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A REVIEW OF VACUUM BREAKDOWN PHENOMENA

by

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SUMMARY: This report is a review of vacuum breakdown phenomena beginning with the work of W. D. Coolidge on high-voltage x-ray tubes. The evolution of field emission in its relationship to breakdown between large electrodes is followed. An account is given of the present views on the part played by field emission in the precipitation of breakdown by cathode-dominated and anode-dominated processes. The effects of clumps, impurities, and electrode metals on high-voltage performance are also discussed.

KEY WORDS: discharge, vacuum breakdown, vacuum switch

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A REVIEW OF VACUUM BREAKDOWN PHENOMENA

G. A. Farrall

I. INTRODUCTION

In the following paragraphs an attempt is made to review a few topics relevant to breakdown phenomena in vacuum. We take as a starting point the work of W. D. Coolidge on high-voltage x-ray tubes. This is followed by an "evolutionary" discussion of field emission up to about 1950 and its uncertain role in accounting for breakdown processes between large electrodes up to that time. Further comment is made upon the so-called "clump" mechanism for breakdown and its probable limitations.

In a subsequent section, the resurgence of interest in vacuum breakdown of the 1960's is treated in terms of Dyke's breakdown criterion for point emitters and the conditions under which the cathode tends to dominate the breakdown process.

The next section is concerned with anode effects, experimental and theoretical, while the last section deals with electrode metals and impurity effects.

Because of the limitation of space and the desire to discuss some topics at length, certain subjects related to breakdown in vacuum have not been mentioned at all. The reader should be aware of these omissions.

A detailed discussion of electrode conditioning was omitted. This is a process such as repeated sparking whereby the breakdown voltage of a gap can be increased to some asymptotic limit which oftentimes is two or more times its initial breakdown voltage. Also omitted were references to circuit effects, the intentional use of coatings or films to increase breakdown voltage, insulators in vacuum, and magnetic effects. The so-called pressure effect, in which the presence of a gas in the 10^{-3} to 10^{-2} torr range can greatly increase breakdown voltage was not discussed.

Frequently in vacuum, a transient, incomplete breakdown will occur accompanied by a localized anode glow. Pulse currents across the gap can be amperes. This phenomenon is referred to as a microdischarge. There is a large literature on this effect and it too has been omitted. There are undoubtedly other omissions which have not been mentioned. It is hoped, however, that the scope of the present report has been made reasonably clear.

II. THE BEGINNING

It is sometimes the practice to begin a historical introduction to the topic of vacuum breakdown with the very colorful descriptions of vacuum discharges by R. W. Wood[1] in 1897. There are, however, strong arguments for beginning with the date, November 8, 1895, marking the discovery of x-rays by Roentgen.[2] The work by Wood was in fact motivated by a desire to produce a point source of x-rays which in Wood's words was ". . . of interest to those bent on getting a tube within the human body and lighting it from within."

More generally it was the desire to build x-ray tubes operating at higher and higher voltages that spurred investigations of the dielectric properties of vacuum. In the time interval between 1895 and 1913, techniques were developed for applying x-rays as a diagnostic tool in both medicine and crystallography. The x-ray tubes developed in this period required for proper operation a residual gas pressure of about 10^{-4} torr. The presence of this gas limited the maximum voltage at which these tubes could be used to about 50 kV, and so also limited the maximum obtainable x-ray energy. By 1913, however, Coolidge had developed the high-vacuum, thermionic tubes[3] which could be operated at voltages limited only by the ability of the electrode structures to support the applied potentials without breakdown. As a consequence, the first meaningful studies of vacuum breakdown phenomena were conducted in an effort to meet this challenge of generating high-energy x-rays. Among the benefits to be reaped from this challenge were the therapeutic use of x-rays and a wide variety of industrial applications which ultimately would require the production of rays from megavolt sources.

In the years between 1913 and 1928, Coolidge and his colleagues made substantial progress in designing high-voltage vacuum structures.[4] They found rigorous vacuum processing to be essential. Mercury diffusion pumps with liquid air traps were used in conjunction with repeated bakeout cycles to 470°C. If a tube contained massive parts these were separately vacuum fired before installation and final bakeout. An important processing step was the operation of the device between bakeout periods at the maximum power of which the device was capable. Sometimes vacuum processing would continue for days before the tube had reached its design levels of thermionic emission current and maximum operating voltage.

In his efforts to improve the voltage capability of x-ray tubes, Coolidge made several significant observations concerning the conditions which lead to breakdown.[4] He noted that at a certain level of voltage the cold surfaces of the cathode would begin to emit electrons. This emission would occur as tiny jets from small regions of the surface and its magnitude would increase sharply with further increase in voltage. He observed that this cold cathode discharge was favored by close electrode spacing and by sharp edges and corners, and particularly noted that the effect was associated with the electric field at the cathode.

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Two types of x-ray tube failures preceded by this emission were noted. The first was a direct breakdown between the electrode surfaces when the voltage was raised to a sufficiently high level. The second was bombardment of the inside glass wall of the tube which after a period of time caused local chipping, then full fracture, of the glass envelope. Two conditions were found necessary to alleviate these problems. The first condition was the reduction of electric field at the cathode by using structures having large radii of curvature; the second was the use of large glass envelopes to increase the distance between cathode and glass. Applying these principles in conjunction with rigorous outgassing and voltage conditioning procedures, single tubes were made capable of operating consistently at 300 kV. Typically such tubes had copper shields at the cathode and the anode separated by a distance of 2 cm. Even today this withstand capability for copper has not been substantially improved. Indeed, to build a high-voltage device today with the best possible withstand capability, one would follow closely the same procedures used by Coolidge 50 years ago.

III. FIELD EMISSION, PROOF, AND UNCERTAINTY

Coolidge was well aware of the fact that cold emission was a reliable indicator of the maximum operating voltage for his devices. Other scientists of the day[5, 6] had also observed emission from cold surfaces and had found it to be independent of temperature up to 1000°K (see, for example, Ref. 7). The Schottky theory of emission,[8] published in 1923, expressed the relationship between emission from a solid in terms of both temperature and electric field-strength. This theory, however, was thought to be inadequate for cold emission because that emission lacked the prescribed voltage[9] and temperature[10] dependence. Further, one had to assume what was considered to be an enormous local field enhancement of the emitting regions in order to make experimental and theoretical field-strengths agree quantitatively.

With the publication in 1928 of a quantum mechanical treatment of emission from cold surfaces by Fowler and Nordheim,[11] the origin of the experimentally observed cold emission was thought to have been determined. However, repeated experiments showed that while the functional dependence of experimental emission current upon field was well represented by the new theory,[12] the magnitude of the apparent electric field at which significant emission was observed in the experiment was of the order of 100 times lower than that predicted by theory (Refs. 13-16). This was one of the difficulties encountered with the Schottky theory.

In an attempt to avoid the possible imperfections of solid surfaces, Beams[17] studied field emission effects using short pulses of voltage on liquid mercury surfaces at just above their freezing point. In addition to finding that surface purity was important, he also learned that even his best surfaces exhibited breakdown at a voltage which was about a factor of 50 lower than would be anticipated by the Fowler-Nordheim theory. Two years later, Tonks[18] developed an approximate calculation to account for Beams' result. He showed that a slightly deformed mercury surface would rupture at a field of 10^6 V/cm in microseconds time. Apparently, then, even a carefully prepared liquid surface offers little advantage.

The questions surrounding the theory of field emission were largely unresolved until 1937 when E. W. Müller invented the field emission microscope (Ref. 19). This device revolutionized the study of surfaces and had an immeasurable impact upon vacuum breakdown studies. We shall, therefore, take time here to mention details of its structure and operation which will be important in later discussions.

The field emission microscope is essentially a finely etched emission tip (frequently tungsten) supported at the center of an evacuated glass sphere. The inner wall of the sphere has a transparent conducting layer and a phosphor layer much like the screen of a cathode ray tube. When voltage (a few 10's of kilovolts) is applied to this device, the highly nonuniform geometry of the tube produces an intense electric field at the emitter tip so that its emission properties can be studied. Moreover, since the geometry of the tip can be studied under the microscope before it is installed, the electric field-strength at the tip can be calculated as a function of voltage. Further, since the active emission area of the tip can be estimated, the current density of the emission can be computed from the total emission current. A precise knowledge of both electric field and current density is required for a direct check of the Fowler-Nordheim equation. Another great advantage of this device is that the emission tip can be made scrupulously clean and its general surface condition checked directly after installation by the emission pattern produced on the anode screen when voltage is applied.

For large area electrodes, the important details of microgeometry, adsorbed gas layers, and impurity content are for the most part unknown, yet each of these factors can strongly influence emission behavior. In the field emission microscope, however, these important details are known. With the new insight into surfaces provided by this device, the validity of the Fowler-Nordheim theory was confirmed, and the emission from cold surfaces at high fields was demonstrated.[20]

Despite the successful demonstration of field emission from point emitters, there still remained to be explained the large discrepancy between fields at which significant emission was observed experimentally on large area electrodes and the Fowler-Nordheim theory. The lack of a satisfactory accounting of this difference led to the exploration of processes other than field emission to account for the breakdown between large area electrodes. One such process is that proposed by Cranberg.

IV. AN ALTERNATIVE TO FIELD EMISSION

By the year 1950, there had been an accumulation of experimental data including that of Trump and of Anderson showing that breakdown voltage was nearly proportional to the square root of the gap length. To account for this observation, Cranberg[21] proposed that when voltage is applied to plane parallel electrodes, a surface charge density proportional to the field is induced on the electrodes. A "clump" or metal particle, adhering loosely to an electrode of unspecified polarity, shares this charge and may subsequently be drawn across the gap by the electric field. Cranberg suggested that when the electrode toward which the clumps travel receives a critical energy input from clump bombardment, breakdown occurs. This mechanism, under the assumption of a uniform electric field between the electrodes, yields a relationship in which the breakdown voltage depends upon the square root of the gap length--in approximate agreement with much of the published data of the time.

There is no real doubt that the presence of particles on electrode surfaces can reduce the breakdown voltage of a gap to a level which is substantially lower than the particle-free case. Examples of this can be seen in Rozanova,[22] Olendzkaya,[23] Poshekhonov and Pogorel'skii,[24] and Chatterton and Biradar.[25] Of these authors, however, only Poshekhonov and Pogorel'skii agree in substance with Cranberg's proposal. Olendzkaya concludes that breakdown voltage (albeit lower with particles) is related to the electric field strength between the electrodes and the rupture of an initial mechanical bond between particle and electrode. In this, Chatterton and Biradar concur. Rozanova believes that the Cranberg mechanism is appropriate only for the abnormally low breakdown values which are occasionally observed in many breakdown experiments. The Cranberg hypothesis is not widely believed to be a convincing model for breakdown events occurring across short gaps although it, or some modification, may be appropriate for cases in which the presence of particles is suspected, or when the gap length is large.

V. FIELD EMISSION AND CATHODE VAPORIZATION

At about the same time that Cranberg published his paper, Dyke and his co-workers were performing experiments on field emission tubes that were to have a substantial impact upon the interpretation of breakdown data obtained for broad area electrodes. Dyke was interested in studying not only the emission at high fields which occurred at voltages below that required to produce breakdown, but also in the transition to breakdown itself. The total emission current in Dyke's device was generally much less than an ampere, but the emitting area of the tip was also small so that the current density could be extremely high. Dyke[26] observed that as the current density approached a critical value in the 10^8 amp/cm^2 range breakdown occurred. The result was quite reproducible so that the voltage at which breakdown would occur could be predicted from the known geometry of the emitter and the emission current. Moreover, since the emission current could be calculated from the Fowler-Nordheim equation the whole process from emission to breakdown could be described mathematically.

The current density was extremely high at the tip upon breakdown. It is reasonable to conclude that the breakdown itself was precipitated by Joule heating and vaporization of the emitter. Thermal calculations in this report supported this conclusion. In the introduction of the paper by Dyke, Trolan, Martin, and Barbour, it is clear that the authors intended their experiment to explain effects on broad area electrodes and that point emitters were used simply to help quantitatively define the problem.

Shortly after Dyke's work, Boyle, Kisliuk, and Germer[27] published a paper describing prebreakdown emission and breakdown phenomena in short gaps in vacuum. The electrodes were crossed wires which we shall consider as large areas. They concluded that breakdown occurred as a consequence of electron emission from a protuberance on the cathode striking the anode surface, which in turn resulted in a flux of positive ions returning to the cathode. The space charge cloud produced by the ion concentration at the cathode acted to further enhance the cathode field precipitating breakdown. These authors disputed the general applicability of Dyke's work to large area electrodes, and suggested that Joule heating of cathode emitters was peculiar to point cathodes and to very small irregularities on large area surfaces.

In 1962, Alpert and Lee[28] reconsidered the experimental data of several authors including that of Boyle, Kisliuk, and Germer. They concluded that breakdown between electrodes of various geometries would occur when the electric field at the emission regions of the cathode surface exceeded some critical value which for tungsten is about 6×10^7 V/cm.

Alpert and Lee indicate that this field-strength can be determined from two experimental measurements. The first is a nondestructive measurement of prebreakdown emission current as a function of voltage. These data can be analyzed to show the factor, β, by which the average electric field is enhanced at the emission site. The second measurement is a determination of breakdown voltage, V_B. The critical breakdown field, E_c, is then given by

$$E_c = \frac{\beta V_B}{d}$$

in which d is the measured electrode separation.

Since emitter field and emitter current density can be expressed in terms of each other via the

Fowler-Nordheim equation, this conclusion was a reaffirmation of the cathode vaporization breakdown mechanism formulated by Dyke applied to broad area electrodes. The most convincing support for this concept comes from the Boyle, Kisliuk, and Germer data which were obtained under high vacuum conditions on tungsten surfaces; that is, the same general conditions, except for electrode geometry, as existed during Dyke's experiments. The critical field for the Boyle, Kisliuk, and Germer work was found to be constant for various gap lengths and nearly identical to the critical field computed for the Dyke experiments. Alpert and Lee point out that the critical field may vary from one electrode metal to another but should be constant regardless of electrode shape, provided that the surfaces are clean and in good vacuum. They also indicate that there may be limitations to the applicability of these ideas at long gap length (>1 mm).

The paper by Alpert and Lee drawing attention to the possible wide applicability of the Dyke breakdown criterion has probably created more activity in the field than any other single paper in vacuum breakdown literature. Much of the appeal of this work stems from the fact that the authors suggest two measurements to be performed in sequence which can then be interpreted in a relatively straightforward manner. Since the appearance of this work, critical fields have been determined under various electrode geometries and have been found to be essentially constants of the material. Tabulations are given in papers by Alpert,[29] Brodie,[30] Kranjec and Ruby,[31] and Bloomer and Cox.[32] Values obtained in the latter reference are fairly typical and are, for example, 5.4×10^7 V/cm for molybdenum, 5.7×10^7 V/cm for stainless steel, and 6.9×10^7 V/cm for copper.

The values of critical field just cited are larger by a factor of 100 or more than the average breakdown field for those various metals. If Alpert and Lee are to be believed, the missing field fact must be accounted for. The crux of the matter is, of course, that the ordinary ridges, bumps, or mounds which can be observed on any metal surface under a low-power microscope would not usually account for a field enhancement of more than two or three.[33]

In their original report,[28] Alpert and Lee discuss the problem in connection with some of their own observations of metal surfaces under the scanning electron microscope. These and especially studies by Little and his associates (see, for example, Ref. 34) at the Naval Research Laboratory suggest the existence of sharp protuberances on metal surfaces said to be capable of producing local field enhancement of about 100. Since that time others have made similar studies.[35-37] In some cases the projections appear as a result of an applied field;[38] in other cases they appear to be part of a solidified splash rim on cathode microcraters.[39, 40] It is, however, difficult to ascertain just how large a field enhancement a given protrusion will produce, and there is some doubt at least in the mind of the author that such protrusions can yield a β much greater than 100. Yet some experiments clearly indicate larger values.[31, 41, 42]

Enough careful experiments have been performed to date to conclude that the Dyke criterion does successfully apply to many experiments carried out under well-controlled vacuum conditions on clean surfaces and for small gaps. In some cases, however, β values are simply too high; in others, the anode is clearly involved. The former case cannot immediately be accounted for. In the next section, however, we shall review some of the experimental evidence for anode involvement in breakdown and explore the theoretical ideas that have been proposed to account for these effects.

VI. INTERACTIONS OF THE ANODE

We have already noted Coolidge's description of two failure modes for x-ray tubes, one of which was bombardment of the anode by cathode emission. Support for the idea of anode interaction was given by Snoddy in 1931[43] and Chiles in 1937,[44] who both observed luminosity at the anode during the early stages of breakdown as well as pitting of the anode after breakdown. Anode pitting was later studied on a variety of metals by Palatnik and Levchenko.[45]

Anderson in 1935[46] measured breakdown over a large range of gap lengths and found that the field at the cathode needed to produce breakdown diminished greatly at long gaps. This he termed the "total voltage" effect. A similar inference of anode interaction could be drawn from the later work of Trump and van de Graaff.[47]

Ahearn[16] showed that if a wire tungsten cathode is spark conditioned opposite a given anode area and then the anode area is replaced by a new area previously shielded from the discharges, breakdown voltage did not change. That is, the conditioning of the electrodes by spark breakdown did not appear to be influenced by the state of the anode surface. The inference that conditioning is primarily a cathode effect was convincingly shown much later for a range of gap lengths.[48]

We must at this point be careful in the interpretation of this result. It is clear that the improvement of breakdown voltage by pulse conditioning occurs primarily at the cathode surface. On the other hand, there is clearly an interaction at the anode with cathode emission at long gaps which results in breakdown at a level lower than would have been the case had only the field at the cathode been the dominant effect. These two findings deal with different aspects of breakdown and are not inconsistent with each other.

Other evidence of anode involvement in breakdown is given by Belan[49] and co-workers whose experiments indicated that breakdown was connected with the attainment of a critical anode temperature.

Little and Whitney showed evidence of anode vaporization affecting breakdown.[50] Pranevichyus and Bartashyus[51] used thin-film anodes which could be penetrated by incident electrons. Use of such films raised the breakdown voltage by 20%. In what appears to be an opposite view, Mesyats and co-workers[52] show that the anode processes do not determine breakdown voltage. This result, however, was obtained with short voltage pulses and small gaps--conditions, which we shall see later, favor breakdown by a cathodic process.

Beginning in the sixties, serious theoretical consideration was given to possible anode processes which could lead to breakdown. Miller, in 1964, for example, points out the possible change in the role of the anode at long gaps.[53] Most of the theoretical effort was focused upon the heating of an anode surface under electron bombardment compared with the heating at the cathode due to Joule and Nottingham[54] effects. Generally, the guiding criterion determining breakdown is that the cathode protrusion or the anode region reaches the melting point. It is generally felt the mechanical instability due to melting would result in breakdown.

Steady-state calculations of anode heating were made by Chatterton in 1966.[55] He found that an anode breakdown was favored by a cathode protrusion having small field enhancement. Further consideration of the problem was given by Utsumi.[56] He concluded that a cathode breakdown mechanism (Dyke criterion) was likely at short gaps but that the anode should dominate the breakdown process at long gap lengths. This view was supported by his own experiments. A similar conclusion was reached by Slivkov in 1970.[57]

In 1967, Charbonnier, Bennette and Swanson considered the transient case of anode bombardment by electron beams and concluded that short-duration-voltage pulses favored cathode initiated breakdown (Dyke criterion) whereas long-voltage pulses were more likely to result in anode instability.[58] Experimental evidence of the transition from cathode to anode dominated breakdown was obtained by Charbonnier, Bennette, and Swanson,[59] and by Smith, Elliot, Chatterton, and Pulfrey.[60]

A more detailed consideration of anode effects upon breakdown is given by Davies and Biondi based upon experimental observations of neutral metal vapor in the gap just prior to breakdown.[61] They conclude that the actual breakdown is due to an avalanche process in the vapor evaporated from a macroparticle in transit which has been detached from the anode by cathode emission. This view is somewhat in opposition to one proposed by Slivkov[62] in which breakdown via the anode is thought to occur as a consequence of ionization of vapor evaporated from the anode. The ions thus produced move to the cathode when they further enhance the field via space change causing breakdown. Although both of the above-mentioned models appear reasonable, a realistic evaluation of them requires more experimental details than presently are available.

VII. METALS AND IMPURITIES

There is little doubt that metals can differ widely in their ability to withstand high voltage in vacuum. This difference may be due to a number of reasons: the bulk properties of the pure metal itself; the rates, degree and types of oxide formation; the maximum outgassing temperature permitted by melting point and vapor pressure; the prior history of thermal cycling; impurity content--the list is nearly endless and contains many items of which we are usually totally ignorant. There is, on the other hand, a practical need to know the relative capabilities of metals prepared under the "usual" procedures. It is this question of relative capabilities which we now consider briefly, recognizing that the reasons for differences in behavior will be, for the most part, ignored.

In 1956, Rozanova and Granovskii[63] made a study of the various electrode metals at a gap length of 2 mm in a well-processed sealed tube where all electrodes were cut to the same geometry. For a part of these studies the cathode was always made of molybdenum while the anode metal was changed. It was found that the anode metals produced increasing breakdown voltage in the sequence graphite, aluminum, copper, iron or nickel, molybdenum, and tungsten. The experiments were repeated using nickel and iron cathodes over a gap range of 0.3 to 2 mm with the same sequence prevailing. As a result of this work the authors drew a conclusion which was to be cited in the literature many times later--that the electrical strength of a vacuum gap depends upon the mechanical strength of the anode if this strength is characterized by Young's modulus.

The findings of Rozanova and Granovskii have generally been confirmed in devices where both electrodes are made of the same metal, but sometimes differences are observed. Erven, Wavre, and Van Heeswijk, for example, studied breakdown between various metals under 60 Hz AC voltage.[64] They concluded that increasing strength occurred in the order copper, chrome copper, aluminum, stainless steel, and titanium. The gap length used was 5 mm and AC breakdown voltages ranged from 85 kV rms for copper to 140 kV rms for titanium. In this case, copper and aluminum are interchanged from the sequence indicated by Rozanova and Granovskii.

Aluminum has often been singled out for study and found to be a disappointingly weak metal, electrically. Bennette, Swanson, and Charbonnier,[59] in a study of tungsten, molybdenum, copper, and aluminum electrodes, have concluded that thermal processes either at the cathode or at the anode determine the breakdown characteristics of each of these metals except one. For aluminum they suggest that breakdown is precipitated by mechanically tearing off of particles from the electrodes.

Experiments by McCoy, Coenraads, and Thayer (Ref. 65) were carried out using several metals having high mechanical strength. Their objective was to determine insulation strengths of these metals (that is, the voltage a given pair of electrodes can withstand without breakdown) rather than the measurement of an average breakdown voltage. A large range of alloys were studied of which we consider only a few. In order of increasing electrical strength these are Hastalloy B, Inconel, 303 stainless, and 304 stainless. Experiments were conducted at a 1 mm gap and strength varied from 15 to 60 kV. The first two and electrically weakest of those metals are nickel-base alloys while the latter have an iron base.

These authors conclude that hardness of a metal is important to electric strength, and they cite the following as an illustration. Electrodes had been formed from hot-rolled 304 stainless plate stock and found to have an insulation strength of 45 kV, whereas previous experiments with electrodes formed from 304 stainless plate stock which had been cold-rolled and annealed had an insulation strength of 75 kV. The plate stock hardness was 76, while that of the bar was 92 (Rockwell B). A repetition of this work using 304 bar stock with differing annealing cycles gave Rockwell C hardnesses of 35 for one sample and 25 to 30 for the other. The insulation strengths of these metals were 65 to 100 kV and 40 to 80 kV, respectively.

Another instance of the hardness effect was reported by Bouchard. (66) He compared the breakdown voltage of OFHC copper and dispersion-strengthened copper cathodes opposite OFHC copper anodes at short gaps in good vacuum (10^{-9} torr). He found the breakdown voltage for dispersion-strengthened copper higher by 21%.

While certain tendencies to high or low electric strength may be attributable to properties of the pure bulk metal of the electrodes, it is clear from many experiments that impurity effects can dominate breakdown behavior. McCoy, Coenraads, and Thayer, for example, clearly show that the presence of dust on electrode surfaces can have a profound effect on electric strength. A similar conclusion was reached by Hurley and Parnell. (67) Biradar and Chatterton (Ref. 68) showed that reproducible Fowler-Nordheim plots could be obtained from protrusions which consist mainly of impurities on electrode surfaces. Farrall and Owens(69) have obtained scanning electron micrographs of silicon-bearing particles known to be emission centers or copper electrode surfaces. Evidently this emission from the cathode not only may occur from metal projections but also from surface inclusions or from the cooperating surfaces of inclusions with the substrate. The role played by insulating particles in emission and breakdown phenomena was suggested many years ago by Langmuir(70) and studied by Kingdon and Lawton. (71) There is no reason to suspect that this effect is any less important now than it was then, even with so-called clean vacuum systems.

VIII. CONCLUSION

In 1929, Coolidge, in summarizing his work on x-ray tubes, indicated that the maximum voltage he could sustain in a single tube was 300 kV. This was across a 2 cm gap between copper surfaces. We find today that in the intervening decade this capability has not been significantly improved upon. We might take some comfort in saying that, although the practical limits of voltage withstand have not been changed much, we know a lot more about breakdown processes now. We know, for example, that in many cases field emission is important; in other cases, anode interaction with cathode emission is significant, and that in still others particle impact may be significant. There also may be other mechanisms documented in the literature and not described here that may account for the findings of a large body of experimental data Yet even being aware of these hypotheses or theories, one oftentimes does not know which is applicable in a given device or which description of breakdown may be important in one device and not in another even though the devices were made in the same way. It therefore becomes important to be able to see and study the regions on a broad electrode surface which are really responsible for the breakdown phenomena we observe. After all, breakdown even on a large electrode is a microscopic phenomenon. If we are to achieve the same success in studying broad area electrodes as has already been accomplished in the study of point emitters, we should adopt the same philosophy and study breakdown on the same microscopic scale in which it occurs.

Impurity effects are obviously important; impurities not only as occluded particles in metal surfaces but also as adsorbates. In this regard we can do no better than to heed the remarks by van Oostrom (Ref. 72) ". . . that a more careful analysis of surface composition and properties may help us to establish the actual parameters which determine the initiation of vacuum breakdown. "

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