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New York University  
Department of Physics  
University Heights  
New York 53, N. Y.

March 12, 1963

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AS AD NO. \_\_\_\_\_

Chief of Naval Research  
Electronics Branch (Code 427)  
Department of the Navy  
Washington 25, D. C.

Dear Sir:

Attached is the Final Report on the Office of Naval Research Contract NONR 285 (34), NR 372-141, entitled, "Determination of Formative Time Lags in Air in a Uniform Field as a Function of Pressure and Electrode Separation and Determination of Formative Time Lags of the Vacuum Spark". This project was under the directorship of Professor Leon H. Fisher until June 1961, and under the directorship of Associate Professor Lawrence A. Bornstein until its conclusion on December 31, 1962.

Part I of this report describes the work done from November 1, 1962 through December 31, 1962. Part II is a summary report for the entire project since its inception.

Very truly yours,

*Lawrence A. Bornstein*

Lawrence A. Bornstein  
Associate Professor of Physics

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In our last report we gave the results of our computations of the transit times of positive ions across positive-point-to-plane corona gaps. These computed ion transit times are so long as to rule out the possibility that ions arriving at the cathode play a significant role in the formation of a self-sustained corona discharge in argon or hydrogen. Our earlier measurements of the formative time lags in these gases at threshold showed lags much shorter than ion transit times.

We have now computed electron transit times for the geometries used in the various gases studied. Because of the highly nonuniform nature of the field in the corona geometry, the electrons traverse the high-field region in a small fraction of the electron transit time for the whole gap. A typical set of computed results are the following:

At 700 mm Hg pressure, with a positive paraboloidal point of radius 0.0091 cm, and a point-to-plane separation of 1.5 cm, the electron transit times in microseconds are

<u>gas</u>	<u>total gap transit</u>	<u>transit of high-field region</u>
hydrogen	2.7	0.003
argon	6.7	0.008
oxygen	0.66	0.001
nitrogen	1.3	0.002

In computing these values, we used the confocal-paraboloids approximation for determining field strengths in the gap, and numerical integration to get the transit times across the various portions of the gaps. The high-field region is taken to mean that region in which electrons have enough energy to ionize the gas.

The formative time lags at threshold in these gases under the above conditions have been measured at (approximately):

<u>gas</u>	<u>formative lag, microseconds</u>
hydrogen	0.01 or less
argon	0.1 or less
oxygen	500
nitrogen	10 <sup>6</sup>

We conclude that in hydrogen and argon, it is not possible to have a discharge formation mechanism in which electrons interact significantly with the anode. It takes too long for photoelectrons emitted at the cathode to reach the high-field region near the anode. On the other hand, the time spent by electrons in the high-field region is short enough in these two gases to be consistent with very short time lags. It would be interesting to know just how short the lags in hydrogen and argon really are; the experimental values given above were the best that could be made with the instruments available at the time.

The long experimental formative times in oxygen and nitrogen do not preclude the possibility of positive ion or of electron action at the electrodes in the development of a secondary mechanism. Indeed, for nitrogen one may even imagine metastable molecules diffusing across the gap in ample time to be the required agent.

Part II

Resume of Principal Lines of Investigation

A. Formative Time Lags in Uniform Fields

Formative time lags of spark breakdown in uniform fields have been measured in air, nitrogen, argon, hydrogen, and oxygen at pressures from one atmosphere down to about 100 mm Hg, and with plane parallel electrode separations of 0.3 to 3.0 cm. The measurements were carried out at voltages very near threshold. For all gases, the time lags decrease as the percentage overvoltage (O.V.) increases. For air, nitrogen, and hydrogen, the variation of time lags with percentage O.V. is independent of pressure; argon and oxygen lags exhibit a complicated pressure dependence. The lags for all gases are independent of the initiating photoelectron current over a wide range. At low O.V., the lags are in the range of tens to hundreds of microseconds, being longest, of all gases studied, in argon and oxygen.

These results show that, at low O.V., breakdown is preceded by a Townsend discharge for all gases studied. At high O.V. the breakdown time is small compared to a Townsend buildup. A Townsend buildup is important in air, nitrogen, and hydrogen at O.V. of one or two per cent, while in argon such buildup is important up to 100 per cent O.V.

From our observations on the dependence of formative lags on pressure, electrode separation, and O.V., we have been able to elucidate the nature of the prebreakdown discharge. In air, nitrogen, and hydrogen, this discharge has been identified as one involving photoelectric emission from the cathode by photons created in the gas in conjunction with electron avalanches. This model gives a good quantitative fit to the data in these

three gases. The relatively long buildup times are attributed to large numbers of successive transits of electrons across the gap before breakdown. In argon, in addition to photoelectric emission from the cathode, the lag is prolonged by a delay in the transmission of radiation through the gas. This delay, estimated as 10 times the electron transit time, may result from either imprisonment of resonance radiation or the time required for the deexcitation of metastable atoms. In oxygen, negative ion formation is instrumental in the delay of breakdown. Of all the gases studied, only oxygen gives a Laue-distribution of lags for successive lags measurements at the same pressure, electrode separation, and O.V.

B. Measurements of Townsend Ionization Coefficients and of the Attachment Coefficient of Oxygen.

Precision measurements of sparking voltages and of current-voltage characteristics in uniform fields of hydrogen, nitrogen, oxygen, argon, and helium have led to determination of the first and second Townsend coefficients,  $\alpha$  and  $\gamma$ , of these gases. The ranges of the ratio of field strength  $E$  to pressure  $p$ , in volts (cm mm Hg)<sup>-1</sup>, over which measurements were made, and the approximate values of the coefficients of the gases in these ranges, are given in Table 5.  $\eta$  is the attachment coefficient of oxygen.

Table 5

<u>Gas</u>	<u>E/p</u>	<u><math>\alpha/p</math></u>	<u><math>\gamma</math></u>	<u><math>\eta/p</math></u>
hydrogen	14 to 22	$10^{-4}$ to $10^{-2}$	$10^{-3}$	-
nitrogen	30 to 45	$10^{-3}$ to $2 \times 10^{-2}$	$10^{-3}$	-
oxygen	46 to 100	$2 \times 10^{-2}$ to 0.3	$10^{-6}$ to $10^{-5}$	0.05 to 0.07
argon	5 to 12	$10^{-5}$ to $10^{-2}$	10 to $10^{-2}$	-
helium	3 to 70	$10^{-2}$ to $5 \times 10^{-2}$	$6 \times 10^{-3}$ to $10^{-1}$	-

The values of  $\gamma$  are, by and large, bigger than expected, while for argon and helium they are huge. These measurements have emphasized the importance of the Townsend buildup in presparking phenomena.

### C. Corona Studies

Formative time lags of the filamentary streamer in positive point-to-plane corona in air over a pressure range comparable to the uniform-field pressure range show no long buildup times such as is found in the uniform field case. Near atmospheric pressure, the lags are too short to be resolved from statistical scatter, but with decreasing pressure the formative lags are resolvable. They are of the order of  $10^{-7}$  second at threshold and show little dependence on O.V. No long buildup process is associated with the formation of the positive point corona in air, and the cathode plays no role in this formation. The corona formative lags in air are too long to be ascribed to the transit time of the initiating avalanche across the high field region of the gap. The corona results in air do not, therefore, preclude a fast secondary process in the gas preceding formation of the filamentary streamer.

In four pure gases studied, the corona formative lags at threshold show a wide range of values. Typical are the following, for a 1.5 cm gap, with a paraboloidal point of radius 0.009 cm, and with the gas at 700 mm Hg:

<u>Gas</u>	<u>Approximate Formative Lag, microseconds</u>
hydrogen	0.01 or less
argon	0.1 or less
oxygen	500
nitrogen	$10^6$ to $10^8$

The lags in hydrogen and argon are much less than the transit times across the gap of either ions or electrons, requiring a secondary mechanism that does not involve the cathode. The long lags in oxygen are probably associated with electron attachment in that gas, while the extraordinary behavior of nitrogen allows for a number of slow processes, perhaps even diffusion of metastables.

Current-voltage characteristics of the prebreakdown discharge in the hydrogen positive point corona indicate the importance of secondary ionization. A second Townsend coefficient  $\gamma$  of  $4 \times 10^{-4}$ , computed from these measurements, is typical and of the same order as that found for hydrogen in the uniform-field work discussed above. For nitrogen, a  $\gamma$  of the order of  $10^{-5}$  is found in this geometry, while for argon  $\gamma$  ranges from about  $3 \times 10^{-3}$  at 300 mm Hg to  $2 \times 10^{-5}$  at 700 mm Hg. These are significantly smaller than the values of  $\gamma$  found for these gases in parallel plate geometry, but consistent with  $\gamma$ 's found by other workers in concentric-cylinders corona gaps.

#### D. Glow Discharge Studies.

Studies of the formative time lags of d.c. glow discharges in air, nitrogen, oxygen, and argon, and of Paschen's law in air, were carried out in glass chambers of two diameters with a very large range of electrode separations, from a few millimeters to 80 cm. As expected, the chamber walls play an important role in such discharges. The detailed behavior of the various gases was generally complicated and not uniform, but a number of observations common to all were made:

- 1) The time lags are several hundred microseconds at about one per cent O.V.
- 2) The lags decrease to a few microseconds at 20% to 40% O.V. (with electrode separations in the range of 4 cm to 10 cm).

- 3) For equal percentage O.V., the lags decrease with increasing ultraviolet illumination of the cathode.
- 4) For equal percentage O.V. and equal illumination, the lags in the narrower glass chamber are longer than those in the wider chamber.
- 5) Time lags increase with increasing gap separation. It is always possible, by using large O.V., to get lags shorter than the transit times of positive ions across the gap, indicating that positive ion action at the cathode is not the secondary mechanism leading to the spark at these overvoltages.

Measurements of sparking voltages in air at various pressures and over a wide range of electron separations revealed no severe departures from Paschen's law -- a rather surprising result in view of the expected accumulation of wall charge.

#### E. Vacuum Spark Studies.

This work was an investigation of the mechanism whereby sparks are initiated between metal electrodes in high vacua. Breakdown at voltages below 50 kilovolts in negative point-to-plane geometry and in crossed-wire geometry and at pressures between  $10^{-6}$  and  $5 \times 10^{-9}$  mm Hg. Electrodes of tungsten, platinum, and nickel-plated steel were used. Current-voltage characteristics and formative time lags were measured. Lags between 0.2 microsecond and 40 microseconds were observed.

Attempts at producing a system with a stable, reproducible breakdown voltage were unsuccessful. These attempts included the outgassing of electrodes, the use of current-limiting resistors in series with the gap, and operation of the gap at high temperature ( $1200^{\circ}\text{C}$ ). As a result of this failure, no clear-cut relation between time lags and percentage O.V. could be found. Comparison of the observed current-voltage characteristics with

the Fowler-Nordheim field emission equation showed that most of the current originated on areas of the cathode where the field was much higher (sometimes by as much as 400 times) than the average field over the cathode. These areas were presumably sites of projections above the cathode. The areas of emission were found to be between  $10^{-9}$  cm<sup>2</sup> and  $10^{-13}$  cm<sup>2</sup>. Extrapolation to breakdown of prebreakdown current-voltage measurements yielded field current densities of  $10^6$  to  $10^8$  amp/cm<sup>2</sup> at the emitting areas.

On the basis of the long formative lags measured and the high current densities computed, it was felt that the initiating mechanism in the vacuum spark is likely to be melting or vaporization of the projections at the cathode. On this model, the observed lag is the time needed for sufficient Joule heating of the emitting areas. It was shown that the lags to be expected on this basis would be universally proportional to the square of the field emission current density. Calculations made on this model of expected time lags were in rough agreement with the observed lags.

Table 1

Bibliography of Publications reporting work done on this contract:

Further Measurements of Formative Time Lags in Spark Breakdown at Low Overvoltages, L. H. Fisher and B. Bederson, Phys. Rev. 78, 331 (1950).

Interpretation of Formative Time Lags in Spark Breakdown in Air at Low Overvoltages, B. Bederson and L. H. Fisher, Phys. Rev. 78, 331 (1950).

Formative Time Lags of Spark Breakdown in Oxygen, G. A. Kachickas and L. H. Fisher, Phys. Rev. 79, 232 (1950).

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Sharpness of the Sparking Potential, G. A. Kachickas and L. H. Fisher, Phys. Rev. 82, 318 (1951).

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Positive Point-to-Plane Corona Studies in Air, M. Menes and L. H. Fisher, Phys. Rev. 84, 1075 (1951).

Formative Time Lags of Positive Point Corona in Air, M. Menes and L. H. Fisher, Phys. Rev. 86, 134 (1952).

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The First Townsend Ionization Coefficient for Hydrogen, D. R. Rose, D. J. DeBitetto, and L. H. Fisher, Nature 177, 945 (1956)

Townsend Ionization Coefficients and Uniform Field Breakdown in Hydrogen and Nitrogen at High Pressures, D. J. DeBitetto and L. H. Fisher, Phys. Rev. 104, 1213 (1956).

Experimental Evidence for the Existence of Secondary Ionization in Oxygen at High Pressures, D. J. DeBitetto and L. H. Fisher, Bulletin of the American Physical Society 2, 86 (1957).

Current and Time Studies of the Positive Point Corona in Hydrogen, L. A. Bornstein and L. H. Fisher, Bulletin of the American Physical Society 3, 87 (1958).

Pre-Sparking Phenomena in Gases in Uniform and Non-Uniform Fields, L. H. Fisher, Proceedings of the Third International Conference on Ionization in Gases, 322 (1957).

Second Townsend Coefficient in Oxygen at High Pressures, D. J. DeBitetto and L. H. Fisher, Phys. Rev. 111, 390 (1958).

Negative Current-Voltage Characteristics in Hydrogen at High Pressures Using Plane Parallel Electrodes, D. J. DeBitetto, L. H. Fisher, and A. L. Ward, Phys. Rev. 118, 920 (1960).

Anomalies in Ionization Coefficients and in Uniform Field Breakdown in Argon for Low Values of  $E/p$ , D. E. Golden and L. H. Fisher, Phys. Rev. 123, 1079 (1961).

Transient Breakdown Studies in Hydrogen at Low Values of  $E/p$ , I. Lessin, D. E. Golden, and L. H. Fisher, Phys. Rev. 124, 993 (1961).

Ionization, Attachment, and Breakdown Studies in Oxygen, J. B. Freely and L. H. Fisher, Bulletin of the American Physical Society 7, 634 (1962).

Table II

Invited Papers presented to discuss work done on this project:

Buildup Processes in Sparks and Positive Corona, L. H. Fisher, presented to the American Physical Society at Washington, D.C., April 1954.

Mechanism of the Electric Spark, L. H. Fisher, presented to the American Physical Society at Seattle, Washington, July 1954.

Time Studies of Corona Discharges, I. A. Bornstein, presented to the American Institution of Electrical Engineers at Montreal, Canada, June 1957.

Ionization Currents in Gases Below Breakdown, L. H. Fisher, presented to the American Physical Society at Los Angeles, California, December 1958.

Table III

Personnel whose work on this contract led to graduate degrees:

M.S. Lawrence A. Bornstein  
Kenneth Rubin  
Marvin Silver  
Robert Burt

Ph.D. Benjamin Federson  
George A. Kachickas  
Meier Menes  
Irving Lessin  
Alex Mayer  
Dominick J. DeBitetto  
Lawrence A. Bornstein  
Leonard Aronowitz  
David E. Golden  
John B. Freely

Table IV

Dissertations at New York University that describe as yet unpublished work done on this project:

Measurements of the Breakdown Potential of Air at Low Pressures with Large Electrode Separations, L. A. Bornstein, 1951 (M.S.)

Current and Time Studies of the Positive Point-to-Plane Corona in H<sub>2</sub>, N<sub>2</sub>, O<sub>2</sub>, and Argon, L. A. Bornstein, 1957 (Ph.D.)

Image Converter Tube for Spark Discharge Studies, K. Rubin, 1952 (M.S.)

Investigation of Shutter Action of the Kerr Effect in Colloids as a Possible Method for the Study of Transient Phenomena in Gaseous Discharges, M. Silver, 1951 (M.S.)

Table IV (Cont'd)

The Formative Time Lag of the Vacuum Spark, R. Burt, 1955 (M.S.)

Formative Time Lags of Glow Discharges in Air, Nitrogen, Oxygen, and Argon, A. Mayer, 1954 (Ph.D.)

Pre-Breakdown Field Emission Currents and Time Lags in Sparks between Metal Electrodes in High Vacuum. L. Aronowitz, 1957 (Ph.D.)

A Study of the Pre-Breakdown Currents in Oxygen and Helium, J. B. Freely, 1960 (Ph.D.)

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