ELECTRICAL BREAKDOWN IN HIGH VACUUM

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ABSTRACT

The phenomenon of charge transfer which occurs when a potential difference is applied between electrodes in a high vacuum has been a subject of continuing technological interest for many years. Despite a great number of papers in the field there remains a great diversity in both the nature of the results and the interpretations thereof. In general such studies have related the nature of prebreakdown currents and material transfer to the initiation of an arc between the electrodes. This paper reviews some recent experimental results and alternative interpretations which have been proposed. Earlier results may be divided into general categories depending on the gap spacings and vacuum conditions. Some recent results for small gap spacings in ultrahigh vacuum will be described and a self-consistent picture proposed for the phenomena observed.
I. Introduction

The mechanisms of electrical conduction between metal electrodes in high vacuum have been under investigation for many years.\(^1\) Since the literature in this field is unusually abundant, it will not be possible to tabulate all the previous observations or to describe all of the hypotheses propounded to explain the phenomena. We shall, therefore, only discuss certain of these observations, based upon selected parameters. We shall report on some of the recent results and experiments in progress at our laboratories and then try to fit these observations and our results into an overall summary of what is known in the field. In particular we shall attempt to present a self-consistent picture of the processes which take place in the case of small gap separations.

The electrical conduction observed is of two general types: a low current high field gradient type in which transfer of charge between electrodes takes place without interaction with residual gases, and a high current low field gradient arc in which vapors of the electrode material play a predominant role. The second type of conduction is observed only after the voltage between electrodes has been increased beyond some more or less well defined limit, the initiation of the arc being referred to as breakdown.

II. Ultimate Limitations

As a starting point for the discussion, it is of interest to inquire what we might expect to be the ultimate limitations on voltage or voltage gradient on the basis of the known properties of the materials used. In the first place, we might expect the ultimate voltage to be limited by certain mechanisms which are entirely dependent upon the electric field. Even with a perfect vacuum we know that an electron current can be drawn from the cathode under the action of a very high field. In Figure 1 we show a curve of current density versus the field as predicted by the theory of Fowler and Nordheim. Thus, if we reach fields somewhere in excess of $10^7$ volts/cm., we should expect currents so high that either the resistive losses in the cathode or the transfer of the energy to the anode would cause either or both electrodes to melt and ultimately to vaporize. If either electrode were vaporized, we would obviously have a vacuum breakdown and, if the fields were sufficiently high, an electrical breakdown.

If the field current didn't in some way cause a breakdown as the electric field was increased, ultimately the mechanical force due to the electric field would rupture the electrodes. For example, at $3 \times 10^7$ volts/cm. the force is equal to the bulk tensile strength of aluminum; at $2 \times 10^8$ volts/cm. the force is equal to the bulk strength of polycrystalline tungsten; and at $6 \times 10^8$ volts/cm. the force is great enough

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Figure 1
Fowler-Nordheim Theory

- Direct currents
- Pulsed currents
- Data reproduced

Figure 2
Field Emission Current vs. Voltage by Dyke
to cause the field evaporation of tungsten atoms from the electrodes.\(^{(3)}\) Hence, at electric fields somewhere between \(10^7\) and \(10^9\) volts/cm. a catastrophic failure of the electrodes should be expected.

In general, experimenters have observed electrical breakdown at fields far less than those indicated here, whereas the currents observed have been far greater than those predicted by the Fowler-Nordheim theory. For example, sizeable currents are often observed at fields below \(10^5\) volts/cm. and breakdown is frequently a problem at fields in excess of this value.

III. Experiments with Electric Fields Greater than \(10^7\) Volts/Cm.

The only experiments in which something like these predictions occur involve the use of the Müllér field emission microscope. Dyke\(^{(4)}\) and his co-workers showed that for a clean single-crystal tungsten point of known geometry, the current followed a Fowler-Nordheim equation up to electric fields of 1 volt per angstrom and current densities of the order of \(10^8\) amperes per square centimeter. A curve of typical results plotted in a more usual way, i.e. \(\log i\) vs. \(\frac{1}{v}\), is shown in Figure 2. They found that breakdown occurred at a critical current density, of the order of \(10^8\) amperes per square centimeter, which happened when the fields were of the order of \(10^8\) volts/cm. At this


point, the current from the field emitter rose at least two orders of magnitude in a very short time. M"uller\(^{(5)}\) showed that when the polarity in the field emission microscope was reversed, very little current was drawn from the point; if the field were raised sufficiently, tungsten was evaporated at the expected value. With clean surfaces, breakdown could be prevented even when fields in excess of \(5 \times 10^8\) volts/cm. were applied. From these experiments we might come to the conclusion that everything is understood in these cases. In actual fact, these are not understood in detail; no quantitative explanation has been provided for the sudden transition to a high current arc in the case of the negative point. Nevertheless, these experiments showed that very high electric fields could be maintained in the point-to-plane geometry. If such fields could be maintained between large electrodes, there would be relatively little motivation to study the matter further.

IV. Experimental Results for Broad Area Electrodes

The motivation to understand the mechanism in detail does arise when we consider electrodes of dimensions comparable to the gap spacing. What happens in such cases? First of all, we typically observe that the current exceeds the Fowler-Nordheim prediction by anywhere from 2 to 20 orders of magnitude. For a typical case, at \(5 \times 10^6\) volts/cm. the current measured may be as high as \(10^{15}\) electrons per cm\(^2\) per second whereas the current predicted is of the order of 1 electron per square

centimeter per century. Furthermore, the breakdown field is consider-
ably less than $10^8$ volts/cm.; it is more like $10^5$ or $10^6$ volts/cm.
Finally, one finds that both the current and the breakdown field
depend on the gap spacing. In other words, there are phenomena which
depend not only on the measured field but also on the total voltage
between the electrodes. As to the functional dependence of current
on field we also see differences depending on the gap spacing. As a
matter of fact, the character of the current depends on the size of
the gap. For small gaps, we observe a continuous current which follows
a curve given by

$$i = Ae - \frac{Bd}{V},$$

which is similar to the Fowler-Nordheim theory in its functional de-
pendence on the voltage, $V$, and the gap spacing $d$. $A$ and $B$ are constants.

Typical results are shown in Figure 3 for data of Boyle, Kisliuk, and
Germer.$^6$ However, for a constant ratio of the voltage, $V$, to the gap
spacing, $d$, we find that the current actually goes up rapidly with
distance. In the case of large gaps a very different kind of phenomenon
takes place. Here we observe so-called "micro-discharges"$^7$ or

$^6$ W. S. Boyle, P. Kisliuk and L. H. Germer, J.A.P. 26, 720 (1955). This
paper is often referred to in this paper as BKG.

Breakdown distance (in cm)

Figure 3

Breakdown Voltage vs. Gap Spacing

1. W. Parkins, AEC-MDDC-858, dated April 10, 1947, copper electrodes.
7. Same as 2.
8. J. L. McKibben, aluminum electrodes.
11. ibid, molybdenum electrodes.
12. Same as 3 only d.c.
15. H. Heard, AEC-UCRL-2252, dated 1953, lead electrodes.
16. A. S. Denholm, see 14; aluminum electrodes.
pulses of current \(^{(8)}\) which merge to form a continuous current as the breakdown voltage is approached.

To try to explain these observations, to reduce the anomalously high currents and to raise the threshold value for voltage breakdown, a large amount of research has been carried out within the last fifty years. As we said before, we will of necessity have to concentrate on a limited number of experimental results, and will bring in other experimental observations as they are pertinent to the discussion. Among these are such observations as the variation of breakdown voltage and prebreakdown current on materials, on the temperature of the electrodes, on the measured value of pressure, on the surface conditions and on the duration of the voltage pulse. It is clearly beyond the scope of this paper to discuss all of these results.

A major number of experiments have been done to determine the breakdown voltage as a function of the gap spacing. Figure 4 shows a composite number of curves for a number of investigators using different materials. It is typical of this data that the differences between investigators for a given material are greater than the differences in the observed values of a given investigator for different materials. If we exclude the data from Dyke's group, we observe that the general trend of these curves shows a nonlinear dependence of the breakdown voltage, \(V_B\), on the gap spacing, \(d\).

Figure 4  
Field Emission Current vs. Voltage  
by Boyle, Kisliuk, and Germer
Cranberg \(^{(9)}\) called attention to this fact and showed that over a wide range of \(V_B\) and \(d\),

\[ V_B = C \frac{d}{2} \]  \(\text{(2)}\)

He brought forth the so-called "clump" hypothesis which attributed breakdown to the acceleration of loosely bound particles or clumps of solid material from one electrode to the other. He showed that the energy density transferred by such a clump is proportional to the product of the electric field and the voltage; on this basis he established a criterion for breakdown which seems to explain the square root law dependence. Other workers have proposed modified versions of the clump hypothesis. For example, I. N. Sivkov \(^{(10)}\) observed a somewhat different voltage-distance relationship.

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\(^{(9)}\) L. Cranberg, J. Appl. Phys. 23, 518 (1952). A criticism of Cranberg's theory is its failure to relate the constant of proportionality, \(C\), to other known physical constants of the electrode materials. If we assume that the kinetic energy of the traversing particle is converted into sufficient internal energy to vaporize it by means of the work of compression, then the constant, \(C\), can be related to other known physical constants as follows:

\[ C = \left( \frac{32 \frac{h_o}{B_o}}{\sqrt{\frac{s}{K}}} \right)^{1/4} \]

where;

- \(B_o\) = modulus of compressibility
- \(\rho\) = density
- \(h\) = heat of sublimation
- \(s\) = approximate thickness of the particle
- \(k\) = a constant which relates the average electric field to the surface charge density.

Relative voltage-holding coefficients can then be calculated giving tungsten \(= 100\), Copper \(= 65\), Al \(= 34\), etc. The derivation closely parallels that of M. A. Cook, The Science of High Explosives, Reinhold, 1958, p. 260. It is interesting to note that the necessary particle velocities are roughly equal to the plasma velocities found by Childs, J.A.P. 8, 622 (1937).

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and derived a modified clump theory. Other groups of observers have proposed a different class of mechanisms for breakdown. These involve the regeneration of positive and negative charged particles at the electrode surfaces, the cross-section for a regenerative process varying with the total voltage between the electrodes.

Our laboratory at the University of Illinois has been carrying out experiments in the last year or two to assess the various theories of breakdown and to obtain data in regions in which it was not previously possible to draw conclusions. Among the experiments which have been carried out:

(11) L. C. Van Atta and R. J. Van de Graaf, Phys. Rev. 43, 158 (1933) proposed a regenerative process involving electrons and positive ions. However, B. Aarset, R. W. Cloud, and J. G. Trump, J. Appl. Phys. 25, 1365 (1954) found that the cross-section for the secondary production of electrons by high energy ions was too small to support such a mechanism up to 2 Mev. Furthermore, A. I. Bennett, J. Appl. Phys. 28, 1251 (1957), carried out a definitive experiment involving all regenerative processes initiated by electrons. He found that in the voltage range below 150 kv, the overall regeneration coefficient was less than 10 as compared to the minimum value of unity required for arc initiation. Also M. Raether, Quarterly Progress Rept., Coordinated Science Laboratory, University of Illinois, for March, April, May, 1960, has shown in an ultrahigh vacuum experiment that for voltages up to 12 kv, the ratio of positive to negative currents does not exceed 10^-6 up to the point of breakdown.

J. L. McKibben and K. Boyer, Phys. Rev. 82, 315 (1951), proposed a regenerative process involving positive and negative ions. L. T. Leland and Roy Olsen, Los Alamos Scientific Lab. Rept. AEC-LA-2344, conclude from their experiments between 25 kv. and 200 kv. that the regeneration coefficient (the product of the respective cross-sections) is an order of magnitude too small to sustain a breakdown. In the range of energies covered, the observed yield of secondaries was a constant to within experimental error; if anything, they noted a decrease in yield at higher energies. Recently, however, W. K. Mansfield, Brit. J. Appl. Phys. 11, 454 (1960), measured coefficients as high as 0.5 for the regeneration of positive and negative hydrogen ions at an energy of 250 kev. (Arnal's theory, Annales de Phisique 10, 830 (1955)).

As things stand at present, experimental observations seem to exclude surface regenerative processes as a cause of breakdown for voltages below 200 kv. Neither experimental observations nor theoretical considerations of the voltage and electric field dependence of these cross-sections provide a plausible explanation of the observed variation of breakdown voltage with gap spacing in any voltage range.
out are the following. In an experiment designed to test the clump theory, Dr. M. Raether\(^{(12)}\) obtained a totally negative result in attempts to detect the formation or transport of clumps for gap spacings of fractions of a millimeter and voltages of the order of 20 kilovolts. Dr. E. Lyman undertook the study of breakdown for the range between the very small gaps of Boyle, Kisliuk and Germer, and larger gap spacings which have been studied in the past. However, Lyman uses ultrahigh vacuum conditions in both regions to see whether the difference in the character of the results is attributable to the difference in vacuum techniques. Finally, we have studied in detail the papers of a large number of workers, to try to understand the mechanisms for breakdown and to develop a self-consistent picture for the process.

V. Experiments of Dyke's group and of Boyle, Kisliuk and Germer

Let us first consider in detail the experiments and theories of Dyke, and of Boyle, Kisliuk and Germer. As noted above, Dyke's work was done in a field emission microscope geometry in which the fixed gap spacing was large compared with the size of the cathode point electrode. In such a case the region in which most of the voltage drop occurs is small compared with the gap and is determined by the shape of the electrode. Since Dyke could calculate the magnitude of the electric field at the point, it is possible to define an effective gap spacing \( d_{\text{eff}} = \frac{V}{E} \), and hence to compare his results on breakdown for different effective gap spacings with those of other workers. This is shown in Figure 5; the curve with solid points is

\[^{(12)}\] M. Raether, Quarterly Progress Rept., Coordinated Science Laboratory, University of Illinois for September, October, November, 1960.
Figure 5
Breakdown Voltage vs. Effective Gap Distance
for Dyke, et al., and BKG

Figure 6
Field Magnification, $\beta$, vs. Gap Distance
due to Dyke, the other to Boyle, Kisliuk and Germer. This comparison is very interesting for several reasons. First of all, the range of values of \( d \) covered in Dyke's research is nearly the same as that of Boyle, Kisliuk and Germer. Secondly, both groups of workers used tungsten electrodes and modern ultrahigh vacuum techniques, which made it possible to have atomically clean surfaces. Finally, although the indicated breakdown fields of the two researchers differ by an order of magnitude, they are both significantly higher than those of the majority of other workers.

Despite the above similarities, the two groups proposed mechanisms for breakdown which differ in a significant manner. Dyke observed that as the voltage is increased the field currents obey the Fowler-Nordheim type of relationship until a critical current density is reached. He showed that when the power dissipated in the cathode point is sufficient to melt it, a sudden increase in current is produced. For the breakdown mechanism, Dyke postulates that the metal vapor released at the melting point is ionized by the electrons and neutralizes the space charge surrounding the point. He does not say why this should happen coincidently at the melting point of the tungsten\(^{(13)}\) nor does he give an analysis which quantitatively explains the space charge neutralization\(^{(14)}\). However,

\(^{(13)}\)It does not seem likely that the relationship between the melting point and the vapor pressure can play a general role in voltage breakdown, since common metals differ by as much as 10 orders of magnitude in vapor pressure at their melting points; furthermore there is no discontinuity in the vapor pressure at the melting point. One would expect, rather, that the major discontinuities at the melting point would be in such mechanical properties as the surface diffusion coefficient or the strength of the materials.

\(^{(14)}\)In fact I. I. Gofman, et. al., Izv. Akad. nauk UzSSR, Ser. fiz-mat. 6, 72 (1960), seriously questions the presence of any space charge limitations at fields up to \( 10^8 \) volts/cm.
Dyke demonstrates beyond question that in view of the relatively large gap space and the short interval during which voltage is applied, the time of flight of any particle across the gap is so large as to exclude any anode mechanism from the breakdown process.

Boyle, Kisliuk and Germer propose a different mechanism. They also attribute breakdown to field-emitted electrons from the cathode, but they explain the arc formation as due to the heating of the anode. They postulate that upon applying the breakdown voltage, the power input to the anode is sufficient to raise it to the boiling point; the resulting tungsten ions travel to the cathode and release enough additional electrons to cause arc formation. Although the authors agree that it is not reasonable to expect the observed increase in current as a consequence of collective space charge neutralization, they postulate a mechanism wherein individual ions so depress the potential barrier at the surface as to pull out additional electrons.

Let us see how Boyle, Kisliuk and Germer explain the vaporization of the anode. Figure 3 shows currents versus voltage from a typical BKG run. For currents of 10 milliamps of 2000 volts, this represents approximately 20 watts. Now how can tungsten be brought to the boiling point in one microsecond with this power input? Boyle, Kisliuk and Germer propose the following explanation. If we assume that the field emission follows the Fowler-Nordheim theory, the shape of the curve (in Figure 3) shows that the current must originate from a single point. If two or more points were effective, the curve would be concave upward with the region with the larger area contributing most of the current at low voltages and the region with larger field multiplication dominant at high voltages. Then, they obtain the area of the emitting point from the intercept of this curve
and the value of the electric field from its slope. The curve shown gives
an emitting area which is of the order of $3 \times 10^{-11}$ cm$^2$ or approximately
500 angstrons in diameter. If we then compare the effective field strength,
$E_{\text{eff}}$, with the ratio of the measured voltage to the measured distance, we
get a field multiplication factor, $\beta$, which is related to the measurements
in the following way:

$$E_{\text{eff}} = \beta \frac{V}{d}.$$  (3)

By determining $E_{\text{eff}}$ or $\beta$ as a function of the measured gap spacing, $d$,
Boyle, Kisliuk and Germer get the curve shown in Figure 6. From these data,
it is possible to understand the anode heating on the basis of the following
picture. The field emission current comes from a single very sharp point.
It is concentrated in a very limited area in which the field may be as high
as 30 times the measured value. If the gap spacing is very small the
current will heat the anode in a localized region. On the basis of these
considerations it must be admitted that a mechanism exists for localized
heating of the anode. However, a review of the BKG calculations on anode
heating and of the proposed mechanism for current amplification has led us
to a different interpretation of their results. This interpretation can
most readily be appreciated if we use the values of the effective field
as obtained from their measurements to replot their data for breakdown
voltage as a function of $d$. If, with their experimental data, we plot
a curve of $V_B$ versus $d_{\text{eff}}$ where, from equation (3),

$$d_{\text{eff}} = \frac{V_B}{E_{\text{eff}}} = \frac{d_{\text{measured}}}{\beta}.$$  (4)
we get the curve in Figure 7. The curve of Dyke, et al., similarly plotted, is shown for comparison. From these curves, we observe an excellent agreement between the results of Dyke and his co-workers and of Boyle, Kisliuk, and Germer, not only as to the slope but also as to the magnitude of the breakdown field, a concept we can confidently use in view of the linear dependence of the breakdown voltage on the gap spacing. It is interesting to note that in addition to this unusually good agreement in the breakdown field, unrecognized by the authors of these papers, there is also an agreement in the observed formative delay and arc formation times. Both authors used microsecond pulses and observed that the time during which the arc was formed was of the order of $10^{-8}$ seconds.

This now clearly reopens the question as to whether it is reasonable to propose two entirely different mechanisms to explain the results of the two experiments, one involving a source of vapor at the cathode, the other at the anode. Certainly, the cathode phenomena dominate in the Dyke experiment, and we believe that the cathode phenomena must dominate in both experiments. In the first place, the general agreement in results seems to be good evidence that the phenomena are similar. Secondly, there is no

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(15) The formative time delay, as defined in these considerations, is the time interval between the application of the pulse and the time at which breakdown is initiated. The rapid build-up of current takes place in the order of 1 to 10 nanoseconds ($10^{-9}$ to $10^{-8}$ sec.). During the formative period the current may increase, but only by a small factor. The formative time is dependent on the amount of over-voltage applied. H. Heard, Univ. of Calif. Rad. Lab. Rept. AEC-UCRL-2251 (1953), using pulses of length 80 nanoseconds, found it possible to attain breakdown with formative times as short as 10 to 40 nanoseconds. However, the rapid build-up of current occurred in times comparable to those of other investigators.

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(16) It should be noted, however, that the agreement of Figure 7 might be fortuitous since the power densities are both exponential functions of the electric field. However, since the power delivered to the anode is a linear function of the current density and the power density generated beneath the anode surface is a quadratic function of the current density, it would be fortuitous indeed if one could get such good agreement between the experiments over three orders of magnitude if both theories were operative.
Breakdown voltage (in volts) vs. Breakdown distance (in cm)

Figure 7
Breakdown Voltage vs. Effective Gap Distance Spacing
BKG compared to Dyke, et al.

Figure 8
Breakdown Voltage vs. Gap Distance
evidence in the BKG experiment of Townsend amplification of the current prior to breakdown, which we would expect if the gas originates at the anode. Finally, the mechanism proposed by BKG for the amplification of current seems subject to considerable question (17).

VI. Comparisons with Other Data

As I said before, Dr. Lyman of our laboratory has been carrying out experiments intended to examine the region of gap spacing between the very small gaps below 1/10 mm and the larger gaps above 1 mm. These are done in ultrahigh vacuum with surfaces as clean and smooth as is possible with modern techniques. Figure 8 shows his preliminary results for tungsten. They are presented in this form to relate them to both Dyke's and Boyle's results. The dotted line is an extension of the results of BKG, assuming the asymptotic value $\beta = 30$ for the field multiplication factor. We see that, although there is a disagreement in magnitude by roughly a factor of 2, Lyman's results are very similar to these authors' results for voltages below 100 kv, and gaps below 1 mm. In this region there is a linear variation of breakdown voltage with gap spacing. However, Lyman found that at larger gaps even with ultrahigh vacuum conditions, there is a departure from linearity and, in fact, his results seem to merge with those of earlier workers as shown in Figure 9. While I wish to stress that these are preliminary results and are being repeated at the present time, I think they are indicative of a change in the mechanism for breakdown at a value of $d$,

(17) P. Kisliuk, J. Appl. Phys. 30, 51 (1959), concludes that "electron emission due to the thinning of the potential barrier by ions approaching the barrier at high fields ...... is not expected to be of importance in high vacuum breakdown because of the high velocity of the ion."
Figure 9
Breakdown Voltage vs. Gap Distance
of approximately 1 mm. It may well be that at this point, the clump mechanism becomes dominant. As for the discrepancy of a factor of 2 in the breakdown field for small gaps, this might be explained in one of two ways. In the first place, Lyman's results were taken with d.c. voltage rather than with short pulses, and a lower breakdown field might be expected. There is also a possibility that for his electrodes, which were of the order of one inch in diameter, the field amplification factor might be larger than those of Boyle, Kisliuk and Germer. Experiments are now being carried out to try to determine $\beta$ for these electrodes. In any case, the nature of the voltage-distance dependence at higher gap spacing suggests a different mechanism. Further study is needed to identify this mechanism.

In any case, Lyman's data confirms the existence of a field dependent phenomenon for gaps below 0.5 mm and suggests large field multiplication factors at very small gap spacing. Most of the data which have been accumulated in the literature have fallen in the region of gap spacing between 1 mm and 1 cm. In this limited region of gap spacing, the breakdown voltage seems to vary with the square root of the distance. It seems desirable to study and extend this region of gap spacing, if possible, under conditions of true cleanliness so as to gain further insight into the mechanisms which take place.

Let us return to the discussion of small gap breakdown. The principal question which remains seems to be the following: is it possible to have points at a broad area electrode surface which cause field amplifications as high as 50, and, if so, how do the points arise? We have initiated a program to examine whether points do, indeed, appear on such a surface.
There is considerable evidence to this effect in the literature \(^{(18,19,20)}\). However, much of the evidence is indirect and does not provide an actual observation of the formation process. With this in mind, a program has been undertaken to examine surfaces for the existence and development of such points. This work is being carried out by Mr. H. Tomaschke and has as its objective the study of the detailed structure of electrode surfaces with an electron microscope. Since the results of Boyle, Kisliuk and Germer suggested the existence of points with a diameter of a few hundred angstroms, we should be able to see these with a modern electron microscope. Thus far our results are quite preliminary; they were obtained with the use of an old and rather dirty electron microscope with a maximum resolution of about 2500 angstroms. Hence, it was not possible to see the detail which we sought. However, we show in Figures 10 through 14 some photographs taken with this microscope which show the results of repeated application of voltage. Figure 10 shows the two tungsten electrodes which, as you see, are of the order of several microns in radius separated by two or three microns. Figure 11 shows the cathode subsequent to being electro-polished, but immediately after insertion in the dirty environment of the electron microscope. Clearly there is a sizeable amount of occluded material, such as dust, oil or other impurity. After one breakdown, the cathode appeared as shown in Figure 12. Obviously, one breakdown was sufficient to remove


most of the loosely held material. Figures 13 and 14 show the cathode surface after successive breakdowns. These photographs show that the electrodes do develop irregularity as breakdown proceeds. There is some evidence for sharp points, but we must have much better resolution (by a factor of 25) before a definitive statement can be made.

As things stand, considerable evidence does exist, both from our own work and that of others, which indicates that enhanced emission originates from a small number of points or whiskers, and that this phenomenon initiates electrical breakdown between electrodes at small gap spacings. Denholm has suggested that these points may grow due to surface migration under the combined action of high electric fields and the thermal effects due to localized field emission.

As to the actual step-by-step processes leading to breakdown, the situation cannot yet be accurately defined. That is, the sudden increase in currents from relatively stable field currents of the order of milli-amperes to arc currents of the order of amperes or greater (the arc current is limited principally by the external circuit parameters) in times of the order of 10 nanoseconds ($10^{-8}$ seconds) has not been explained in detail. It is difficult to visualize a sizeable increase in current density above the maximum observed values of $10^8$ amps/cm.$^2$ from a given individual point. Both Dyke, et al. and BKG propose mechanisms whereby the presence of evaporated atoms enhance the emission of electrons by affecting the field
in the vicinity of the point. Both treatments are open to serious question and lead us to propose that the field emission process is stable so long as the point maintains its original geometry. However, when the metal reaches the melting point, catastrophic changes in the configuration of the emitter whisker may take place and both the emitting area and the field magnification can change in a drastic manner. In fact, the resulting heating of the point could easily vaporize it. These considerations lend credence to the possibility proposed by Flynn (24) for the formation of a cloud of plasma or a "plasma jet" originating at the cathode. In any case, a catastrophic change in the shape of the point is observed after breakdown.

VII. Summary

To summarize our present status, we have analyzed existing data and taken new data which indicates that for gaps below 1 mm, electrical breakdown is field dependent. We have presented a phenomenological picture for small gap spacings which involves the initiation of electrical breakdown by the vaporization of cathode points. For gaps above 1 mm, the process seems to have

(21) I. Langmuir, Phys. Rev. 33, 954 (1929), for example, showed that for a plane parallel configuration there is an upper limit to the effect of space charge neutralization on the enhancement of current. For instance, the space-charge limited current due to an infinite sheet of negatively charged particles can at most be increased by a factor of approximately two. It has not been demonstrated that the extrapolation to the actual point-to-plane configuration would change the maximum enhancement factor appreciably.

(22) T. Tucker, J. Appl. Phys. 32, 1894 (1961) and private communication. Using exploding wire techniques, Tucker showed that for tungsten wires of .001 inch diameter, it is possible not only to melt but to vaporize the metal in a few nanoseconds with current densities through the wire of roughly $10^8$ amps/cm$^2$.

(23) F. Webb, H. Bingham, and A. Toolestrup, Phys. of Fluids 3, 318 (1961), completely vaporized and partially ionized a .001 inch diameter aluminum wire in 40 nanoseconds time at current densities of $4 \times 10^8$ amps/cm$^2$.

(24) P.T.G. Flynn, Proc. Phys. Soc. B68, 564 (1955), has proposed this mechanism for the discharge triggered in high-vacuum x-ray tubes. In his picture, as the plasma jet proceeds from the cathode, the effective gap decreases. Hence the electric field increases rapidly with time and produces the observed increase in total current.
a different dependence of breakdown voltage on gap spacing; it would seem that a voltage dependent phenomenon such as the transport of charged macroparticles enters the picture. At larger gap spacings, data has not been taken over a sufficiently wide range to determine the voltage-distance law with great accuracy. More data should be taken at very high voltages and the question of regenerative processes should be investigated in this region under ideal conditions of cleanliness and vacuum.