UNCLASSIFIED

AD **430336**

DEFENSE DOCUMENTATION CENTER

FOR

SCIENTIFIC AND TECHNICAL INFORMATION

CAMERON STATION, ALEXANDRIA, VIRGINIA

UNCLASSIFIED

64-9

CALCULATIONS OF
ELECTRICAL BREAKDOWN IN GASES

A.L. Ward

10 January 1964

DDC

FEB 25 1964

HARRY DIAMOND LABORATORIES
FORMERLY: DIAMOND ORDNANCE FUZE LABORATORIES
ARMY MATERIEL COMMAND
WASHINGTON 25. D. C.

HARRY DIAMOND LABORATORIES

Milton S. Hochmuth
Lt. Col, Ord Corps
Commanding

B. M. Horton
Technical Director

MISSION

The mission of the Harry Diamond Laboratories is:

(1) To perform research and engineering on systems for detecting, locating, and evaluating targets; for accomplishing safing, arming, and munition control functions; and for providing initiation signals: these systems include, but are not limited to, radio and non-radio proximity fuzes, predictor-computer fuzes, electronic timers, electrically-initiated fuzes, and related items.

(2) To perform research and engineering in fluid amplification and fluid-actuated control systems.

(3) To perform research and engineering in instrumentation and measurement in support of the above.

(4) To perform research and engineering in order to achieve maximum immunity of systems to adverse influences, including counter-measures, nuclear radiation, battlefield conditions, and high-altitude and space environments.

(5) To perform research and engineering on materials, components, and subsystems in support of above.

(6) To conduct basic research in the physical sciences in support of the above.

(7) To provide consultative services to other Government agencies when requested.

(8) To carry out special projects lying within installation competence upon approval by the Director of Research and Development, Army Materiel Command.

(9) To maintain a high degree of competence in the application of the physical sciences to the solution of military problems.

CALCULATIONS OF ELECTRICAL BREAKDOWN IN GASES

A. L. Ward

1

CONTENTS

Illustrations

Figure

1. Geometry and symbolism of gas discharge gap, showing basic
    mechanisms.

2. Calculated voltage-current density static characteristics
    for argon; $p = 10$ torr, $d = 1$ cm. The parameter for each
    curve is J_O, the externally produced photocurrent density.

3. Calculated V-J static characteristic for methane: $p = 60$ torr
    $d = 1$ cm. The parameter for each curve is J_O.

4. Plot of the fractional lowering of the breakdown voltage, $\Delta V_B/$
    V_{BO}, as function of $J_O/\gamma p^2$ for argon and methane.

5. The variation of the ionization efficiency, η, as a function
    of the distance from the cathode for designated current den-
    sity values in argon at 10 torr.

6. Comparison of calculated and measured growth of current as a
    function of time in air. Percent overvoltage is shown for
    each calculated curve. Tau is the time constant for the de-
    layed photon mechanism.

7. Comparison of calculated and measured breakdown voltage as a
    function of breakdown times in air for applied voltages ris-
    ing linearly with time.

ABSTRACT

A brief review of the basic processes leading to electrical
breakdown in gases is given. Formulae are derived for calcula-
ting the breakdown voltages of tubes filled with noble or molecular
gases. An electronic computer program for calculating complete
voltage versus current-density static characteristics is outlined.
The calculated lowering of the breakdown voltage with increased
ultraviolet irradiation of the cathode illustrates the utility of
the time-independent computer program. The actual breakdown
transition is calculated using the Townsend model, as modified by
space charge, in a dynamic computer program. The agreement of the
calculations with published breakdown data is excellent, even for
the short breakdown times previously thought explainable only by
gas photoionization streamers.
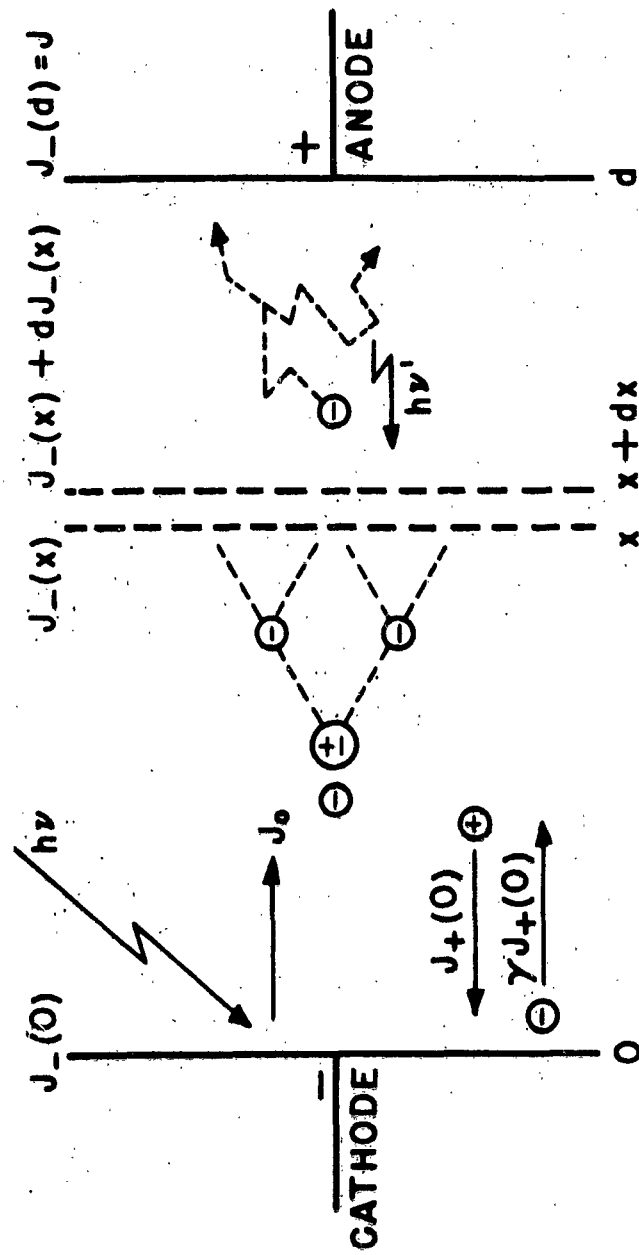
1. INTRODUCTION

The study of the passage of electricity through gases contribu-
ted importantly to the development of atomic theory. Atomic physics
has now yielded in popularity to nuclear physics, but many problems
in "gas discharges" are still unsolved. Important among these prob-
lems is the full understanding of the breakdown process. There has
recently been a rebirth of interest in "gaseous electronics," espec-
ially in the areas of plasmas, upper atmospheric studies, and gas-
eous lasers.

When the voltage applied across a gas between parallel elec-
trodes is slowly increased above a precise value, the gas suddenly
changes from an insulator to a conductor. The resulting collapse
of voltage across the tube is known as breakdown. For some decades
it has been possible to calculate very accurately the breakdown volt-
age as a function of the properties of the gas and the electrodes.
However, the breakdown transition itself is still a matter of active
controversy.

It is the purpose of this report to summarize some of the cal-
culations being made on an electronic computer in an effort to fully
understand electrical breakdown of gases.

2. BASIC PROCESSES

Let us consider a gas contained between parallel circular plates
whose separation is small compared with their diameter, so that we
may safely limit ourselves to a one-dimensional problem (fig. 1).
Although strong electric fields are incapable of ionizing atoms
(or molecules) directly, comparatively moderate fields can accelerate
electrons already present in the gas to sufficient energy to ionize
atoms by collisions. Electrons are always available due to radio-
active sources or cosmic rays. However, to insure that electrons are

CATHODE

ANODE

$J_-(0)$

$h\nu$

J_0

$J_+(0)$

$\gamma J_+(0)$

$J_-(x)$

$J_-(x) + dJ_-(x)$

$J_-(d) = J$

$h\nu'$

0   x   x+dx   d

PRIMARY IONIZATION

$dJ_-(x) = \alpha(x)J_-(x)dx$

$J_-(x) = J_-(0)\exp\int_0^x \alpha(x)dx$

$J_-(x) + J_+(x) = J_-(d) = J$

SECONDARY IONIZATION

$J_-(0) = J_0 + \gamma J_+(0)$

$J = \dfrac{J_0 \exp\int_0^d \alpha(x)dx}{1 - \gamma\left[\exp\left(\int_0^d \alpha(x)dx\right) - 1\right]}$

Figure 1. Geometry and symbolism of gas discharge gap, showing basic mechanisms.

available without unpredictable delays, ultraviolet light is usually directed upon the cathode to produce electrons by the photoelectric effect. This results in a photocurrent, J_o, as indicated in figure 1. These electrons will drift toward the anode in an applied electric field with a drift velocity proportional to the field. The drift velocity in the field is small compared with the thermal velocity of the electron, hence the path of an electron is a zig-zag one, crudely illustrated in figure 1. Due to the small mass of the electron, little of the energy gained from the applied field is lost in collisions with the heavy atoms. Hence, with a sufficient applied field, an electron gains enough energy to ionize, creating a new electron and a positive ion. The positive ion returns slowly to the cathode but the new electron will also be able to ionize, creating a chain reaction, known as a Townsend avalanche. However, gas ionization alone is insufficient (except at high overvoltages) to cause breakdown. Secondary ionization processes include the liberation of electrons from the cathode by positive ions, photons, and metastable (long-life excited) atoms. Since the numbers of photons and metastables created are proportional to the number of positive ions, we may (in the time-independent case) consider a single general secondary coefficient, γ, defined as the number of electrons produced at the cathode, from all causes, per incident positive ion. From these basic processes the electrical breakdown voltage may be calculated.

Townsend's primary ionization coefficient, α, is defined as the number of electrons liberated by an electron traveling 1 cm in the direction of the field. Then, since the electron current density, J_-, is proportional to the number of electrons crossing an area of 1 cm^2 per second

$$d[J_-(x)] = \alpha(x) \, J_-(x) \, dx \tag{1}$$

where x is the distance measured from the cathode. For fields not too close to the breakdown field, secondary effects may be neglected and α, a function of the field, E, is a constant, since the field is constant. Then

$$J_-(x) = J_o \exp \alpha x, \tag{2a}$$

$$J = J_-(d) = J_o \exp \alpha d, \tag{2b}$$

where d is the anode distance, and the electron current at the anode is equal to the total current, a constant. Then the positive ion current density, $J_+(x)$, is given by

$$J_+(x) = J - J_-(x) \tag{3}$$

Experimentally, it is found that if the field is kept constant by increasing the applied voltage in proportion to the gap distance,

a straight line is obtained when J is plotted logarithmically as a function of d, for d not too close to the sparking distance. This enables α to be measured experimentally. It is further found that α/p, where p is the gas pressure (usually measured in torr), is a function of E/p. Since the mean free path of the electron is inversely proportional to the pressure, E/p is a measure of the energy gained by the electrons between collisions.

Townsend found that the primary ionization coefficient may be expressed as a function of the field as

$$\alpha/p = A \exp (-Bp/E) \tag{4a}$$

where A and B are constants for each gas. Townsend derived this expression theoretically but erroneously. It does, however, fit the experimental data for most of the molecular gases over a wide range of E/p values. It has been further found empirically that the experimental data for the rare, or noble, gases closely fit the expression

$$\alpha/p = C \exp \{-D(p/E)^{1/2}\} \tag{4b}$$

where C and D are constants for each gas.

As the gap distance is increased further, keeping E constant, (2) is no longer obeyed as secondary processes become important. The electron current leaving the cathode now becomes

$$J_-(0) = J_o + \gamma J_+(0) \tag{5a}$$

also from (3)

$$J_-(0) = J_o + \gamma [J - J_-(0)] = J_o + \gamma J)/(1+\gamma) \tag{5b.}$$

Integrating (1) with the boundary condition (5b)

$$J = \frac{J_o \exp \alpha d}{1 - \gamma(\exp \alpha d - 1)} \tag{6}$$

This shows that the current increases at a rate greater than exponentially and tends to become unlimited and independent of J_o as the denominator of (6) approaches zero.

Using (4) to eliminate α and solving (6) for $V_o = Ed$, the voltage, neglecting space charge, as a function of current density is

$$V_o = \frac{Bpd}{\ln \{Apd/\ln u_o\}} \tag{7a}$$

8

for the molecular gases and

$$V_o = \frac{pdD^2}{(\ln\{Cpd/\ln u_o\})^2} \tag{7b}$$

for the noble gases, where

$$u_o = (1+\gamma)/[(J_o/J)+\gamma] \tag{7c}$$

Consideration of (7) shows that the voltage in the absence of space charge approaches a limit as J increases to the point where J_o/J can be neglected compared with the secondary coefficient, γ. This limit is known as the Townsend breakdown voltage, and is given by

$$V_{BO} = Bpd/\ln\{Apd/\ln(1+\gamma^{-1})\} \tag{8a}$$

for molecular gases and

$$V_{BO} = pdD^2/[\ln\{Cpd/\ln(1+\gamma^{-1})\}]^2 \tag{8b}$$

for the noble gases. Here the subscript indicates the breakdown voltage for no field distortion.

This criterion for the breakdown voltage is more informative and much more satisfactory than the usual statement that the breakdown criterion is given by equating the denominator of (6) to zero. The latter criterion is meaningful, however, in that it expresses the fact that each electron leaving the cathode produces, on the average, one replacement secondary electron at the cathode through the various ionization processes.

It will be noted from (8) that the breakdown voltage for a given gas is a function only of the pd product. This is known as Paschen's law. It may be further shown by differentiating (8) with respect to pd that V_{BO} attains a minimum value

$$V_{BO}(min) = B \ln (1+\gamma^{-1}) \ e/A \quad \text{(Mol gases)} \tag{9a}$$

$$V_{BO}(min) = D^2 \ln (1+\gamma^{-1}) \ e^2/4C \quad \text{(Rare gases)} \tag{9b}$$

at pd values of

$$(pd)min = \ln (1+\gamma^{-1}) \ e/A \quad \text{(Mol gases)} \tag{10a}$$

$$(pd)min = \ln (1+\gamma^{-1}) \ e^2/C \quad \text{(Rare gases)} \tag{10b}$$

9

It may be further noted that for high values of pd, the voltage becomes nearly proportional to pd, since the logarithmic term in the denominator is relatively constant.

Values of α and γ, experimentally determined to give the best fit to (6), used in (8) give accurate values of breakdown voltage over a wide range of pd values for all gases in which careful tests have been made.

The derivation of (7) considered α as a constant, which is no longer even approximately true as the current density increases without limit, due to the distortion of the field by space charge. When αd is replaced by $\int_0^d \alpha dx$, the problem of determining J as a function of the applied voltage can no longer be solved analytically. However, modern electronic computers can solve the problem to sufficient accuracy. The next section outlines such a program developed at HDL.

3.   STATIC COMPUTER PROGRAM

Although it had been recognized for decades that the field distortion from positive-ion space charge accumulation near the cathode plays some role in breakdown, mathematical complexity prevented a quantitative study of that role. Some qualitative understanding was obtained by making various approximations, but quantitative predictions were sometimes not verified by experiments. These disagreements had cast some doubts on the space charge mechanism.

In order to include the effect of space charge in the Townsend model for breakdown, Poisson's equation

$$dE/dx = e[n_+(x) - n_-(x)]/\epsilon_o \qquad (11)$$

is used, where e is the elementary charge, ϵ_o is the permittivity of free space, and n_+ and n_- are the charge densities of ions and electrons, respectively. The charge densities are related to the respective current densities by the relations

$$J_\pm = n_\pm e \mu_\pm E \qquad (12)$$

where $\mu_\pm$ are the particle mobilities, which are sometimes considered to be constant and sometimes, more properly, functions of the field. Equations (11) and (12) are combined as

$$\frac{dE}{dx} = \frac{1}{\epsilon_o \mu_+ E(x)} \left[J - \left(1 + \frac{\mu_+}{\mu_-} \right) J_-(x) \right] \qquad (13)$$

10

Equation (1), using (4), gives a second first-order nonlinear differential equation with the two variables, $J_-(x)$ and $E(x)$. This equation and (13) are solved by use of the Runge-Kutta method, a sophisticated numerical procedure, and a digital computer.

Two boundary conditions are required for the solution of the two equations. The current density is known at both boundaries: (5b) giving that at the cathode while that at the anode is the total current density of interest. Unfortunately, the field is unknown at both electrodes. Consequently, a value of the field at one electrode is assumed and the current then obtained at the other electrode is checked with the desired boundary condition. From this result, a more accurate value of the boundary field is assumed. This iterative process is continued until the desired accuracy is attained. The initial field guess for the lowest current density is obtained from (7), but for subsequent higher current densities, the use of the last previous correct boundary field saves iterations.

The voltage across the gap is then found by integrating the field across the gap. The entire voltage current density static characteristic is then obtained point by point. The computer print-out also includes the distribution of the field, voltage, and charge densities across the gap.

The results of the computer program went beyond the highest expectations. Not only was the breakdown transition region accurately calculated, but the calculations have proved to be the most accurate yet made of the cathode fall region in the glow discharge, going well into the high-current density abnormal-glow region at low pressures.

A few typical results of the calculations are presented. One of the key tests of any breakdown theory is the prediction of the effect that varying the externally produced photocurrent, J_o, has upon the breakdown voltage. One rare gas, argon, and one molecular gas, methane, are chosen to illustrate the calculated lowering of the breakdown voltage by increasing J_o. The results for argon, assuming $\gamma = 0.02$, are shown in figure 2, while those for methane, assuming $\gamma = 1 \times 10^{-8}$, are shown in figure 3. The much greater lowering of the breakdown voltage in methane has been observed experimentally and is largely due to the low γ value. This may be understood by considering (7) where it is seen that J_o is important when J_o/J cannot be neglected compared with γ. Since the J/p^2 value at which space charge becomes important is roughly the same in all gases, this means the breakdown voltage is lowered more in gases with small γ values. The lowering of the breakdown voltage is plotted as a function of $J_o/\gamma p^2$ on a log-log plot for the two gases in figure 4. It is seen that the lowering of the breakdown voltage is about the same magnitude for the two gases, whereas there is a disagreement of orders of magnitude for a plot against J_o (instead of $J_o/\gamma p^2$). It may be further noted that the lowering of the breakdown voltage is proportional to the 2/3 power of J_o for small
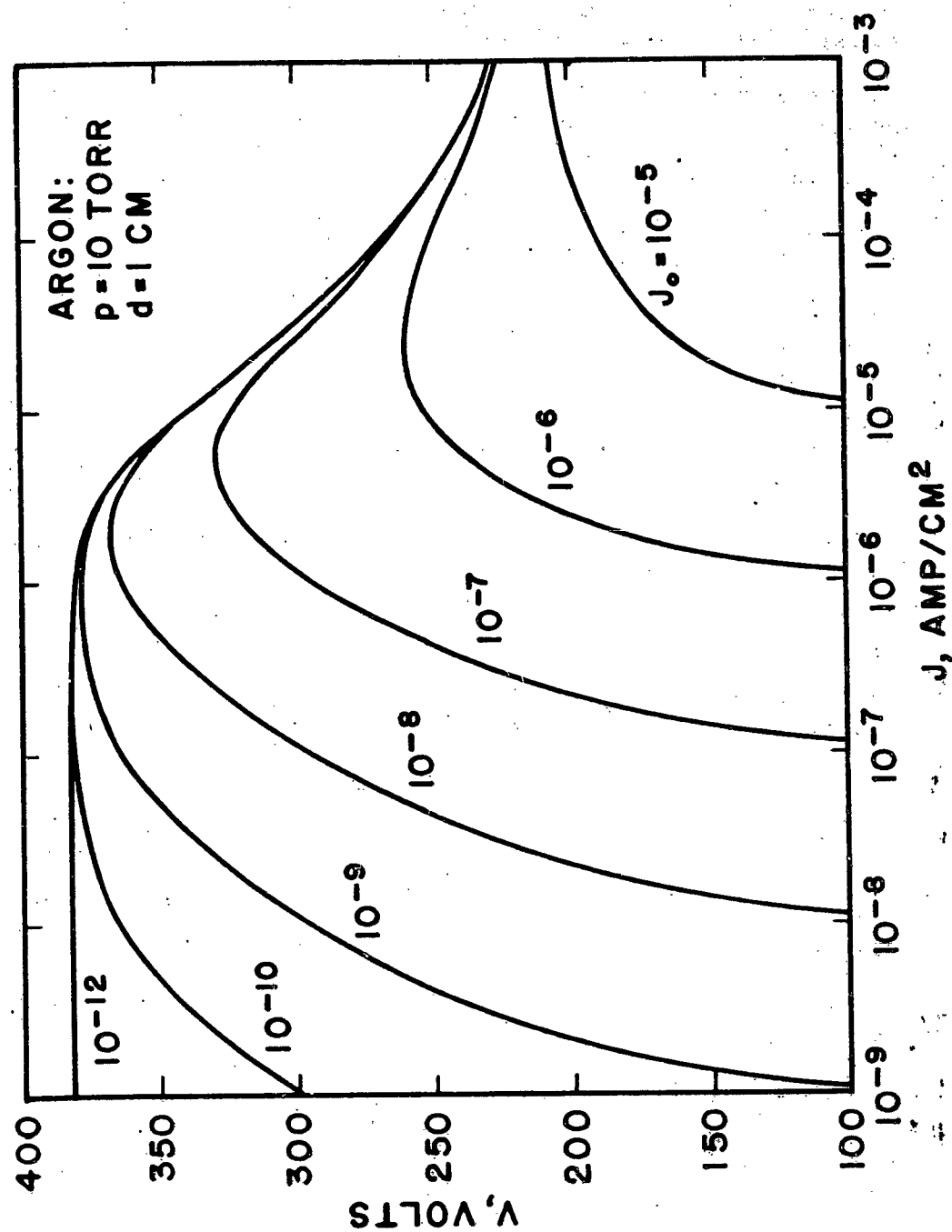
Figure 2. Calculated voltage-current density static characteristics for argon; p = 10 torr, d = 1 cm. The parameter for each curve is J_o, the externally produced photocurrent density.
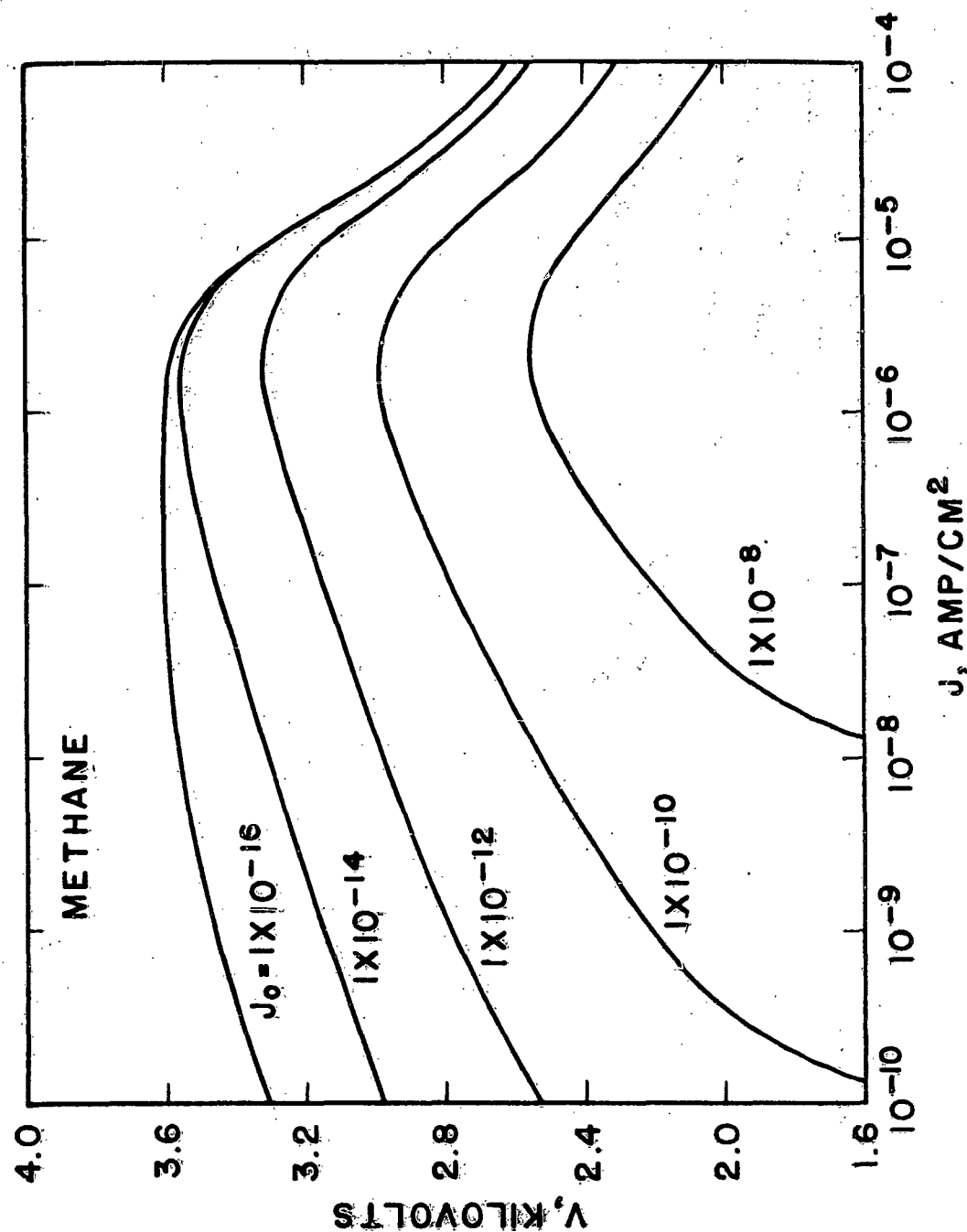
Figure 3. Calculated V-J static characteristic for methane: $p = 60$ torr
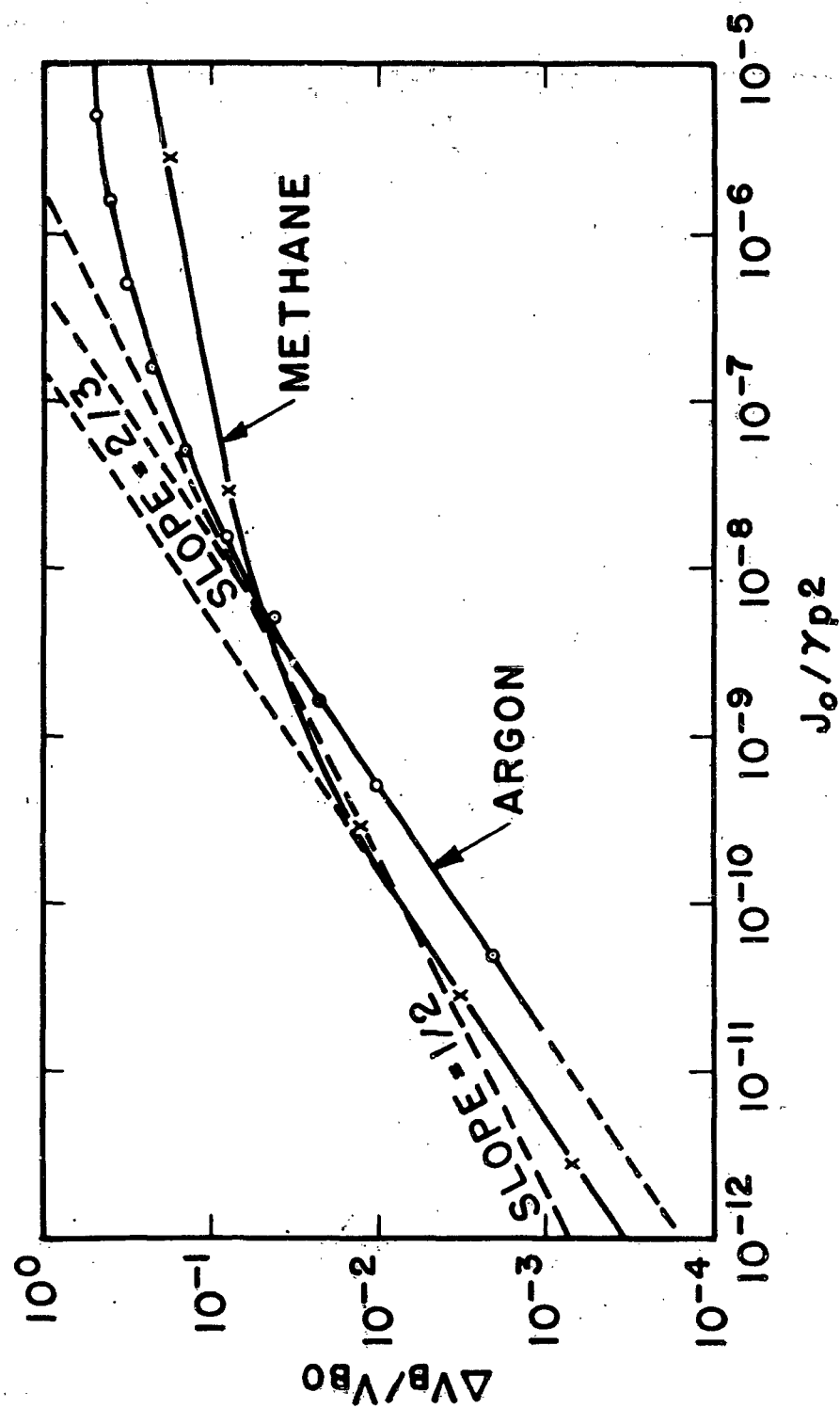$d = 1$ cm. The parameter for each curve is J_o.

13

Figure 4. Plot of the fractional lowering of the breakdown voltage, $\Delta V_B/V_{BO}$, as a function of $J_o/\gamma p^2$ for argon and methane.

14

$J_o/\gamma p^2$ values but proportional to the 1/2 power for higher values of $J_o/\gamma p^2$. These two individual variations had been predicted previously by separate conflicting approximations; the computer results show that there is a transition between regions where each is valid. Experimental results have supported this transition.

The lowering of the voltage needed to maintain discharges at higher currents results in an effective negative resistance. This negative resistance leads to relaxation oscillations in gas tube circuits. The lowering of the maintaining voltage may be understood in terms of the ionization efficiency, η, defined as the number of ionizations per volt and given by $\eta = \alpha/E$. η has a maximum when plotted as a function of E/p. This maximum corresponds to the minimum breakdown voltage of the Paschen curve. Consequently, when the pd product is greater than its value for the minimum breakdown, η is less than its maximum value. The field near the cathode is increased due to accumulation of the slow-moving positive ions, and thus the ionization efficiency is increased, while both E and η decrease near the anode. If the gas is in the pd region where α increases faster than linearly with E, then the increase of η near the cathode is greater than its decrease near the anode. Thus the average efficiency of ionization across the gap increases, requiring less voltage to maintain a higher current density. This behavior is illustrated in figure 5 for argon.

One of the chief difficulties is comparing experimental data with the calculated results is that the experimenter measures the total current while only the current density can be calculated. As long as the discharge area remains constant, this does not present a serious problem. However, it is easily seen that the negative slope of the static characteristic leads to a contraction of the discharge. Consider two adjacent areas of discharge, one with a higher than average current density, the other with a lower than average current density. Since the metal electrodes force the same voltage drop across the gap in each area, the former area is above the static characteristic as a result of its higher current density and the latter below the static characteristic owing to its lower current. Consequently the current density increases still more in the region of higher current density and decreases in the area of lower current density. This unstable condition causes a contraction of the discharge until the current density attains the normal current density of the glow discharge, i.e., the differential resistance becomes positive. The initial unequal current densities are caused by diffusion to the edges at low pressures and result from the statistics of single avalanches at high pressures. Also, since the negative resistance increases with increasing pressure, the contraction of the discharge is more pronounced and rapid at higher pressures while it is gradual at lower pressures.
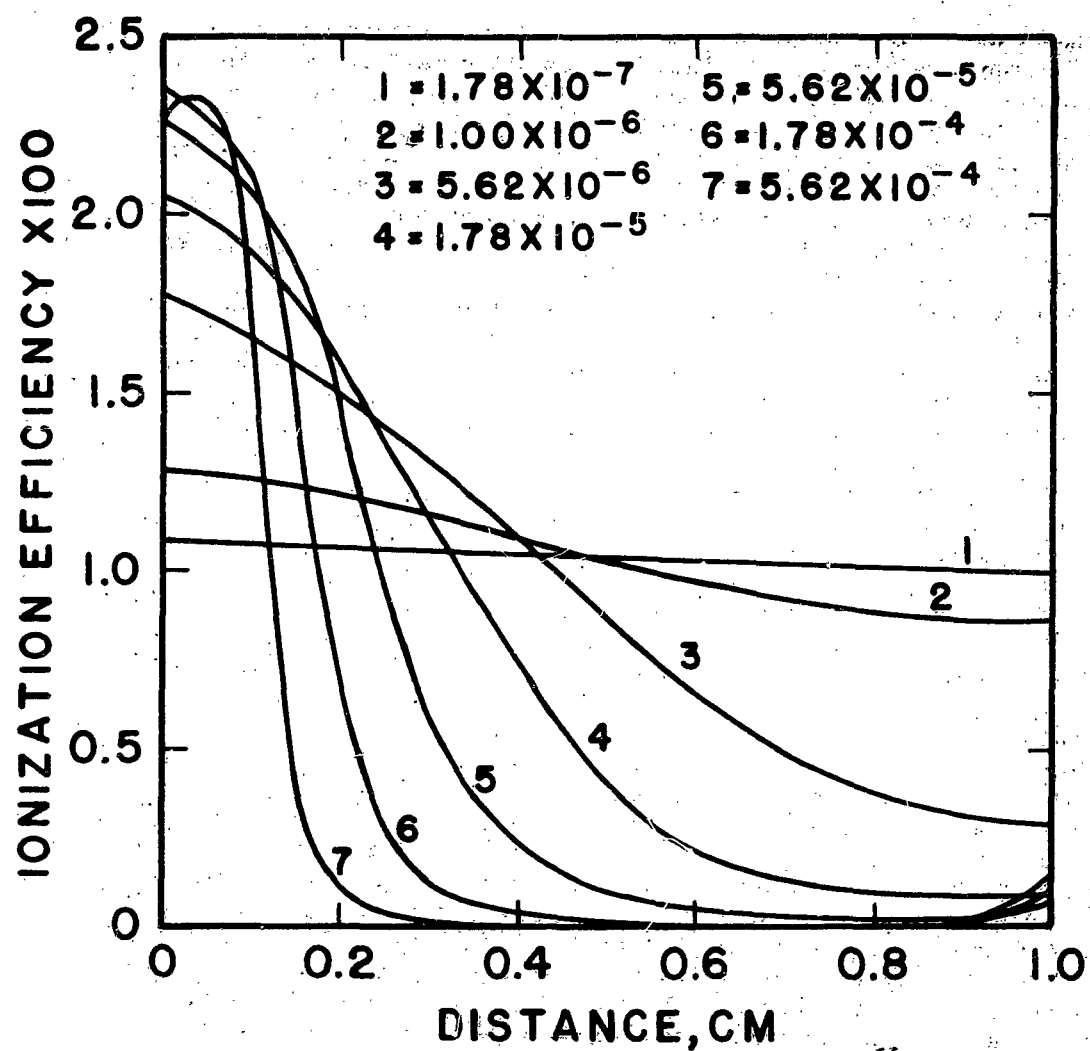
Figure 5. The variation of the ionization efficiency, η, as a function of the distance from the cathode for designated current density values in argon at 10 torr.

4. DYNAMIC COMPUTER PROGRAM

The static Townsend model for the breakdown of gases gives an accurate value for the breakdown voltage but cannot detail the breakdown transition itself. However, it was once generally accepted that breakdown occurred by the avalanche process whenever an overvoltage was applied, the breakdown time being shorter for higher overvoltages. The process envisioned a number of ion or electron transit times, depending on whether the dominant secondary mechanism was due to ions or photons at the cathode.

However, by the middle thirties, breakdown times of less than an electron transit time were noted. This seemed incompatible with the Townsend model and a new streamer theory of breakdown was developed, based upon photoionization in the gas. The streamer theory is qualitatively satisfactory, but too complex to be checked quantitatively. At present it is generally accepted that the Townsend theory is valid at low pressures and low overvoltages while the streamer mode operates at high pressures and high overvoltages. However, most efforts to define the transition region have been completely unsuccessful.

It was decided to use the computer to make accurate calculations of the dynamic breakdown transition using the Townsend model, but including space charge. A very brief outline of the formulation is given.

The continuity equations for the electron and ion current densities are

$$\partial(J_-/v_-)/\partial t = \alpha(x,t) \; J_-(x,t) - \partial J_-/\partial x \qquad (14a)$$

$$\partial(J_+/v_+)/\partial t = \alpha(x,t) \; J_-(x,t) + \partial J_+/\partial x \qquad (14b)$$

where v_- and v_+ are the electron and ion drift velocities, respectively, and t is the time. Equations (14) show that when the generation of particles (first term on the right side of each equation) exceeds the equilibrium gradient of those particles (second term on the right), charge accumulates in the gap and the current increases. When the two terms are equal, the stationary state is attained, in agreement with (1) and (3). These two partial differential equations, together with Poisson's equation (11) are solved on the computer by using finite difference equations.

The role of ions and photons in the secondary ionization at the cathode must be separated in the dynamic case. The electron current density at the cathode is given by

$$J_-(o,t) = J_o + \gamma_i \; J_+(o,t) + \gamma_p \int_o^d \delta(x,t) \; j_-(x,t) \; dx \qquad (16)$$

where γ_i and γ_p are the secondary coefficients for ions and photons and δ is the excitation coefficient defined analogously to Townsend's first ionization coefficient, α. For most calculations, δ is set equal to α. The ion current at the anode is zero, supplying the boundary condition for the ion current.

The boundary condition on the field is given by requiring that the gap voltage plus the voltage drop across a series resistance be equal to the applied voltage. The latter may be programmed to be a constant, have a step function, or have a sinusoidal increment. The last provision also allows simulation of a linear rise of voltage with time.

The initial distribution of the densities of electrons and ions across the gap, as well as the initial gap voltage, must also be supplied. Generally an initial equilibrium (static) distribution is assumed and the current growth noted for a step voltage or a linear rate of voltage rise. Another interesting initial distribition simulates the result of a short pulse of ultraviolet light striking the cathode.

Only two examples will be chosen from the many sequences of dynamic calculations made thus far. The first is for a 1-cm gap in air near atmospheric pressure. The parameters were chosen to fit the experimental conditions of Bandel, whose measurements were made at the University of California. It was found that his data could be fitted by assuming that $\gamma_i = 0.20\ \gamma$ and $\gamma_p = 0.80\ \gamma$, where $\gamma = \gamma_i + \gamma_p$. This is shown in figure 6. No fit could be obtained to his data when γ_i was assumed to be zero and a delayed photon mechanism was assumed. The latter mechanism is more generally accepted than the former at atmospheric pressure. It is hoped that further calculations will settle the question.

The other example is for air at atmospheric pressure and a gap of 5 cm. The parameters were chosen to fit the experimental measurements of Park and Cones at the National Bureau of Standards. They measured the breakdown voltage as a function of the linear rate of rise of the applied voltage. The comparison of the calculated and measured breakdown voltages is shown in figure 7. The agreement is good. For the highest rate of voltage rise, the breakdown time is less than one-tenth the electron crossing time. This shows that the Townsend model is able to predict the observed short breakdown times. Furthermore, the calculated field and density distributions across the gap in the final stages of breakdown indicate that a peak of the emitted light travels from the anode to the cathode at the velocities attributed to the photoionization streamer. There seems no longer to be a reason to postulate the photoionization streamer in parallel-plate geometry breakdown. It is of course recognized that photoionization is the dominant mechanism for point-to-plane geometries and in lightning discharges.
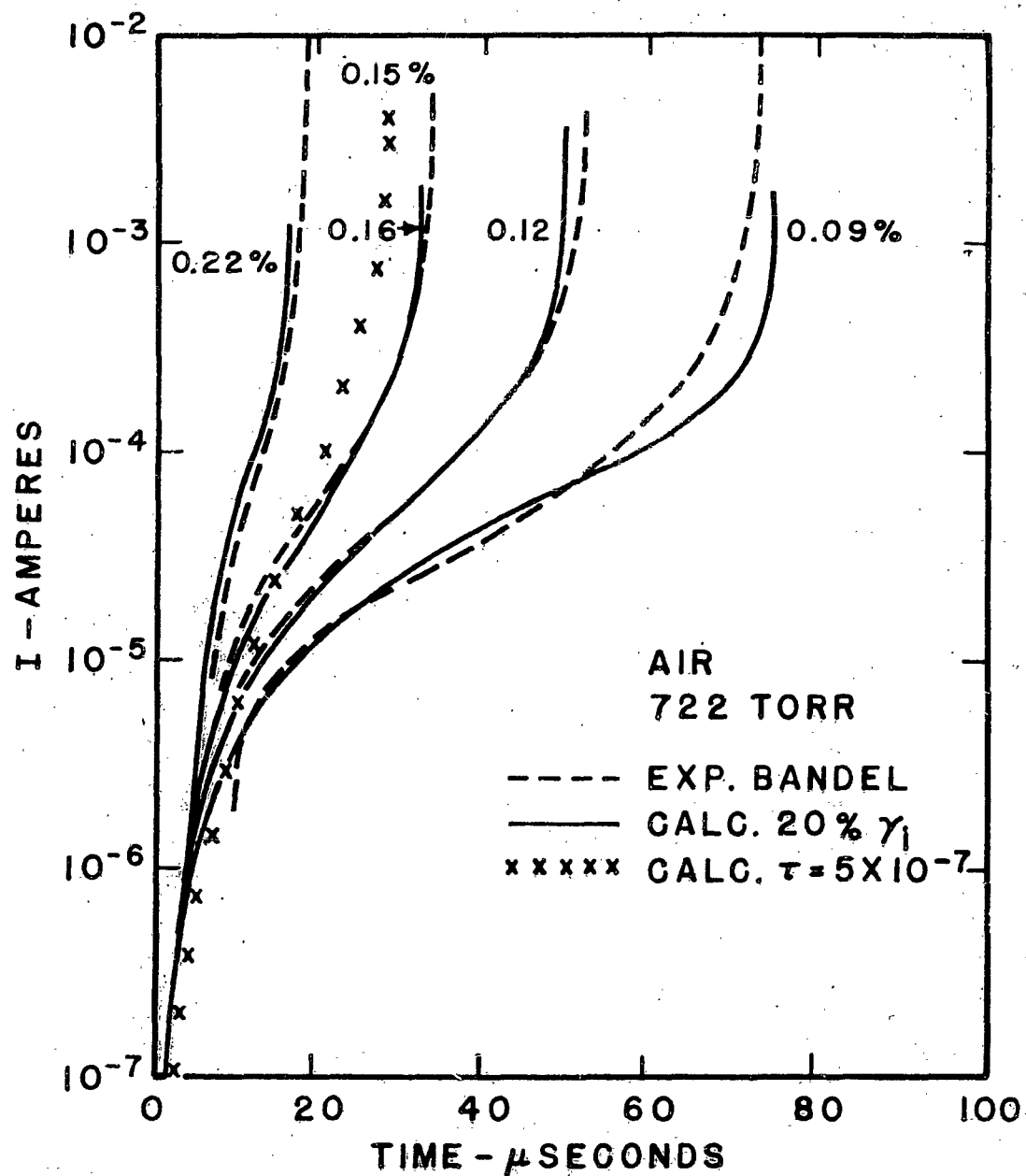
18

Figure 6. Comparison of calculated and measured growth of current as a function of time in air. Percent overvoltage is shown for each calculated curve. Tau is the time constant for the delayed photo mechanism.
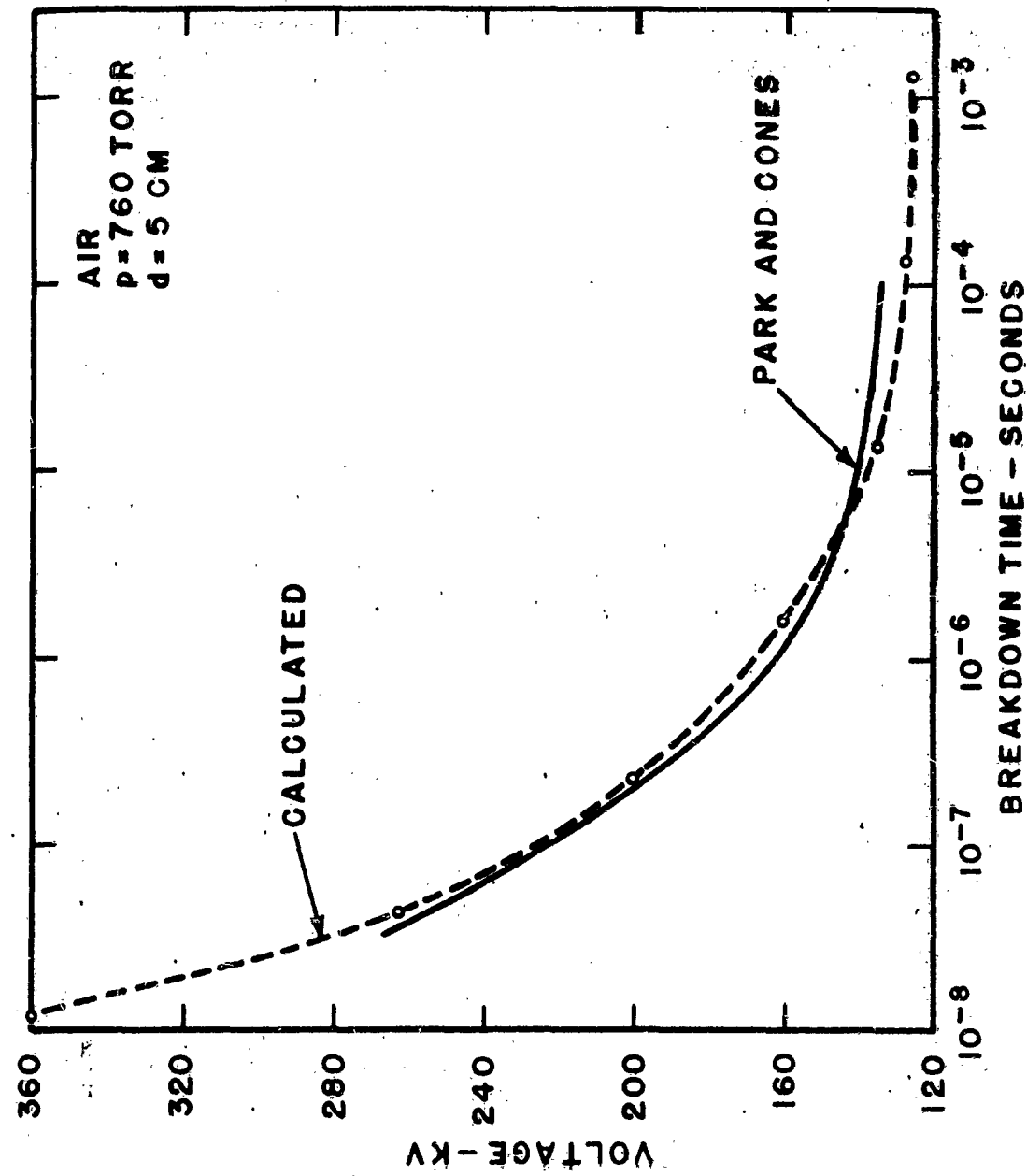
Figure 7. Comparison of calculated and measured breakdown voltage as a function of breakdown times in air for applied voltages rising linearly with time.

20

Another facet of the dynamic computer program has been the calculation of the impedance properties of a discharge. It has been shown that the discharge has an inductive component that varies approximately inversely with the current, in agreement with observations. The first detailed calculations of relaxation oscillations in the negative slope region of the static characteristic have been made.

A further important result from these calculations has been the calculation of the effect of space charge upon the diffusion of charge carriers.

5. SUMMARY

A brief review of the basic processes leading to breakdown in a gas tube has been given. It has been shown that although these processes have been known for decades, it is only with a modern electronic computer that the quantitative details may be learned. The static computer program was able not only to fit the breakdown region but proved also to be valid for the cathode fall portion of the glow discharge, well into the abnormal glow region. Subsequently, the dynamic program has shown that the Townsend model is sufficient to explain the short breakdown times, previously thought inconsistent with that model. The work reported herein is continuing and further significant results are expected.

6. BIBLIOGRAPHY

(1) L. B. Loeb, "Basic Processes of Gaseous Electronics," (University of California Press, Berkeley, 1955)

(2) J. M. Meek and J. D. Craggs, "Electrical Breakdown of Gases," (Oxford, London, 1953)

(3) J. R. Acton and J. D. Swift, "Cold Cathode Discharge Tubes," (Academic Press, New York, 1963).

(4) A. L. Ward, Phys. Rev. 112, 1852 (1958)

(5) H. W. Bandel, Phys. Rev. 95, 1117 (1954)

(6) J. H. Park and H. N. Cones, Jour. Res. Nat. Bur. Standards, 66c, 197 (1962)

DISTRIBUTION

Commanding General
U.S. Army Materiel Command
Washington, D. C. 20315
     Attn: AMCRD-RS

Office of the Chief of Research & Development
Department of the Army
Washington, D. C. 20310

Commanding Officer
Picatinny Arsenal
Dover, New Jersey
     Attn: Tech Library - SMUPA-VA6

Commanding Officer
U.S. Army Research Office
Box CM, Duke Station
Durham, North Carolina (3 copies)

Commander
U.S. Naval Ordnance Laboratory
White Oak, Silver Spring 19, Maryland
     Attn: Tech Library

Department of the Navy
Bureau of Naval Weapons
Washington, D. C. 20360
     Attn: DLI-2, Tech Library

Commander
Naval Research Laboratory
Washington, D. C. 20360
     Attn: Tech Library

Headquarters
Defense Documentation Center
Cameron Station Building No. 5
5010 Duke Street
Alexandria, Virginia
     Attn: TISIA (20 copies)

National Bureau of Standards
Washington, D. C. 20234

Microwave Laboratory
W. W. Hansen Laboratories of Physics
Stanford University
Stanford, California
     Attn: Dr. F. W. Crawford

University of Michigan
Department of Electrical Engineering
Ann Arbor, Michigan
  Attn: Prof. W. G. Dow

University of California
Department of Physics
Berkeley, California
  Attn: Prof L. B. Loeb

Thomas A. Edison Industries
Edison Laboratories
West Orange, New Jersey
  Attn: R. W. Crowe

Raytheon Manufacturing Company
Receiving Tube Division
55 Chapel Street
Newton 58, Massachusetts
  Attn: P. W. Stutsman

University of Minnesota
Dept of Physics
Minneapolis, Minnesota
  Attn: Prof. H. J. Oskam

Bell Telephone Laboratories, Inc.
Murray Hill, New Jersey
  Attn: A. D. White/M. A. Townsend

Lockheed Missile and Space Co.
3251 Hanover
Palo Alto, California
  Attn: Dr. Leon Fisher

Minneapolis Honeywell Regulator Company
500 Washington Ave., South
Hopkins, Minnesota
  Attn: B. T. McClure

Sandia Corporation
Albuquerque, New Mexico
  Attn: G. W. McClure

DISTRIBUTION (Cont'd)

General Electric Company
Nela Park Laboratories
Cleveland, Ohio
    Attn: Dr. Carl Kenty

Atomic Weapons Research Establishment
Aldermaston, Berks, England
    Attn: Dr. Patrick Hutton

Department of Physics
University of Wales
Swansea, U. K.
    Attn: Prof. Llewellyn-Jones

Department of Electrical Engineering
University of Liverpool
Liverpool 3, England
    Attn: Prof. J. M. Meek/Prof. J. O. Craggs

Department of Physics
Queen's University of Belfast
Belfast 7, Northern Ireland
    Attn: Prof. K. G. Emeleus

Mullard Research Laboratories
Redhill, Surrey, England
    Attn: Dr. G. F. Weston

Clarendon Laboratory
Oxford University
86, Kingston Road
Oxford, England
    Attn: Prof. Alfred Von Engel

Electrical Engineering Department
Queen Mary College
Mile End Road
London E. 1, England
    Attn: Dr. Thomas J. Lewis

Institutt for Teknisk Fysikk
Norges Tekniske Högskole
Trondheim, Norway
    Attn: Ing. R. S. Sigmond

Institut F. Angewandte Physik
Universität Hamburg
Jungiusstr. 11,
Hamburg 36, Germany
    Attn: Prof. H. Raether/Dr. W. Köhrmann

Internal

Horton, B. M./Hochmuth, M. S., Lt. Col
    Apstein, M./Gerwin, H. L./Guarino, P. A./Kalmus, H. P.
    Schwenk, C. C./Spates, J. E.
Hardin, C. D., Lab 100
Sommer, H., Lab 200
Hatcher, R. D., Lab 300
Hoff, R. S., Lab 400
Nilson, H. M., Lab 500
Flyer, I. N., Lab 600
Campagna, J. H./Apolenis, C. J., Div 700
DeMasi, R., Div 800
Landis, P. E., Lab 900
Seaton, J. W., 260
Van Trump, J. H., 930
Kaiser, Q. C., 920
Ward, A. L., 930 - 15 copies
Reddan, M. J., 930
Belknap, D. J., 930
Hershall, P., 930
Young, R. T., 320
Harris, F. T., 310
Rotkin, I./Godfrey, T. B./Bryant, W. T.
Distad, M. F./McCoskey, R. E./Moorhead, J. G.
Brenner, M., 720
Technical Information Office 010 - 5 copies
HDL Library - 5 copies
Technical Reports Unit, 800

(Two pages of abstract cards follow.)

AD _____
Accession No. _____

Harry Diamond Laboratories. Washington 25, D. C.

CALCULATIONS OF ELECTRICAL BREAKDOWN IN GASES -- A. L. Ward

TR-1193, 10 January 1964, 10 pp text, 7 illus., Department of the Army Proj 1A010501B010, AMCMS Code 5011.11.83800, HDL Proj 96600, UNCLASSIFIED Report

A brief review of the basic processes leading to electrical breakdown in gases is given. Formulae are derived for calculating the breakdown voltages of tubes filled with noble or molecular gases. An electronic computer program for calculating complete voltage versus current-density static characteristics is outlined. The calculated lowering of the breakdown voltage with increased ultraviolet irradiation of the cathode illustrates the utility of the time-independent computer program. The actual breakdown transition is calculated using the Townsend model, as modified by space charge, in a dynamic computer program. The agreement of the calculations with published breakdown data is excellent, even for the short breakdown times previously thought explainable only by gas photoionization streamers.

1. Electrical breakdown—Gas tubes
2. Gas Tubes—Electrical breakdown
3. Calculations—Gas breakdown
4. Current growth—Gas tubes