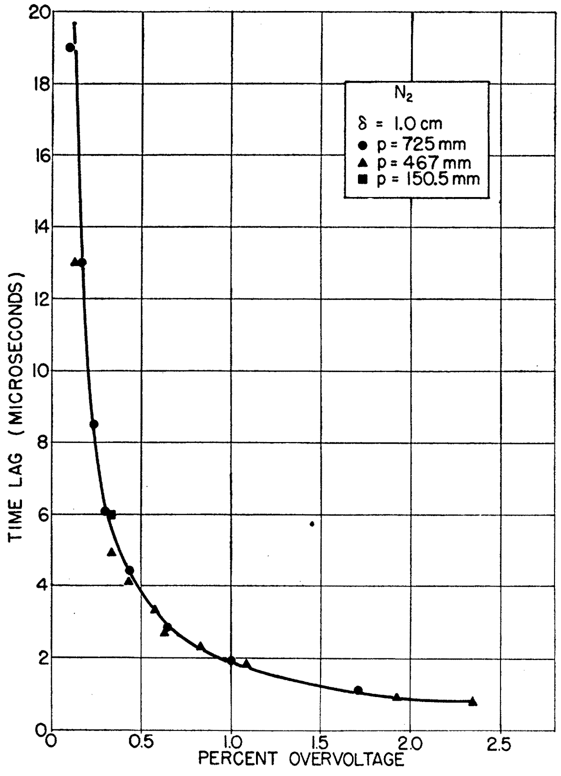

FIG. 8. Calculated time lags *vs* percent overvoltage showing pressure independence of time lags.

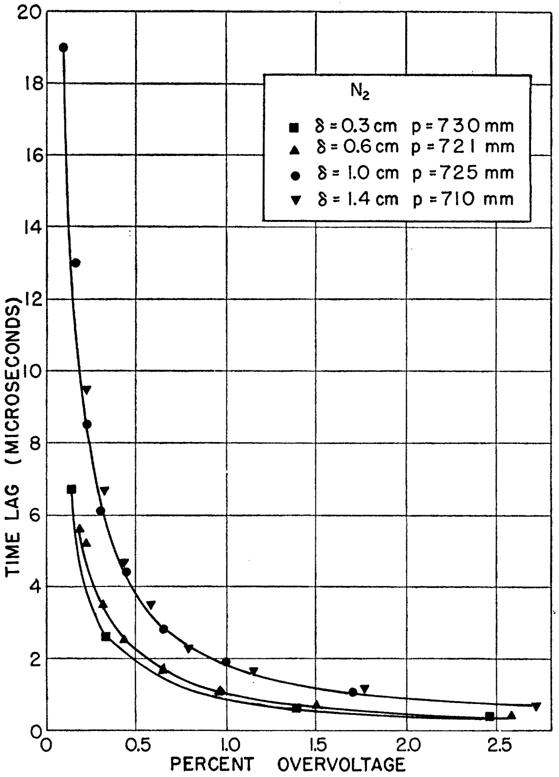

FIG. 9. Calculated time lags *vs* percentage overvoltage for various electrode separations near atmospheric pressure.

where $\Delta\alpha = \alpha - \alpha_s$. Since $n\delta = v\tau$, where τ is the time lag and v is the electron velocity, Eq. (6) may be written

$$\tau = (\log N)/v\Delta\alpha. \qquad (7)$$

Equation (7) was used to calculate formative time lags in N_2. Masch's[5] values of α were used and Nielsen's[18] measurements of electron mobility in N_2 were extrapolated. The value $N = 10^5$ was chosen to fit the observed time lag at one overvoltage at atmospheric pressure and at an electrode separation of one centimeter. The results are illustrated in Fig. 7. where measured and calculated time lag data are given for $\delta = 1$ cm and $p = 725$ mm. Of fourteen curves calculated (using $N = 10^5$) for comparison with the data at various pressures and electrode separations, seven gave fits as good as the one shown in Fig. 7; the remaining seven yielded curves parallel to the measured ones but displaced on the average some 70 percent. In addition, the calculations yielded time lags which are independent of pressure as illustrated in Fig. 8 where calculated time lags are plotted for three pressures for $\delta = 1$ cm. Figure 9 shows calculations of time lags near atmospheric pressure for four electrode separations. Using Posin's[14] values of α, one does not obtain quite as good agreement especially as regards the pressure independence of the time lags. On the whole, the data must be considered well represented by Eq. (7). In view of the crudeness of the assumptions made, the agreement is even better than might be expected. It therefore seems reasonable to assume from these calculations that the secondary mechanism active in the spark breakdown of N_2 (and pure N_2) for the range of variables studied is photoemission at the cathode or photo-ionization in the gas near the cathode. The cathode photoelectric effect has some advantages over the gas ionization mechanism since the former requires photons only one-quarter as energetic as those required in the latter process.

Entirely analogous computations show that the results of FB in air are also described satisfactorily by Eq. (7). For these computations, electron velocity measurements of Nielsen and Bradbury[19] were extrapolated, and N was again chosen to fit one measurement.

One notices from Eq. (7) that for positive ion bombardment of the cathode the time lags would be longer by the ratio of the electron to the positive ion velocity. Thus time lags calculated on the positive ion mechanism are some two hundred times greater than those observed.

We are indebted to Dr. M. Menes for a number of stimulating discussions; we also thank Professor L. B. Loeb of the University of California for continued interest and for the extended loan of the discharge chamber.

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[18] R. A. Nielsen, Phys. Rev. **50**, 950 (1936).

[19] R. A. Nielsen and N. E. Bradbury, Phys. Rev. **51**, 69 (1937).