The Initiation of Electrical Breakdown in Vacuum*

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The hypothesis is suggested that initiation of high voltage breakdown in vacuum is due to traversal of the high voltage gap by a clump of loosely adhering material. The implication of this hypothesis for uniform-field gaps is that the breakdown voltage is proportional to the square root of the gap length. A summary the literature is presented which supports this conclusion for a range of voltages from 20 kilovolts to 7 megavolts, and for a range of gap distance from 0.2 mm to 6 meters. Additional qualitative evidence is presented which tends to support the proposed hypothesis.

I. INTRODUCTION

THE phenomenon of electrical conduction between metal electrodes in high vacuum has been observed and studied for many years. The conduction is of two kinds: cathodic electron emission, which is very sensitive to the cathodic gradient and occurs only at very high gradient (of the order of megavolts/cm); and a low gradient, heavy current arc in which vapors of the electrode materials play a role. The only method by which the second type of conduction has been obtained has been by application of progressively higher voltage. The onset of the arc limits the practical usefulness of vacuum as electrical insulation and is therefore referred to as breakdown.

In 1928, with the formulation of the Fowler-Nordheim[1] theory of cold electron-emission from metals, a theoretical basis was provided for the interpretation of the first phenomenon. The comprehensive analysis of Stern, Gosling, and Fowler[2] showed substantial agreement of theory and experiment, and the Fowler-Nordheim theory has been regarded as reasonably well established, at least in the domain of low voltage and high gradient.

The initiation of breakdown, which is the concern of this paper, is a matter of much less theoretical interest, but of great practical importance for the design of high voltage vacuum apparatus; and about this there is much less agreement. Up to 1936, with the work of Hull and Burger,[3] Snoddy,[4] Beams,[5] and Ahearn,[6] it appeared to be fairly well established that breakdown was initiated by cold electron-emission from points on the cathode, these electrons producing intense localized heating of the anode. The conditions studied by these workers were those of uniform and cylindrical fields, with high cathode gradient, but low (less than 30 kv) total voltage. Even in this work, however, the evidence has not been entirely concordant: *viz.*, Ahearn's observation of the effect on breakdown of the glass walls surrounding the electrodes, and Beam's calculation that the measured breakdown gradient from a pool of mercury, fitted into the Fowler-Nordheim relation, gives less than 1 electron/cm^2/sec as the initiating current density.

In 1935, with the work of Anderson,[7] who used the segmented-tube technique suggested by Van de Graaff to obtain high voltage in vacuum, it became clear that the explanation in terms of cathode gradient, though possibly applicable to some cases, could not explain satisfactorily the results obtained with high voltage gaps. His work, together with data taken subsequently with the same or similar apparatus by Trump and Van de Graaff,[8] showed breakdown to be associated with progressively lower cathode gradient as the gap distance and voltage were increased, and this has been denoted the "total-voltage" effect. Because of the great sensitivity of emitted current to cathode gradient in the Fowler-Nordheim relation, these results cannot be reconciled with an initiation hypothesis which depends on heating of the anode to some critical temperature by field-emitted electrons.

This difficulty has led Anderson and Trump and Van de Graaff to postulate that positive ions as well as electrons play a role, one particle producing the other at opposite electrodes, breakdown resulting when the product of positive-ion yield per bombarding electron at the anode, and electron-yield per positive ion at the cathode exceeds unity. Experimental determination[8–10] of these yield functions, however, have given results too small by several orders of magnitude, particularly for the positive-ion yield per electron.

Very low gradient current-loading phenomena observed in Van de Graaff accelerator tubes have led to the postulation by Blewett[11] of a "Malter-layer" effect, and by McKibben and Boyer[10] of a positive-ion-nega-

* Work done under the auspices of the AEC.
[1] Fowler and Nordheim, Proc. Roy. Soc. (London) **A118**, 229 (1928).
[2] Stern, Gosling, and Fowler, Proc. Roy. Soc. (London) **A124**, 699 (1929).
[3] Hull and Burger, Phys. Rev. **31**, 1121(A) (1928).
[4] B. Snoddy, Phys. Rev. **37**, 1678(A) (1931).
[5] J. W. Beams, Phys. Rev. **44**, 803 (1933).
[6] A. J. Ahearn, Phys. Rev. **50**, 238 (1936).
[7] H. W. Anderson, Trans. Am. Inst. Elec. Engrs. **54**, 1315 (1935).
[8] J. G. Trump and R. J. Van de Graaff, J. Appl. Phys. **18**, 327 (1947).
[9] I. Filosofo and A. Rostagni, Phys. Rev. **75**, 1269 (1949).
[10] J. L. McKibben and K. Boyer, Phys. Rev. **82**, 315(A) (1951).
[11] J. P. Blewett, Phys. Rev. **81**, 305(A) (1951).

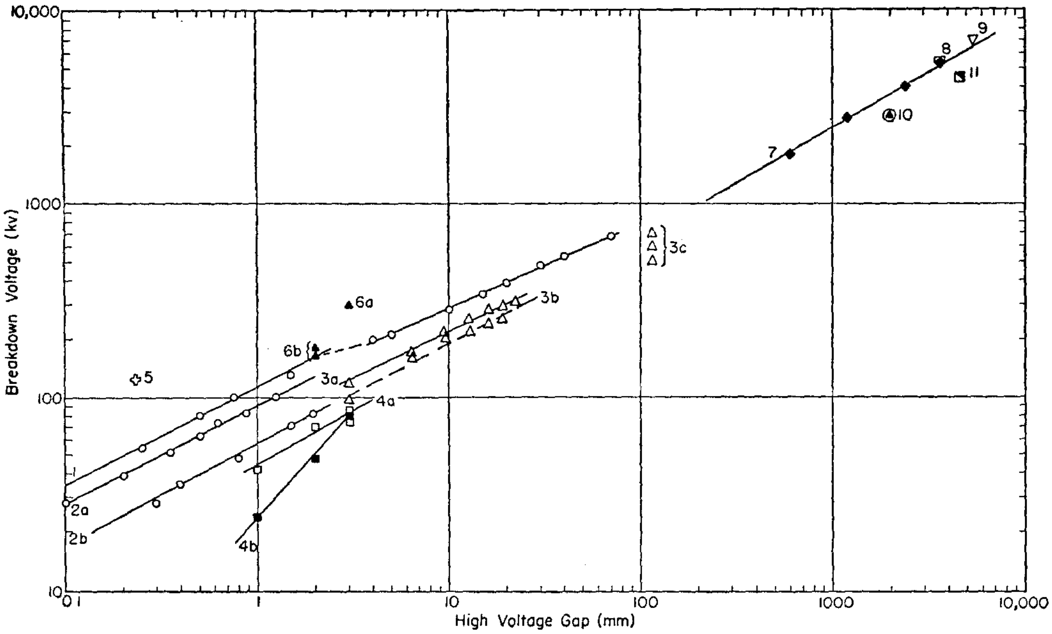

FIG. 1. Plot of data from the literature of breakdown voltage *vs* distance from highest to lowest potential electrode, for uniform-field and near-uniform-field geometry. Numbers on curves indicate sources as listed below.

(1) Trump and Van de Graaff, (see reference 8) 1-inch sphere steel anode, 2-inch steel disk, outgassed with glow discharge.
(2) Wm. Parkins, "Vacuum Sparking Potentials under Surge Conditions," MDDC 858, 18 February, 1946. Voltage applied in pulses of 3×10^{-7} sec rise time. (a) Tungsten hemispheres 2-inch diameter, out-gassed by spark discharge. (b) Copper hemispheres 2-inch diameter, out-gassed by spark discharge.
(3) J. L. McKibben and R. K. Beauchamp, "Insulation-Flashover Tests in Vacuum and Pressure," AECD 2039. (a) Flat aluminum. (b) Flat cold-rolled steel. (c) Van de Graaff test-section 4½ inches long, aluminum rings sandwiched between Mykroy rings, steel anode plate, negative end open to vacuum system in simulation of operation as beam tube, results on three test-sections.
(4) Gleichauf (see reference 12). (a) Kovar cathode, 18–8 st. steel anode, flat with rounded ends. (b) Copper, flat, with rounded ends (hole in center of anode).
(5) R. J. Piersol, British Assoc. Advancement of Science, Report 359 (1924). Molybdenum spheres after heating to 1400°C.
(6) J. L. Hayden, Am. Inst. Elec. Engrs. J. **41**, 852 (1922). (a) Molybdenum spheres 1-cm diameter out-gassed to red heat, polished. (b) Molybdenum spheres 1-cm diameter.
(7) Los Alamos big Van de Graaff, polished aluminum electrodes.
(8) Robinson *et al.*, Phys. Rev. (to be published).
(9) J. G. Trump (private communication on performance of new 12-Mev Van de Graaff machine, polished aluminum electrodes.
(10) Los Alamos small Van de Graaff machine (not limited by tube sparking), steel electrodes.
(11) Wisconsin Van de Graaff machine (not limited by tube sparking), steel electrodes.

tive-ion chain-reaction. This loading may be so severe that with power supplies of limited regulation, no breakdown can be observed. The relationship of these phenomena, and the mechanisms postulated to explain them, to breakdown itself it is not clear. In the case of the results obtained by McKibben and Boyer at least, it appears that loading and breakdown are due to different mechanisms, so that when the former is cleared up the latter has a chance to assert itself. This situation seem analogous to that with very short gaps, where ordinary field-emission is apparent, and the attainment of breakdown depends on sufficiently lowering the resistance of the power-supply, or clearing up the field emission by the smoothing of roughened surfaces. In what follows an attempt will be made to interpret the breakdown phenomenon for both long and short gaps in common terms, and in this picture the loading is incidental.

II. PROPOSED HYPOTHESIS AND SUPPORTING DATA

A hypothesis is proposed herein, the implications of which are briefly elaborated, and a summary of pertinent evidence is presented. The hypothesis is that the initiation of breakdown is due to detachment by electrostatic repulsion of a clump of material loosely adhering to one electrode, but in electrical contact with it; traversal by the clump of most or all of the high voltage gap, and impingement on an electrode at much lower, or at the lowest potential. It will be shown that this hypothesis and the experimental data are consistent with production by the clump of local temperatures in excess of any known boiling points. It will be assumed that production of such a condition will lead very quickly to the development of the full breakdown. Details of the subsequent events are excluded from the scope of this paper. Considering the scarcity of evidence regarding these details, there appears to be virtually no basis for preference among the various speculative possibilities. For the present it is not necessary even to specify on which electrode the clump is assumed to originate.

A quantitative formulation of this initiator hypothesis may be set down very simply as follows. Assume that breakdown will occur when the energy per unit area W delivered to the target electrode exceeds a value C', a constant, characteristic of a given pair of electrodes. This quantity W is just the product of the gap voltage

V by the charge density on the clump. The latter is proportional to the field E at the electrode of origin so that the breakdown criterion becomes simply

$$VE \geqq C, \tag{1}$$

where C is a product of C', some numerical factors, and possibly a field intensifying factory due to microscopic field inhomogeneities in the neighborhood of the clump during detachment from its parent electrode. For the case of plane-parallel electrodes where $E=V/d$, this criterion predicts at once that the voltage which a gap can sustain is proportional to the square-root of the gap length for a given pair of electrodes.

$$V \geqq (Cd)^{\frac{1}{2}}. \tag{2}$$

The prediction of this simple result has led to search of the literature for pertinent evidence, a summary of which is given in Fig. 1 in the form of a double-log plot of voltage *vs* length of gap, for uniform and nearly uniform field conditions. The only contradictory evidence is that provided by a three-point curve given by Gleichauf[12] for copper electrodes in the range 1 to 3 mm, whereas all other data are consistent with this prediction. Experimental data reported in the literature are usually given in the form of voltage-gap plots on linear scales, without further analysis.[13] The most striking features of Fig. 1 are the clustering of the data about straight lines of slope $\frac{1}{2}$, and the range of 10^5 in gap over which the relationship is approximately valid. Also noteworthy is the fact that the data of the various investigators, most of whom have taken pains to obtain conditions favorable to high voltage, do not vary greatly from one another and that a typical value for the constant C is about 3 megavolts squared per foot.

It is clear that if the voltage-field product plays the significant role assigned to it here, the single quantity C suffices as a figure of merit for the vacuum insulating qualities of a given gap, and provides a basis for comparison of data taken under different conditions of gap and voltage.

The magnitude of C is clearly a function of the condition of the electrodes. It is interesting to note that points 5 and 6*a* in Fig. 1 were obtained by different workers for well-outgassed molybdenum, and correspond to values of C of 20 and 6 megavolts squared perfoot, whereas points 6*b* represent molybdenum not outgassed.

Using the foregoing data, one may attempt a crude estimate of temperatures produced by a clump traversing a gap, as follows. The energy W' delivered by the clump per atom struck on the surface of the target electrode is just

$$W' \cong Ca^2/4\pi, \tag{3}$$

where a is the interatomic distance. If n is the depth of electrode, expressed in number of atom layers which share the energy of the clump, the local temperature attained is

$$T \cong Ca^2/4\pi nk, \tag{4}$$

where k is Boltzmann's constant. From the empirical data above C is typically 10^6(*ab*volts^2/cm), equivalent to 2.7 megavolts^2/ft, which gives, for $n=1$, $T \cong 10^6$ °K, or disruptive temperatures (i.e., temperatures above metallic boiling points) may be expected for penetrations of several hundred atomic layers.

The impact velocity v on the assumption of spherical clumps of radius r whose density is of order unity is given by

$$v \cong [C/8r]^{\frac{1}{2}}. \tag{5}$$

For $r \cong 10^{-2}$ to 10^{-6} cm, $v \cong 10^4$ to 10^6 cm/sec. These estimates imply that breakdown due to small clumps could be effective for the full gap-voltage up to megacycle frequencies for short gaps. These data therefore suggest that one way of obtaining further evidence regarding high voltage breakdown in vacuum is to study the effect of frequency of applied voltage on the relation between breakdown-voltage and gap-distance.

One pertinent bit of evidence in this connection is the result reported by Halpern *et al.*[14] that at 2800 mc/sec, 2.0 megavolts were supported across a 2.0-inch gap, or 24 megavolts^2/per foot, presumably across unoutgassed copper. This is much higher than has ever been obtained at dc with copper and is consistent with the fact that clump breakdown for the full gap-voltage is here precluded by transit time considerations. At present there appears to be no firm evidence of a "total-voltage" effect under conditions wherein clump breakdown at full voltage is precluded by transit-time considerations.

The data of Fig. 1 are pertinent to the special case of uniform geometry. The question naturally arises as to how well Eq. (1) is satisfied for more general cases. Relevant to this question are the data of the upper part of curve 1 in Fig. 1. The data for this curve were taken with a 1-inch diameter spherical anode and plane cathode for the low voltage region, the extension to higher voltage requiring the insertion along the gap of plane electrodes to control the potential distribution. Thus the gradient is not accurately calculable for the higher voltage range, though it is reasonable to assume the deviation from uniformity is not great. It is interesting to note, however, that the high voltage extension of curve 1 has a slope definitely smaller than 0.5 (almost 0.43), and this deviation is in the proper direction if either electrode gradient enters into the picture, as assumed in Eq. (1).

Other data relevant to this question are summarized in Table I. It is clear that these are too limited to be conclusive. The spread of the results is consistent

[12] P. Gleichauf, J. Appl. Phys. 22, 766 (1951).

[13] It is understood via private communication from E. Bretscher and J. L. McKibben that a summary of data similar to Fig. 1 has been assembled by R. L. Fortescue of the British Atomic Energy Research Establishment at Harwell.

[14] Halpern, Everhart, Rapuano, and Slater, Phys. Rev. **69**, 688A (1946).

TABLE I.

Reference	Geometry	Anode	Cathode	Electrode treatment	V(10^6 volts)	E_{cathode} 10^6 volts/ft	VE_{cathode} 10^{12} volts²/ft
C. C. Chambers J. Franklin Inst. **218**, 463 (1934)	Cylindrical	Nickel	0.5 Mil tungsten	Wire heated to 2800°K for 30 min.	0.011±10%	78	0.86
			1.6 Mil tungsten	Cylinder heated to dull red heat for 5 min.	0.023±10%	60	1.30
A. J. Ahearn, reference 6 and Phys. Rev. **44**, 277 (1933)	Cylindrical	2 cm diam nickel	Thoriated W 1.0 Mil		0.017	60	1.0
			Thoriated W 1.0 Mil		0.024	78	1.9
			Pure W 0.6 Mil		0.015	84	1.3
			Pure W 1 Mil		0.023	81	1.9
R. C. Mason, Phys. Rev. **52**, 126 (1937)	Line-plane	2″-diam. Cu disk	28 mil tungsten wire in 1″-diameter seimi-circle	Everything baked out to 500°C	0.035	18	0.63
K. Hashimoto, reference 15	Point-plane	Nickel Plane	Nickel point	Conditioned by sparking	0.030 for 1 mm separation		
		Nickel Point	Nickel plane		0.090 for 1 mm separation		

equally with an interpretation in terms of cathode gradient, and in terms of voltage-field product. Applicability of the proposed theory to these cases is suggested, however, by the fact that values of C are in the same range as the data of Fig. 1. If the mechanism for these cases is indeed the same as for the uniform-field, high voltage gap, one is almost obliged to say for these cases, more specifically than has been said thus far, that it is the product of the total voltage by the *cathode* gradient which controls the beginning of the discharge. Hashimoto's data,[15] though they do not allow the calculation of gradients, indicate that breakdown for a high gradient anode is of the same order of magnitude as for a high gradient cathode, other things being the same, and may therefore be interpreted in terms of a similar mechanism. The fact that it is higher is in agreement with many other reported qualitative observations. This suggests that, generally, the gradient which controls breakdown, and the place of origin of the hypothetical clump, is at the cathode, subject to the stipulation that the anode is not at substantially higher gradient, in which case it dominates.

In addition to the voltage-field product, certain qualitative aspects of vacuum breakdown can be plausibly explained by the initiation mechanism postulated here. The so-called conditioning process is well known, whereby maintenance of a gap at high voltage, with or without occasional sparking, improves the insulation strength of the gap. One surmises, on the clump theory, that conditioning is simply the process of detachment of the most loosely adhering material, and its firm embedment by acceleration across the gap. Direct evidence for such material transfer is cited by Anderson who used copper and steel for anode and cathode, respectively, and reported deposition of a brownish deposit on the cathode before any breakdown had occurred, with 20 minutes steady application of high voltage. After breakdown sufficient material was transported to provide direct spectroscopic evidence of transfer from the anode. No data are given on transfer from the cathode.

Another well-known fact about vacuum breakdown is its sporadic character. Thus, a gap may hold voltage for minutes or hours, then suddenly break down, and there is no evidence reported of current build-up, or other continuous cumulative effect prior to breakdown. Such a characteristic seems quite in accordance with a hypothesis which postulates a single event as initiator. The difficulty of reproducing breakdown voltages, even for a given gap, is also in agreement with the general character of a clump mechanism. It may be added that at least some of the electronic loading referred to in the introduction, particularly that which appears close to the breakdown voltage, may be due to clump-initiated cathodic emission corresponding to a voltage-field product less than the critical value C.

From the practical point of view of improving the high voltage insulating characteristics of vacuum, experience agrees with what one might expect from the predictions of the hypothesis. Elimination of loose material, the first obvious step, need hardly be recommended to the experimenter in this field. Presumably, measures which have proven successful in the past, such as cleaning, choosing proper materials, and high temperature bake-out either have progressively removed or consolidated the loose material, or have increased the threshold temperature for the development of breakdown.

Very recently quantitative data of a sort similar to that given in Fig. 1 have become available[13] on breakdown in a vacuum gap of variable length bridged by an insulator. These are replotted in Fig. 2, for the one case known, a Pyrex cylinder between flat copper electrodes. The slope of the straight line obtained again

[15] K. Hashimoto, J. Phys. Soc. Japan **2**, 71 (1947).

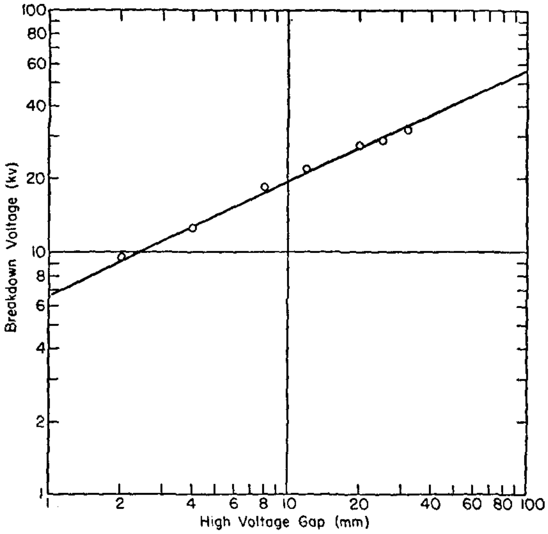

FIG. 2. Replot of data from Gleichauf (see reference 12) of breakdown-voltage *vs* gap-distance for Pyrex cylinder between flat copper electrodes.

is 0.5, but the value of C is here only 0.1 megavolts squared per foot. This is in accord with the well-known result that, at least in short lengths, insulators in vacuum are inferior to the vacuum gap between metal electrodes themselves. Thus, all the data on very short gaps in Fig. 1 were obtained with an arrangement that provided a much longer breakdown path along the insulator than across the gap itself. For the larger gaps the length of insulator required becomes troublesomely long. The now well-known device for circumventing this difficulty is to segment the insulator, arranging in effect a sandwich of alternating insulators and conductors, the latter tied to a potential dividing system. The data of Fig. 1 given by McKibben, and by Trump and Van de Graaff were obtained with two- and four-decker sandwiches, respectively. Modern high voltage x-ray and Van de Graaff accelerator tubes represent a large scale extension of this principle. It is interesting to note that the data of Figs. 1 and 2 together provide one with a guide for estimating the performance of Van de Graaff accelerator tubes as a function of their length, and provide the sort of data necessary to determine in a systematic way the segmentation interval for the tube and potential dividing system.

III. CONCLUSION

The results given here should be useful for practical purposes independently of the validity of the clump hypothesis itself. In addition, these results provide a quantitative criterion for the appraisal of any proposed theory of the initiation mechanism. In fact the strongest single reason for considering the clump theory is that, at present, it is the only one available which predicts the voltage-field constancy without artificial, *ad hoc* assumptions.

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Conference on Medium Energy Nuclear Physics

The University of Pittsburgh is planning to have a Conference on Medium Energy Nuclear Physics (in Pittsburgh, Pennsylvania) on June 5, 6, and 7. The program will be limited to studies of nuclei with $A > 4$, using projectiles accelerated in electrostatic generators or conventional cyclotrons.