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Significance of Formative Time Lags in Gaseous Breakdown

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Delineating formative time lag studies of gaseous breakdown as conventionally carried out, this type of investigation is analyzed as it applies to two breakdown types. These are (1) the breakdown thresholds set by the generic Townsend relation, in many instances difficult to detect, but for which time scales observed delineate the well-established atom physical mechanisms active; (2) the more dramatic transient spark-like breakdowns, involving appearance of negative resistance characteristics caused by alterations of the gas, the electrodes, or space charge disposition of an unpredictable character. On this basis, the various breakdown phenomena known are listed and characterized as to their amenability to profitable time lag studies. It is further indicated that in contrast to time lag studies, the fast oscilloscopic analysis of breakdowns delineating transient current, potential, and luminosity as a function of space and time can prove invaluable and areas requiring this type of analysis are indicated.

1. INTRODUCTION

CONTEMPORARY with the development of oscilloscopes capable of resolving the temporal sequence of electrical breakdown in gases prior to World War II, it was recognized by investigators that much might be learned as to basic mechanisms active by this means. The first significant study was that of Engstrom and Huxford,[1] delineating the role of metastable atoms in the breakdown of argon-filled tubes and the work of Schade,[2] on the buildup of a Townsend discharge at low pressures. Subsequent to World War II, many investigations have been carried out leading to very important conclusions as to secondary processes active and quantitative determinations of the coefficients as well as to the sequence of mechanisms active. Perhaps one of the most significant advances in this connection came from the investigations of Fisher[3] and his associates in discovering that the filamentary spark breakdown in uniform field geometry very near threshold consisted of an initial Townsend-like glow discharge functioning in most cases by a photoelectric secondary emission from the cathode by which a positive-ion space charge distortion is built up leading to an ultimate filamentary streamer spark. This work has later been more accurately substantiated quantitatively in detail in air by Bandel,[4] in pure A by Menes,[5] and more recently by Kluckow[6] and Vogel[6] in air in Raether's laboratory. The underlying theory for the space charge influence had initially been proposed by Steenbeck[7] and independently by Varney, White, Loeb, and Posin,[8] and has more recently been more completely developed by Crowe, Bragg, and Thomas[9] and by Ward.[9] A time lag investigation has also been carried out by Menes and Fisher[10] for a positive point-to-plane corona discharge.

It is in this direction that attention must be called to a current source of confusion and one which can become worse owing to a general ignorance of gaseous electronic breakdown processes and their significance. It is urgent that clarification be made at this time by means of definition of terms.

2. FORMATIVE TIME LAG STUDY DEFINED

Formative time lag studies have, in principle, conventionally been carried out as follows.

First the influence of the statistical fluctuations in the appearance of triggering or initiating electrons producing time lags of their own are avoided. This is done by providing adequate triggering electrons or by varying the number of triggering electrons so that formative time lag data may be corrected for them. Then either the potential to be used is suddenly applied, its application starting the oscilloscope sweep, or an approach potential is applied just below breakdown value and an additional step potential is abruptly applied to give the desired total potential.[3,4] The step voltage then triggers the sweep. On other occasions, the potential is applied to a swept gap and the breakdown is initiated by a burst of photoelectrons released from the cathode by an auxiliary discharge,[11] the latter triggering the sweep. The change in potential or current signalizing the achievement of breakdown is recorded on the oscilloscope and the breakdown time is thus observed. In some cases, the oscilloscope may be replaced by a

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* Assisted by a grant from the Office of Naval Research.

[1] R. W. Engstrom and W. S. Huxford, Phys. Rev. **68**, 67 (1940).

[2] R. Schade, Z. Physik **104**, 487 (1937); **111**, 437 (1939).

[3] L. H. Fisher and B. Bederson, Phys. Rev. **78**, 331 (1950); **81**, 109 (1951). G. A. Kachickas and L. H. Fisher, Phys. Rev. **79**, 232 (1950); **88**, 878 (1952); **91**, 775 (1953).

[4] H. W. Bandel, Phys. Rev. **95**, 1117 (1954).

[5] M. Menes, Phys. Rev. **98**, 561(A) (1955); M. Menes and L. H. Fisher, Phys. Rev. **94**, 1 (1954).

[6] R. Kluckow, Z. Physik **148**, 564 (1957); J. K. Vogel and H. Raether, Z. Physik **147**, 141 (1957); J. K. Vogel, Z. Physik **148**, 355 (1957).

[7] M. Steenbeck and A. von Engel, *Elektrische Gasentladungen* (Verlag Julius Springer, Berlin, 1934), Vol. 2, p. 52.

[8] Varney, White, Loeb, and Posin, Phys. Rev. **48**, 818 (1935).

[9] Crowe, Bragg, and Thomas, Phys. Rev. **96**, 10 (1954). A. L. Ward, Phys. Rev. (to be published); Bull. Am. Phys. Soc. Ser. II, **2**, 68 (1957); and Diamond Ordnance Fuze Laboratories Report T. R. 500, August 30, 1957 (unpublished).

[10] M. Menes and L. H. Fisher, Phys. Rev. **86**, 134 (1952).

[11] H. J. White, Phys. Rev. **48**, 113 (1935); E. O. Lawrence and F. G. Dunnington, Phys. Rev. **35**, 396 (1930); **36**, 1535 (1931).

Kerr cell shutter[11] or other device and observation of breakdown may be made optically by photocell and shutter. Studies of this nature reveal the time scale of a succession of events terminating in a breakdown. Only if the conditions causing the breakdown or current growth are delineated such that the mechanisms involved lie within categories of atomic physical phenomena, the temporal aspects of which are known, can such time lag studies prove of interpretive value. That is, primarily only if the breakdown mechanism involves an equation such as the generic Townsend threshold equation, the component parameters of which are clearly defined and determinable through other studies, is such analysis valid.

3. GASEOUS BREAKDOWN THRESHOLD

When with adequate but not excessive electron triggering, any system of gaseous conductors has the potential difference raised to a point where there is a transition from a field-intensified current proportional to the triggering electron current, the current becomes self-sustaining without the presence of the initiating electrons; the transition point is designated as the *breakdown threshold*.[12] The breakdown observed may be characterized by some descriptive term such as a Townsend breakdown, a Geiger counter pulse breakdown, a Trichel pulse corona breakdown, etc. Such a transition is quantitatively defined by an equation of general type originally proposed by Townsend which has the form $\gamma \exp(\int \alpha dx) = 1$. Here γ is the probability that on the average, by some secondary mechanism, each electron of the avalanche of $\exp(\int \alpha dx)$ electrons produced by electron impact (starting with one electron) in the gas will liberate a *secondary* electron to continue a current sequence. The quantity α is the number of electrons created per cm path in the direction of the field X in the gas. Since generally X, the field, varies along the path x, then the integral of αdx over the extent of field must be used to indicate the avalanche size.

When this product of the average probabilities governing avalanche size and secondary liberation in principle exceeds unity by a trivial amount, charges accumulate in the gap and a self-sustaining current builds up. Such a current at threshold may be intermittent owing to the large statistical fluctuations of single values of the product and even of a sequence of them.[6,13] In addition, the space charges accumulating in the gap may, as in uniform field geometry, favor increase in current by augmenting $\int \alpha dx$,[7–9] or as is the case in positive point or wire corona[14–16] and negative point corona in air, they may inhibit discharge by reducing the fields. Thresholds for these low-order current breakdowns irrespective of regions of intermittence, or space charge complications subsequent to breakdown, are more or less observationally clearly defined though possibly not characterized by any very abrupt changes in current for small changes in potential. The thresholds appear to be reproducible and reversible such that potentials for offset and onset of current should not differ significantly except insofar as the statistical fluctuations create a zone of indefinite width. The breakdown may or may not be accompanied by luminous manifestations. Threshold currents may be very small and thus, under some conditions, these thresholds may be hard to detect. Provided that the discharge does not alter the gap or the electrodes materially, thresholds are reproducible and significant physically through application of the various forms of the relation. The basic criterion of threshold where doubt exists may be determined by removal of the triggering source or reduction in its intensity. If this does not affect the current, the threshold has been reached. It is also obvious that if threshold currents are feeble it is unwise to use too heavy a current of initiating electrons, for in that case field intensification leads to such heavy currents below threshold that the threshold is hard to locate and it often is altered in value in an unpredictable fashion by introducing space charge distortions.[10,17,18] Normally, natural thresholds are not very much altered by their own space charge except for the exaggeration of the statistically intermittent region.

Since in this type of breakdown the threshold is set by the prototype equation, then a true formative time lag analysis of its buildup is meaningful and will have significance relative to the processes at work with due attention to the effect of geometry, drift velocities, etc., on the time scale.

4. CATASTROPHIC OR SPARK-LIKE BREAKDOWNS

Many years ago, Toepler plotted currents as abscissas and potentials as ordinates for various types of gaps, and by such means delineated a succession of conductive states of gases as potentials and currents varied. These diagrams have been elaborated by Penning and Druyvesteyn[19] and by the writer[12] in later years. In these, starting with different geometrical forms, the rise of current with potential as the triggering ionization current is more completely swept out by the field is followed by a more rapid rise of current as field-intensified currents through avalanche formation and secondary effects appear. In some geometries, these curves will exhibit rather abrupt increase of current as potentials pass thresholds for self-sustaining discharges,

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[12] See, for example, L. B. Loeb, *Encyclopedia of Physics* (Springer-Verlag, Berlin, 1956), Vol. 22, pp. 446, 450, 451, 453.

[13] R. J. Wijsman, Phys. Rev. **75**, 833 (1949); especially W. Legler, Z. Physik **140**, 221 (1955); Ann. Physik **18**, 374 (1956). L. Frommhold, Z. Physik **144**, 396 (1956); **150**, 172 (1958).

[14] M. R. Amin, J. Appl. Phys. **25**, 210 (1954).

[15] M. R. Amin, J. Appl. Phys. **25**, 627 (1954).

[16] L. B. Loeb, Phys. Rev. **86**, 256 (1952).

[17] A. F. Kip, Phys. Rev. **54**, 141 (1938).

[18] H. W. Bandel, Phys. Rev. **84**, 95 (1951).

[19] F. M. Penning and M. J. Druyvesteyn, Revs. Modern Phys. **12**, 87 (1940); **13**, 72 (1941).

e.g., changes from 10^{-10} to 10^{-7} ampere as in positive point-to-plane geometry in air. All of these curves have positive slopes, i.e., dV/di is positive indicating a positive resistance characteristic, even in the worst cases, for a small range of current increase above threshold. In uniform field geometry with air, the range of overvoltage (i.e., the difference between applied potential and threshold potential for self-sustaining discharge relative to the applied potential) of positive resistance is very small and is rapidly replaced by one in which dV/di becomes negative. This *decline in potential with increase in current* is an *unstable regime* and can be followed and studied only with the application of external current limiting resistors. In uniform field geometry, the cause for this as indicated is the favorable influence of positive-ion space charge on the $\int \alpha dx$ for lower ranges in the value of α.[7–9] As shown by Bandel[4] and Kluckow[6] as well as surmised by Fisher[3] and his associates, and the writer,[20] the increased avalanche size leads to the formation of an anode streamer and to breakdown to the familiar filamentary spark as recently shown by Hudson.[21,22] Unless limited by power supply, or external resistance, the spark channel leads to a power arc. Analogous phenomena appear in highly asymmetrical fields with positive point-to-plane or positive wire-to-outer-cylinder geometry, with however a much larger range of overvoltage required before the filamentary spark appears.[21,23,24] This statement is valid only provided that the cathode is sufficiently remote from the stressed anode so that it does not materially contribute secondary mechanisms to the discharge. Such large overvoltage plateaus stem from the heavy internal space charge resistance in the low-field cathode region. A third example is that of the glow discharge with nonuniform fields between symmetrical electrodes at lower pressures. This discharge at a point where the current or current density reaches a sufficiently high value changes its positive value of dV/di to a negative one and goes over to a power arc.[22,25] The *transition phenomena* conditioned by the instability inherent in a negative characteristic differ from the *threshold phenomena* in that they are transient, irreversible, usually proceed with very high velocities in short time intervals and are often accompanied by large changes in current and luminous manifestations. These *catastrophic transitions* belong to a class of phenomena which, in analogy to the most frequently and earliest observed transition, may be properly characterized as sparks or spark-like transitions relative to the first class of breakdowns.

Because of the relatively dramatic character of these transitions and their importance in applications, it is natural that the thresholds and properties of the thresholds, or better, of the current and potential values at which transitions take place, should be of interest.

It is also natural that time lag studies should be applied to the phenomena. It is, however, at this point essential to indicate the cause and nature of this class of phenomena in order that the significance of the data taken be appreciated.

5. CHARACTERISTICS AND CONDITIONS LEADING TO SPARK-LIKE TRANSITIONS

It is noted that in the cases of spark-like transitions indicated so far, they are all related to the instability resulting from a negative resistance characteristic. In fact, it can be shown much more generally that inherent instabilities in which by changes in gas, cathode condition, space charge distribution, and secondary emission processes, the operating discharge of whatever nature has the balance set by the relation $\gamma \exp(\int \alpha dx) = 1$, maintaining the discharge, suddenly altered to a condition $\gamma \exp(\int \alpha dx) \gg 1$, the negative resistance characteristic then appears. This follows since in general, the large proportion of the initial potential drop, which went to the carrier *creating* mechanisms on being partly relieved of this function, is thrown across the gas column to augment the current. This heavy overvolting of the discharge multiplies carriers and augments currents. In many cases, it produces asymmetries in charge disposition of such an extreme nature that the regular current-balance mechanism of conduction, diffusion, ionization, etc., which operate on moderate time scales, can no longer function to equalize gradients. Thus redistribution of ionization and equalization of potential gradients to the more highly conductive states possible at higher current densities are achieved by a series of *ionizing-potential space waves sweeping from cathode to anode and/or vice versa* at *velocities which at times approach* 10^{10} cm/sec.[22,25] The nature of these phenomena constitute material for another paper. It is of importance at this point to note that the more dramatic transitions partake of such mechanisms as inherent in their appearance. The conditions leading to such transitions may now be listed.

(a) In uniform field geometry, as long as the first Townsend coefficient, α/p, increases more rapidly than linearly with the ratio of field strength to pressure, X/p, positive-ion space charge formation acts in such a fashion as to increase $\int \alpha dx$ across the gap. When at, or somewhat above, threshold for the Townsend break-

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[20] L. B. Loeb, Phys. Rev. 81, 287 (1951).

[21] G. G. Hudson, Ph.D. thesis, University of California, September, 1957 (unpublished); Proceedings of the Eight Annual Gaseous Conference, Schenectady, New York, October 20–22, 1955, paper A5; G. G. Hudson and L. B. Loeb, Bull. Am. Phys. Soc. Ser. II, 2, 86 (1957); L. B. Loeb, Bull. Am. Phys. Soc. Ser. II, 1, 379 (1956).

[22] L. B. Loeb, Report at the Terzo Congresso Internazionale sui Fenomeni D'ionzzazione nei Gas, Venice, June 11–15, 1957 (unpublished); Italian Physical Society Report, Milan, October, 1957 (unpublished), pp. 646–674.

[23] H. W. Bandel, Phys. Rev. 84, 95 (1951).

[24] G. L. Weissler, Phys. Rev. 63, 96 (1943).

[25] R. G. Westberg, doctoral thesis, University of California, February, 1958 (unpublished); Bull. Am. Phys. Soc. Ser. II, 1, 395 (1956); 2, 82 (1957); 2, 375 (1957); Phys. Rev. (to be published).

down the current density creates an adequate positive-ion space charge density, despite loss factors, so that the magnitude of the avalanche $\exp(\int \alpha dx)$ at the anode permits streamer advance through localized positive-ion space charge and photoionization in the gas, then an ionizing-potential space wave called the primary streamer moves at $\sim 10^8$ cm/sec towards the cathode. This sets in motion the sequence of such pulses that create the highly luminous conducting path of the spark that follows.[6,21,22,26] Here instability is a property of the variation of field strength across the gap and the variation of the Townsend coefficient with field strength. The effective overvoltage beyond the Townsend breakdown threshold yielding a feeble glow discharge in air at atmospheric pressure directly to yield a streamer-producing avalanche, has been shown by Köhrmann[26] to be around 6%. Similar conditions apply to other gases but the overvoltage for streamer-forming avalanches is far above the Townsend threshold, e.g., in argon by 100%. On the other hand, this peculiar property of the uniform field gap insures that the Townsend discharge in adequate geometry, once initiated at very little above its threshold, given sufficient time, builds up a space charge and current density leading to ultimate spark breakdown. How far above the preceding Townsend threshold the potential leading to the unstable current lies depends on gap conditions such as loss of carriers, the influence of statistical fluctuations, and the initiating photoelectric current from the cathode. These matters have only recently been discussed by Kluckow[6] experimentally for air and by Ward theoretically for argon.[9]

The potentials generally lie so close together that only through formative time lag studies[3,4] was it possible to discover that the Townsend discharge threshold nearly coincided with the sparking potential threshold, the formative time lag of the spark increasing from streamer-propagating values $\sim 10^{-7}$ sec to 10^{-4} sec and in argon even to 10^{-3} sec as the Townsend threshold is approached from above.

In this situation formative time lag studies were imperative and revealing since the basic principles and theory had long been developed.

(b) In highly asymmetrical gaps such as point-to-plane or coaxial cylindrical gaps with highly stressed anode and under conditions where secondary mechanisms from the cathode are ruled out by long gaps, thresholds are of the burst pulse or Geiger-counter type[14,17,18] and are caused by photoelectric ionization in the gas near the anode. These thresholds are, at relatively low potentials, fairly sharply defined and the discharge current is interrupted at first and later limited by the positive-ion space charge motion in the low-field region. The subsequent spark breakdown instability requires potentials several times greater than those at corona threshold.[18] Formative time lag studies of *corona thresholds* here are in order and as indicated for air by Menes,[10] they are characteristically very short and consistent with the nature postulated for the breakdown.

The subsequent catastrophic transition to a spark by anode streamer depends on avalanche size reaching the streamer-propagating proportions for which there is a basic theory[27] and the removal of the space charge field to a degree such as to permit the anode streamers to form and cross the gap.[18,21,22] The latter condition is not readily calculable, even if it were amenable to theoretical treatment. As Hudson's recent studies indicate, at the point where the first streamer complex can cross the cathode, breakdown *can* occur. However, the time lag studies would be capricious in the extreme and probably meaningless since, as Hudson observed, minor uncontrollable factors in point shape lead to a varying succession of many streamers most of which cannot yield a spark, and it is only after a number of abortive streamers have started and failed that a successful one is observed. Since such streamers are subject to large statistical fluctuations, the time delay between application of the sparking potential and the occurrence of the spark can vary from 10^{-6} second or so up to milliseconds. As potential rises, then the lags rapidly decrease. The statistical study of such lags can at best throw some light on the statistical fluctuations of streamer vigor but can throw no light on mechanisms.

(c) In other asymmetrical gaps, such as point-to-plane geometry or coaxial cylinders with highly stressed anode, under conditions in which secondary cathode mechanisms can be of influence (e.g., in short gaps, sometimes at low pressures, with single and very pure nonreactive gases), so that cathodes can remain reasonably clean, there will be Townsend-type discharges of very low order usually starting with a photoelectric γ_p from the cathode. The point at which such discharges initiate may be hard to determine, especially if many triggering electrons from the cathode are present. Under most conditions, the cathodes are coated with very thin layers of oxide or other adsorbed gases. These do not greatly alter the low photon γ_p, but poison cathodes for effective ion bombardment liberation γ_i.[28] Thus after the very small diffuse Townsend γ_p conditioned self-sustaining discharge sets in, or even before it sets in with a commensurate triggering electron field-intensified current near threshold, the cathode is bombarded by low-energy positive ions. These will in time "clean up" the cathode to such an extent that the gap will be overvolted since γ_i can change by factors of 5 or

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[26] H. Raether, *Ergebnisse der exakten Naturwissenschaften* (Springer-Verlag, Berlin, 1949), Vol. 22, pp. 73–119; W. Köhrmann, Z. angew. Phys. **7**, 183 (1955); Ann. Physik **18**, 379 (1956); Appl. Sci. Research **B5**, 288 (1956).

[27] L. B. Loeb and R. J. Wijsmann, J. Appl. Phys. **19**, 797 (1948).

[28] E. J. Lauer, J. Appl. Phys. **23**, 300 (1952); L. Colli and U. Facchini, Phys. Rev. **96**, 1 (1954); E. L. Huber, Phys. Rev. **97**, 267 (1955); J. H. Parker, Phys. Rev. **93**, 1148 (1954).

more.[28–30] In many cases, this leads to the contraction of a diffuse glow to active localized discharge spots on cathode and anode usually accompanied by an increase in current.[29,30] Once the spot forms on reduction of potential, the higher current will persist but will gradually decrease in value until the spot goes out and the current drops to its initial low value.[29,30] Here the offset potential may be a hundred or so volts below the onset potential. The investigator studying the breakdown phenomena in such a system will take the sudden current jump and luminosity to represent a discharge threshold, usually ignoring the less notable initial breakdown. He will, however, discover that the threshold for the current jump, or the spot formation, is not at all fixed and will vary with the rate at which potential is raised. Here formative time lags can vary from fractions of a second to minutes depending on the field-intensified or predischarge current and the potential applied. The higher the potential applied, the shorter is the formative time lag.[29,30] Offset potentials may be fairly uniform but depend on the soiling of the gas by the surface cleanup on successive breakdowns. Attempts to apply the Townsend-type breakdown threshold relation will prove meaningless.[29] The formative time lags representing a cleanup of a variable and uncontrollable film have no significance. Thus time lag studies are not warranted in such breakdown investigations. Breakdowns of this nature have been observed with fairly pure N_2 and H_2 in coaxial cylinders and point-to-plane corona with baked-out chambers and clean but not flashed Ni cathodes.[29,30] As little as 1% O_2 added to the N_2 at once changes the character of the discharge to one functioning by photoionization near the anode.[28,29]

On raising the potential, the localized spot current increases to a limited extent and current further increases by the development of multiple spots. Eventually potentials reach values where some other type of instability occurs at one spot and a power arc materializes via a spark-like transition, the nature of which is not known. Here again a time lag study would be futile since it would depend on the alterations in carrier disposition in the gap as well as changes in cathode mechanisms needed for the transition.

(d) In low-pressure glow discharge tubes with oxide or otherwise contaminated cathodes such as Al, Cu, Ni, W, etc., above threshold for the normal glow discharge, a sudden increase in potential leading to a fivefold or tenfold current increase in the abnormal region will cause the oxide film to clean up by ion bombardment after a variable time.[25] As the film cleans up and thins, the heavy ionic charge across the thin insulating film of oxide appears to cause a fairly complete ionization of the film and liberates a current equivalent to amperes of electrons from the cathode in a few millimicroseconds.

The field distortion so produced propagates ionizing potential space waves back and forth through the tube leading to a transient power arc of hundreds of amperes as recently shown by Westberg.[25] Again thresholds of this spark-like transition have no significance and formative time lags vary over wide ranges depending on the previous state of the oxide layer, current distribution, and density.

6. ASYMMETRICAL GAPS WITH HIGHLY STRESSED CATHODE

In asymmetrical gaps with highly stressed cathode, discharges in most cases will begin as low-order Townsend breakdowns.[24,29,30] However, as the writer has shown, such cathodes are inherently unstable.[31] The high fields near the cathode reduce back diffusion loss, and concentrate the discharge near the cathode so that conservation of photons is greater. The rate of ionization, being greatest near to, but somewhat detached from the cathode, creates a positive-ion space charge cloud near the cathode, further enhancing the cathode fields. On the other hand, the sensitive high-field volume at the cathode for triggering electrons is very small. Thus the predischarge field-intensified currents are usually very weak.[23] Care must be used in not creating too many carriers by photoelectric effect from the cathode wire.[17,18] The high cathode fields lead to heavy bombardment of the cathode by positive ions of high energy and thus cause heavy sputtering of the cathode surface and rapid cleanup.[32] Here there are two cases to consider.

(a) The gases used do not attach electrons to form negative ions. Thus the electron space charge in the low-field region is unable to control the current.

As the potential is increased, the initial currents will be very small. At some point, a low-order Townsend discharge will start with a photoelectric γ_p at the cathode owing to the ever-present oxide layer, unless the cathode has been flashed in an Alpert vacuum. Very quickly the oxide film cleans up and the unstable over-volted cathode goes over to a power arc unless a limiting resistor of high value is in series.[29,30] The growth of the current from the easily missed low-order breakdown threshold depends on the initial condition of the cathode and its rate of cleanup. The threshold is hard to fix accurately and while it could be predicted by the threshold equation, γ is not known with the variously contaminated cathode surfaces. The distances involved are small, fields are high, and the changing nature of the secondary actions under bombardment yield very short formative time lags unless the cathode is badly corroded. Time lag studies would depend for their interpretation on the particular stage in the rapidly developing power arc, at which the breakdown was

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[29] C. G. Miller and L. B. Loeb, J. Appl. Phys. **20**, 494 (1949).

[30] C. G. Miller and L. B. Loeb, J. Appl. Phys. **22**, 614 (1951).

[31] L. B. Loeb, Phys. Rev. **76**, 250 (1949).

[32] Loeb, Kip, Hudson, and Bennett, Phys. Rev. **60**, 719 (1941); G. L. Weissler and M. Schindler, J. Appl. Phys. **23**, 844 (1952).

taken to be completed. Thus time lag studies would be relatively of no significance.

(b) The discharge occurs in a gas attaching electrons to make negative ions.[14–16,23,30] Such gases usually are also quite active in forming adsorbed layers on the cathode surface. Two effects can be looked for. First, the oxide layers would initially be heavy and cleanup would take notable times. As the film cleans up, the oxygen or active gas competes with the cleanup process in reforming the films. Thus thresholds or transition points in discharges which may be used as breakdown criteria in time lag studies *depend on current density* while formative time lags are increased owing to delayed clean up. The second influence of the negative-ion-forming gas will be introduction of internal resistance by negative-ion space charge accumulations in low-field regions. This at once extends the potential region for spark-like transitions to arcs to values well above the initial low-order Townsend discharge threshold. Finally, where much dissociative attachment in the high-field region occurs, the space charge accumulation may render the discharge intermittent as with the Trichel pulses in point-to-plane corona.[15,16] Space charges clear more rapidly and a streamer-like process appears to form in the negative glow region. Breakdown to a spark is presumably by some streamer mechanism at present unknown.[18] The transition potential and/or current is ill-defined and statistical time lag studies would be meaningless.

CONCLUSIONS

It is seen in the foregoing that there are essentially two types of breakdowns having observable thresholds. The first of these consists of those initial breakdown processes governed by the relation $\gamma \exp(\int \alpha dx)=1$. The second is an irreversible transient set of phenomena marking transitions between discharge forms and usually governed by alterations of the field or of electrodes by space charge disposition, cleanup of electrode surfaces, etc., producing over-volted instabilities with negative dV/di leading to transitions the thresholds for which are largely indeterminate depending on past history, current density, etc. Thus the study of the second class of breakdowns by *conventional* time lag techniques is futile and will lead to more confusion than knowledge.

On the other hand, most instructive and essentially very valuable are all of the much more difficult investigations of the *temporal sequence of events in all breakdown or spark-like transitions*.[6,14–16,21,25,28,33] These involve triggering the sweep of the oscilloscope at either the initial Townsend breakdown in a sequence such as with uniform-field geometry, or on the first rise of current in a transition and measuring currents, if possible potentials at the electrodes and in the gap by probes, as well as scanning the visual aspects of the discharge at various points across the gap with photomultiplier and viewing slits. From plots of current or potential at various points and of light intensity (proportional to local rate of ionization) with time, cross plots of current, potential, and light intensity as a function of position in the gap at various times during breakdown lead to very important information as to the physical processes involved.

Currently, all too little information has been obtained by this means. Partially investigated to date have been (a) the sequence in uniform-field breakdown in air, except for the study of the final streamer phase of the process,[4,6] (b) the negative point-to-plane Trichel pulse corona in air,[15] (c) the positive point-to-plane burst pulse corona,[14] (d) preonset streamer pulse corona in air,[34] (e) the breakdown sequence by streamers both in point-to-plane corona and in near-uniform-field geometry,[21] (f) the Geiger counter pulse in counters electrically[35] but only incompletely for air by photomultiplier,[35] and (g) the glow-to-arc transition for various gases at low pressures.[25]

Urgently needed are studies of these phenomena where they occur in other and perhaps purer gases. Probably the most urgent and interesting would be the mechanism of the transition to a power arc in pure N_2, H_2, and A with positive highly stressed anode and clean cathodes with cathode active. Here a study of presumably short point-to-plane gaps with photomultiplier and fast sweep is indicated. Quite analogously, it is desirable to analyze the breakdown of the negative point in point-to-plane geometry with clean electrodes and pure gases in properly outgassed systems.

Finally, it might be added that much can be learned about the *initial steps* of breakdown under various conditions, but preferably in uniform field or coaxial cylindrical geometry where field conditions are well understood, by initiating a discharge through a geometrically and temporally narrow and controlled burst of ionization or electrons, triggering the sweep by the current rise, and with fast sweep studying the succession of ionizing events with fast oscilloscope.[28] Such studies have been common since World War II and were carried out by von Gugelberg in Switzerland, by Molnar and Hornbeck and Varney, at Bell Telephone Laboratories with photoelectric triggering[33]; and by Lauer, Huber, and Colli and Facchini[28] in the writer's laboratory, in coaxial geometry with collimated single α-particle triggering. They should be much further exploited in the near future.

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