GENERAL ELECTRIC

GENERAL ELECTRIC COMPANY
CORPORATE RESEARCH AND DEVELOPMENT

Schenectady, N.Y.

A STUDY OF THE DIELECTRIC PROPERTIES OF ELECTRODE SURFACES WHICH HAVE BEEN SUBJECTED TO ARCING AT HIGH CURRENTS IN VACUUM

by

G. A. Farrall and R. H. Johnston, General Physics Laboratory

Report No. 71-C-134 May 1971

TECHNICAL INFORMATION SERIES

CLASS 1

GENERAL ELECTRIC

General Electric Company
Corporate Research and Development
Schenectady, New York

TECHNICAL INFORMATION SERIES

AUTHOR Farrall, GA Johnston, RH	SUBJECT breakdown	NO. 71-C-134 DATE May 1971
TITLE A Study of the Dielectric Properties of Electrode Surfaces Which Have Been Subjected to Arcing at High Currents in Vacuum		GE CLASS 1 NO. PAGES 11
ORIGINATING COMPONENT General Physics Laboratory		CORPORATE RESEARCH AND DEVELOPMENT SCHENECTADY, N.Y.

SUMMARY

A study has been made of the dielectric properties of electrode surfaces subject to arcing at levels ranging from 100 to 45,000 peak amp. The same electrode surface was maintained as arc cathode throughout the experiment. The single half-cycles of arcing were programmed so that the next level of current to be studied was higher than the preceding.

After each arc, measurements were made of the prebreakdown emission from each electrode surface (arc cathode and arc anode) separately. A sequence of 100, 2 μsec pulses was then applied with first the arc cathode electrode as pulse cathode and then the arc anode surface as pulse cathode. Since the Fowler-Nordheim plot obtained from prebreakdown emission measurement is most likely to be unique for a given emitter or emitter complex, the plots themselves can be used as a guide to determine whether or not a dominant emitter complex present before an arc has survived and is still dominant after the arc. From such measurements it was found that for the 2-inch-diameter copper electrodes used in this study, a current of about 5000 amp was required to wipe out consistently reappearing arc cathode emitters. A still higher current is required to consistently remove persistent anode emitters.

The breakdown measurements show that, although some degradation of breakdown voltage occurred on both anode and cathode surfaces due to arcing, this effect was not a strong function of current. Further, the anode fared no worse than the cathode surface even after arc currents at which anode melting must have occurred.

From the measurement of slopes of the Fowler-Nordheim plots it was found that emitters having relatively low field enhancement factors were present after arcing at high current even when anode melting was clearly present. Attempts to predict breakdown voltage, by applying the results of the emission measurements to a conventional cathode dominated breakdown model, were not successful.

KEY WORDS breakdown, breakdown in vacuum, high current arcs

INFORMATION PREPARED FOR ______________________

____

Additional Hard Copies Available From
Corporate Research & Development Distribution
P.O. Box 43 Bldg. 5, Schenectady, N.Y., 12301

Microfiche Copies Available From
Technical Information Exchange
P.O. Box 43 Bldg. 5, Schenectady, N.Y., 12301

RD-54 (10/70)

CONTENTS

Page

A STUDY OF THE DIELECTRIC PROPERTIES OF ELECTRODE SURFACES WHICH HAVE BEEN SUBJECTED TO ARCING AT HIGH CURRENTS IN VACUUM

G.A. Farrall and R.H. Johnston

I. INTRODUCTION

When a vacuum gap is subjected to high voltage, a small emission current can be observed passing between the electrodes. This current originates from one or more microscopic areas on the cathode surface. The variation of this emission with voltage is often used to assess the ability of the gap to withstand high voltage. Because the range of currents and voltage over which emission can be measured is large, it is likely that the emission characteristic--the dependence of current upon voltage--is unique for a given set of emitters on the electrode surface. That is, if one observes an experimental emission characteristic from a given electrode surface and then completely alters that surface as perhaps might be done by the passage of a high current arc, the emitters on that surface might well be changed. Thus, the emission characteristic obtained afterwards would be different from that obtained previously. On the other hand, if the arc failed to destroy the dominant emitters and did not produce other stronger emitters, the emission characteristics should remain unchanged.

Uniqueness attributed to emission characteristics is, of course, an assumption since in most practical cases we cannot see the microscopic areas from which the emission originates. However, the wide range of voltage and current over which emission is possible as well as the possible variations in the detailed shape of a given emission characteristic make it very unlikely that two different collections of emitters will produce the same result. The uniqueness assumption is, therefore, regarded as valid and is used in the present study to assess the extent to which single arcs alter the emission properties of the arc cathode and arc anode surfaces.

A second part of this experiment consists of measuring the breakdown voltage of the gap after arcing using the arc cathode and arc anode successively as cathode to the high-voltage pulse. Since the initiation of breakdown is regarded as essentially dominated by the electrode which is cathode to the applied high voltage, this procedure is intended to demonstrate the deterioration by the arc of breakdown voltage observed for the arc anode and arc cathode surfaces separately.

The third part of this work is an attempt to relate observed breakdown voltages to emission measurements.

II. PROCEDURE

The objective of the experimental procedure followed was to conduct emission measurements and breakdown measurement on electrodes which had been subjected to arcs having peak currents ranging from 100 to 45,000 amp. The electrodes used were copper, 2 inches in diameter, and were freshly machined to remove all traces of cathode tracking and anode melting produced during previous use. These were installed in the device shown in Fig. 1. The levels of arc current studied were low at the beginning of the experiment and increased in steps so that in no instance was a trial at one current followed by a trial at a lower current during the main interval of the experiment. Further, the polarity of the arc, with one exception, was the same throughout the work.

The detailed procedure was as follows. The fully open gap length was adjusted to 6.7 mm (≈1/4 inch) with the tube mounted on an operating mechanism. Following manual closure of the gap, the mechanism was opened by solenoid to draw an arc having a peak current of some predetermined value. After the arc, the gap was shortened without touching the opposing

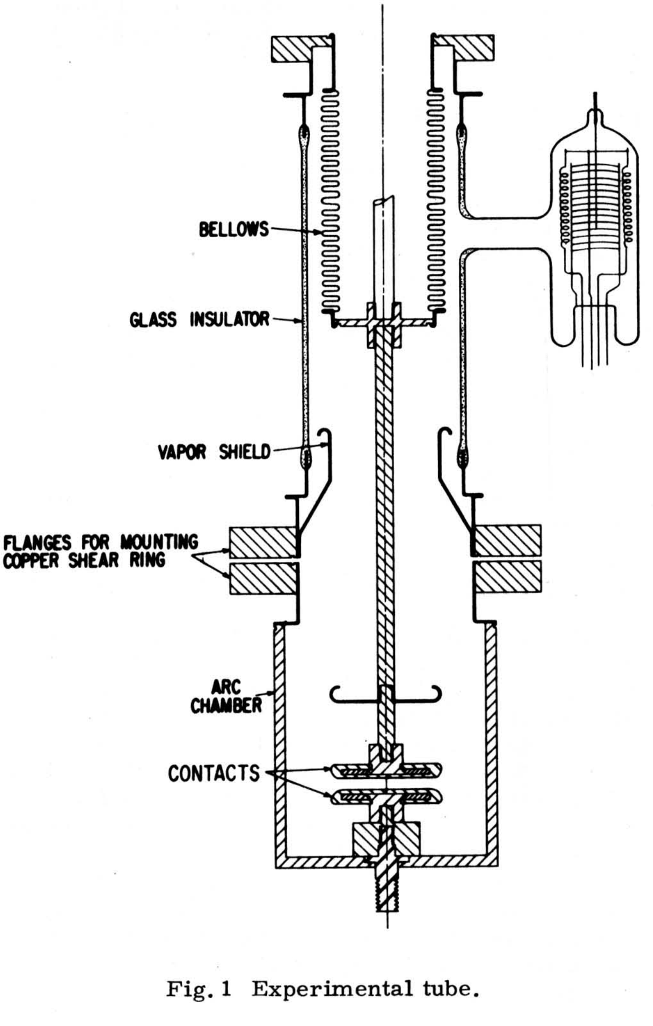

Fig. 1 Experimental tube.

surfaces to 2 mm and then DC high voltage applied to the gap with the arc cathode surface initially negative. Emission current, commonly less than a microampere, was measured as a function of high voltage for both increasing and decreasing steps of voltage. Following this the polarity of the high voltage was reversed in order to measure the emission from the arc anode surface. Next, the gap was subjected to a sequence of 100 high-voltage pulses. These pulses had a time width of about 2 μsec and, in the absence of breakdown, rose to a maximum value of 100 kV. This was sufficiently great that breakdown occurred on the rise of each pulse. The level of voltage breakdown for each pulse was recorded, and the polarity of this sequence of applied pulses was such that the cathode during breakdown was the original arc cathode. Following this series of pulses, the emission measurements described previously were repeated for both electrode surfaces. Then a second series of 100 high-voltage pulses was applied to the gap with the breakdown cathode situated at the old arc anode surface. Finally, a third group of emission measurements was obtained for both electrodes. This concluded one full cycle of measurement for a single half-cycle arc. Because of the rather extensive measurements associated with each arc, only two arcs were studied at each level of current. The levels of current were increased in a 1, 2, 5 log sequence starting at 100 amp and continuing to about 50, 000 amp.

III. EXPERIMENT

The emission measurements for the two electrode surfaces prior to arcing are shown in Fig. 2. The data have been plotted with current in microamperes divided by kilovolts squared, as a function of reciprocal kilovolts. (If the observed emission is produced by the field emission process the data points for such a plot should lie on a straight line.) A major difference between the two electrode surfaces is the magnitude of current which is observed for each at a given voltage. This difference is in part due to the asymmetry of the field in the experimental tube where one electrode is electrically common to the arc chamber. This effect is important to the emitters on the edge of the electrodes.

A. The Change in Emission with Arcing Current

Emission data recorded after the first 100 amp arc are similar to those obtained prior to arcing and are given in Fig. 3. After arcing, however, the level of emission current for the arc cathode surface at a given voltage is three to four times greater than before. The detailed dependence upon voltage, however, except for this constant factor, is essentially the same. The emission from the anode surface lies in the same range as before but rises somewhat more rapidly than before at higher voltage. The arc cathode thus appears to have been essentially unchanged where the anode shows slight modification perhaps produced by deposition of metal vapor eroded during the arc.

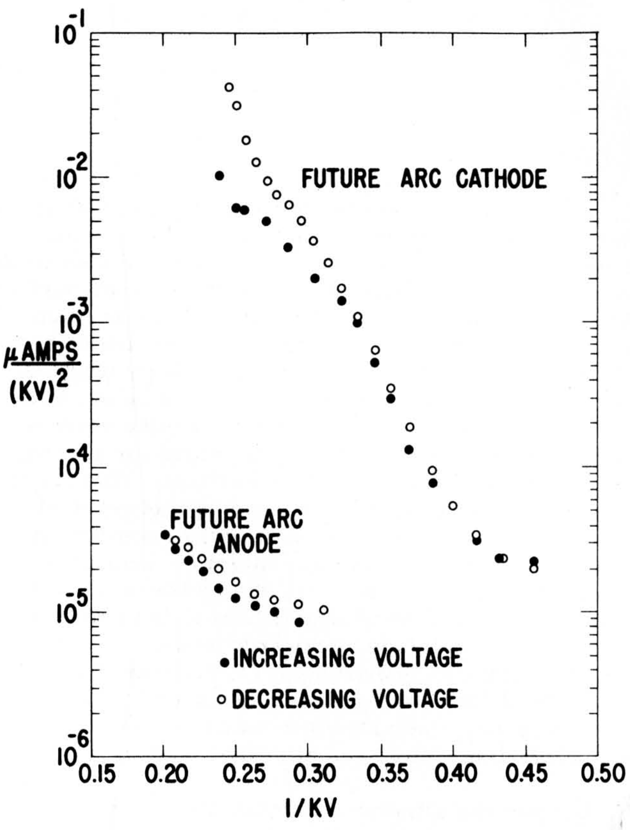

Fig. 2 Emission characteristics of each electrode prior to any arcing.

During the subsequent few low current trials there were more extensive changes in the cathode and minor changes in the anode emission after arcing. At moderately higher currents, however, the arc does not seem to produce any major changes. In Figs. 4(a) and (b) we compare emission characteristics of the anode and cathode surfaces obtained prior to a 500 amp arc with those recorded following a 1000 amp arc. The curves for the respective electrode surfaces are markedly alike despite the fact that in the time interval between, the contacts had been subjected to two arcs at 500 amp and one arc at 1000 amp. Further, each electrode surface had been cathode to a pulsed electrical breakdown 200 times. In Fig. 5 is shown the emission curve for the arc anode surface at a still later point in the experiment. Between the time the data of Figs. 4(b) and 5 were recorded, the anode had been subjected to three additional arcs, one at 1000 amp and two at 2000 amp, and had been the cathode to 200 pulse breakdown events. Incidentally, the first arc at 2000 amp was of reversed polarity and was the only such arc during the experiment. This was followed by two arcs at normal polarity.

While changes in cathode emission are seen

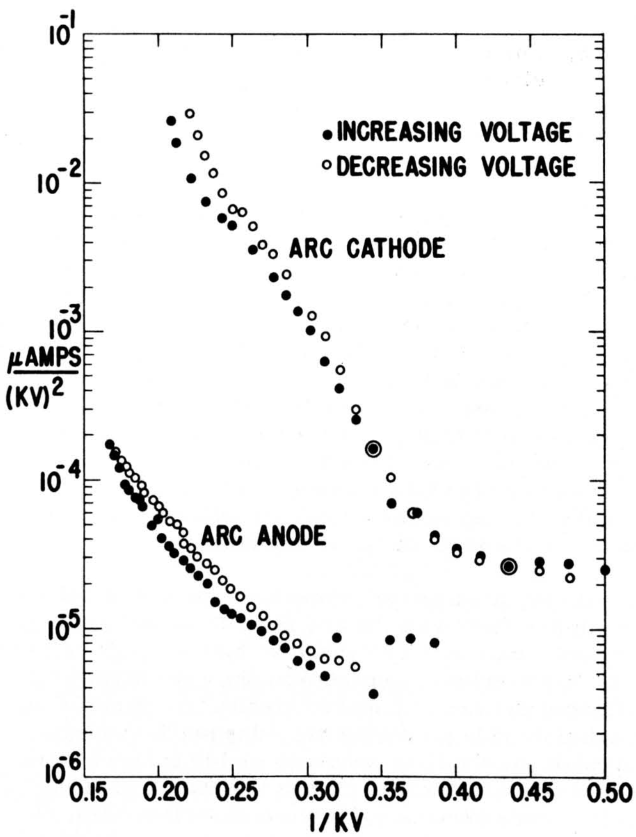

Fig. 3 Emission characteristics of each electrode following first 100 amp arc.

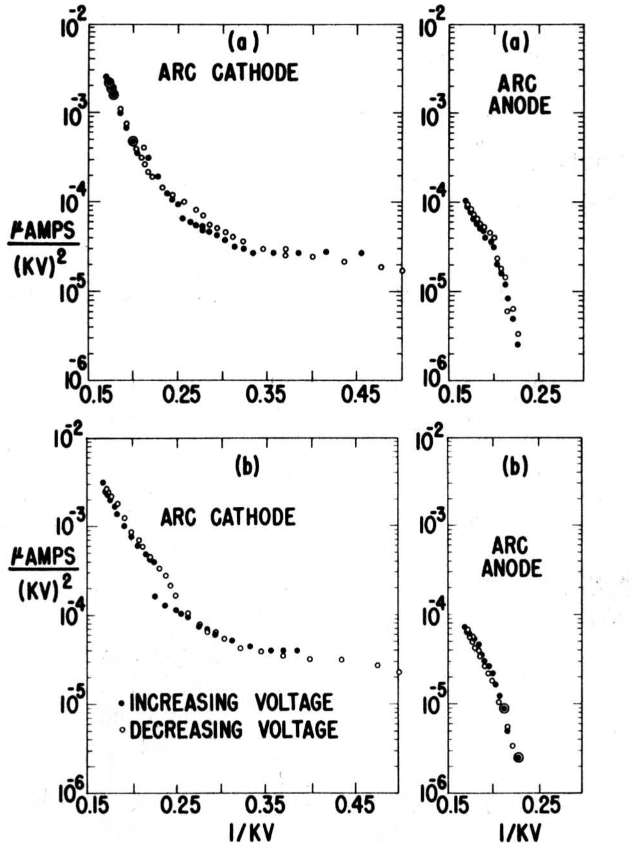

Fig. 4 Emission data for each electrode: (a) before, and (b) after two arcs at 500 amp and one arc at 1000 amp. In addition each electrode surface had been cathode to 200 pulse breakdown events.

occasionally at all currents within the range of this experiment, significant changes following each arc occur only at currents of 5000 amp and higher. At this level, the changes are quite unmistakable. We illustrate this in Figs. 6(a) and (b). These show the data recorded for the arc cathode and arc anode surfaces just before and just after the first 5000 amp arc. We note that both cathode and anode surfaces changed. On all subsequent trials the cathode surface changed after each arc, but on two 10,000 amp trials the anode surface was essentially unchanged.

It is likely that the causes for electrical breakdown between two electrodes subject to arcing is due to some defect or defects in very localized areas on the surfaces of those electrodes. We have observed in previous work that these area defects can easily be destroyed if traversed by the arc cathode spots. We assume that they also can be destroyed by anode melting. We conclude, therefore, that the breakdown between contacts subject to arcing can be controlled by the prior history of the contacts rather than by present arcing providing that the current is below some limit. In the case of electrodes of this experiment we would expect that what we might term a

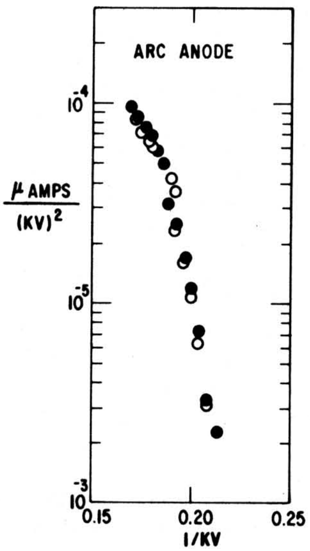

Fig. 5 Arc anode emission following one additional arc at 1000 amp, two additional arcs at 2000 amp, and 200 pulse breakdown events after Fig. 4(b).

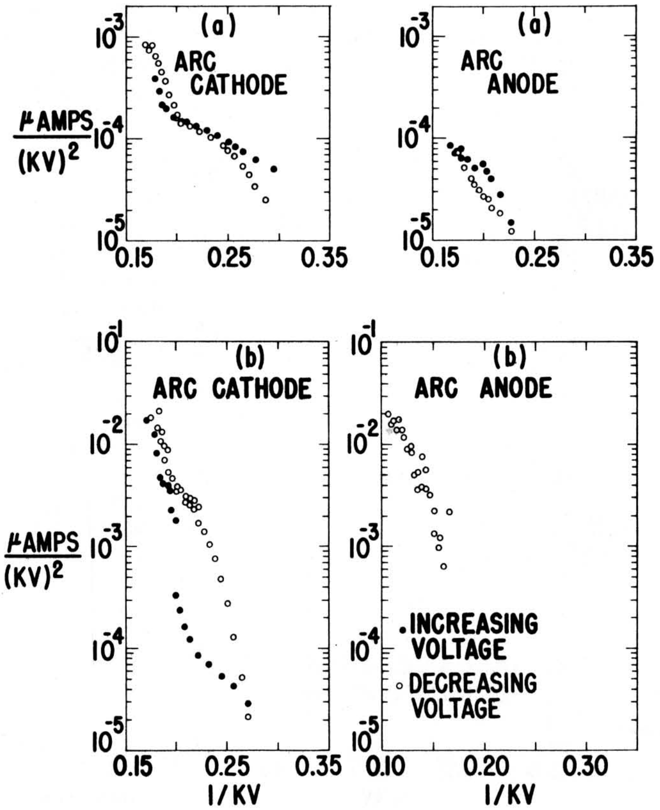

Fig. 6 Electrode emission data: (a) before, and (b) after a single 5000 amp arc.

dielectric defect in the surface of an electrode can survive an arc on the cathode surface at currents up to 2000 to 5000 amp on the cathode and a somewhat higher limit on the anode. We should emphasize, however, that this conclusion, at least for the cathode, assumes only a few arc trials. We would expect that a surface defect on the cathode will ultimately be destroyed even at 100 amp given a sufficient number of arc trials since cathode tracking, although limited to a small area of the electrode surface at 100 amp, will eventually tend to cover the entire electrode surface after repeated trials.

B. Pulse Breakdown Measurements

As was indicated earlier, each arc of this experiment was followed by:

1. Measurements of emission from each electrode.
2. 100 pulse breakdown events with the arc cathode surface as breakdown cathode.
3. Further measurements of emission from each electrode.
4. 100 pulse breakdown events with the arc anode surface as breakdown cathode.
5. Further measurements of emission from each electrode.

We are now concerned particularly with items 2 and 4.

It is the purpose of the two sequences of pulses, after the arc to determine the extent to which the arc itself has degraded the breakdown voltage of each electrode surface. It has been shown in earlier work(1) that, when two electrodes are subjected to single half-cycles of arc current, the breakdown voltage between those electrodes after the arc is lower than it was prior to arcing. It was further shown that if a sequence of pulses is applied to the gap after an arc, the breakdown voltage on the average increased with the number of pulses applied. This increase was found to be due to changes at the pulse cathode surface. The anode was little involved.

In the present experiment a sequence of pulses is applied first with the arc cathode as high-voltage cathode, then with arc anode as high-voltage cathode. The first series is expected to show the degrading effect of the arc at the arc cathode. Because of the negligible role played by the pulse anode during breakdown, the first sequence of 100 pulses is not expected to materially change the condition of the pulse anode surface. The second series, then, should show the degradation at the arc anode despite the intervening 100 pulses of the first series.

Shown in Fig. 7 is a typical series of measurements giving the breakdown voltage for each of 100 pulses applied with the arc anode as pulse cathode. These data followed a half-cycle arc at 100 amp peak current. Similar results have been obtained following each arc of this experiment for both electrode surfaces. To summarize these data we choose to average the first five breakdown values and the last 50 values. The former of these numbers is an index of the degrading effect of the arc on breakdown voltage for the electrode surface under study. The average of the last 50 is a measure of the "conditioned" breakdown voltage with the degrading effect of the arc largely removed.

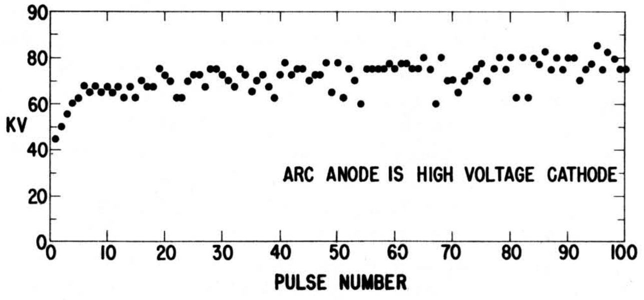

Fig. 7 Typical pulse breakdown series showing low breakdown voltage on first few pulses.

In Fig. 8 is given the average of the last 50 pulses applied to the gap after each arc for both electrodes. This should remain constant throughout the experiment. At 10,000 amp the points are specifically higher due to a slight lengthening of the gap by electrode erosion during the arc. At 25,000 amp there appears to have been both erosion and tilt of one electrode by magnetic force on the electrode support. These effects compensated for each other leaving a net gap length between areas of closest approach close to the original setting. At 45,000 amp there was more bending of the electrode support. More important than this effect, however, was the melting by the arc of the electrode surface which produced, upon cooling, thin flakes of electrode metal. These flakes tended to partially bridge the gap. These bridges could be detected by gradual closure of the gap and observing an erratic electrical continuity across the gap prior to firm closure. We shall comment further upon this effect later. It is sufficient to say at this point that this was cause for the reduction in breakdown voltage at 45,000 amp.

One consistent point that emerges from Fig. 8 is that the breakdown voltage for the arc anode surface is usually higher than for the cathode at all currents. This relationship also holds if one considers only the average of the first five pulses. These voltages would probably be about the same if there were no dissymmetry of field in the arc chamber. Evidently as far as breakdown voltage is concerned, the anode fares no worse than the cathode even at high current where anode melting can occur.

With the few trials at each current level of this experiment, it is clearly not possible to draw any accurate conclusion regarding the average value of breakdown voltage of the first pulse applied to the anode and cathode after arcing. However, the average of the first five values of breakdown considered for all arc currents used can suggest the trend of the degradation of breakdown voltage of each electrode with increasing current. In order to reduce the effect of slight variations in gap length, the average of the first five breakdown voltages have been divided by the average of the last 50 and plotted in Fig. 9. On the whole, the average of the first five pulses amounts to about 80% of the conditioned voltage. There appears to be slight trend to lower voltages at higher currents, but this effect may be due more to the accumulation of watt-seconds of arcing rather than to the specific magnitude of current. The points at 45,000 amp may be deceptive in that with the gap partially bridged by a metal flake only a very small area of each electrode may be involved in actual breakdown. In any event, there appears to be no major difference in the degrading effect of the arc at the arc cathode and arc anode surfaces.

Earlier we mentioned the melting and flaking at the 45,000 amp trial. We now consider this effect in somewhat greater detail. Observation of such particles in the gap is not new, but their effect on the performance of a device is often dramatic. Several years ago during work on an experimental high current arcing device, it was found that such particles were capable of completely spanning a 1/2-inch gap. In the present experiment, the effect observed is similar.

Toward the end of this experiment the electrodes were subjected to a single arc at 45,000 amp. Flaking was detected. In an attempt to remove the flakes, the electrodes were arced once at 200 amp, once at 25,000 amp, and then two more times at 200 amp. Following this sequence the breakdown data of Fig. 10 were recorded using the arc cathode surfaces as high-voltage pulse cathode. The electrode gap was then closed and partial bridging found still to be present.

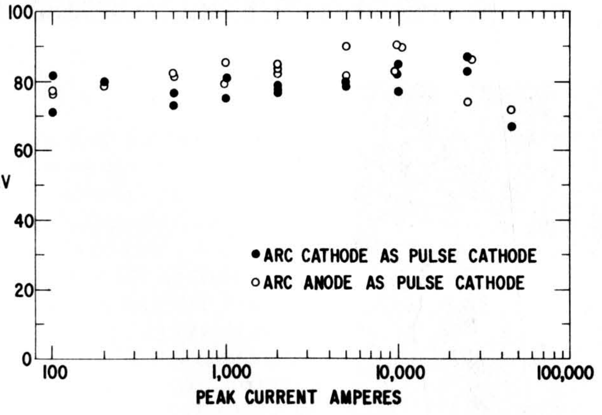

Fig. 8 Average breakdown voltage for last 50 pulses of 100 pulse sequence applied to each electrode after arcing at various currents.

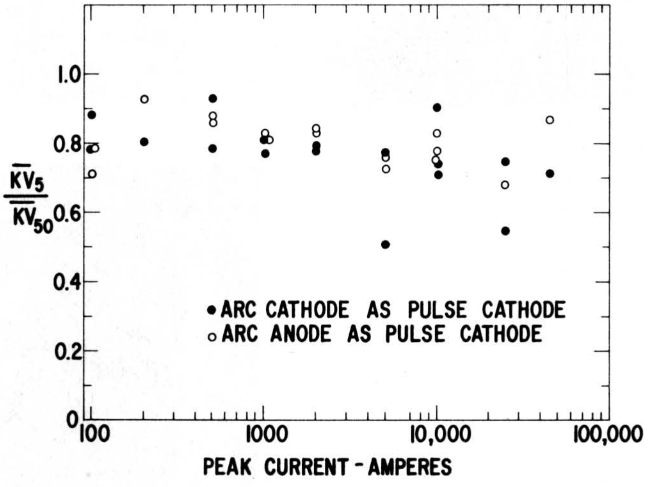

Fig. 9 Average breakdown voltage of first five pulses divided by average of last 50 pulses in 100 pulse sequence applied to gap after arcing at various currents.

The data of Fig. 10 appear to be representative of at least two different gap lengths. While we have no direct observations, it seems reasonable that the effect is produced by the raising and deflection of a copper flake on the electrode surface. This assumption was lent some credibility when the experimental tube was opened after the experiment. Figure 11 is a photograph of the electrode surfaces. On the surface of the electrode which was used as arc cathode can be seen a copper flake which stands over 3/8 inch high. As we have mentioned earlier, the arcing polarity on these electrodes was maintained the same throughout the experiment with the exception of 1 arc at 2000 peak amp. The melting visible on the cathode was apparently produced by the proximity of the cathode surface to the anode surface at a time when the anode was melting.

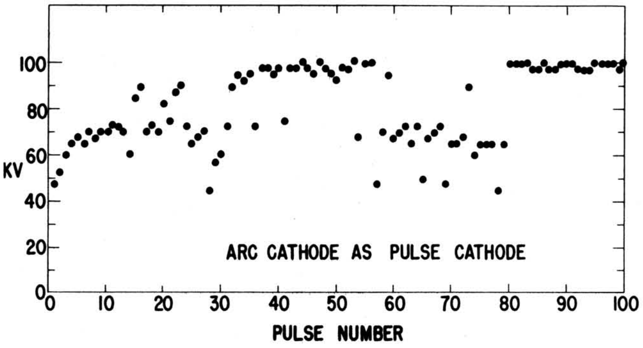

Fig. 10 Sequence of 100 breakdown events across gap following 45,000 amp arc.

The principal aim of the work of this section was to determine the relative effects of breakdown degradation at the arc cathode and arc anode surfaces. We conclude that the degradation at the anode is generally no worse than at the cathode, even at currents where melting at the anode can be expected. At high current, however, anode melting and flaking are expected to be a major detriment to voltage withstand capability.

C. The Question of Field Emission

One of the objectives of an experiment involving emission measurements in vacuum devices is to try to determine the probable mode of electrical breakdown. If the emission current as a function of voltage are plotted in the form log I/V^2 vs $1/V$, the result should yield a straight line of negative slope if simple

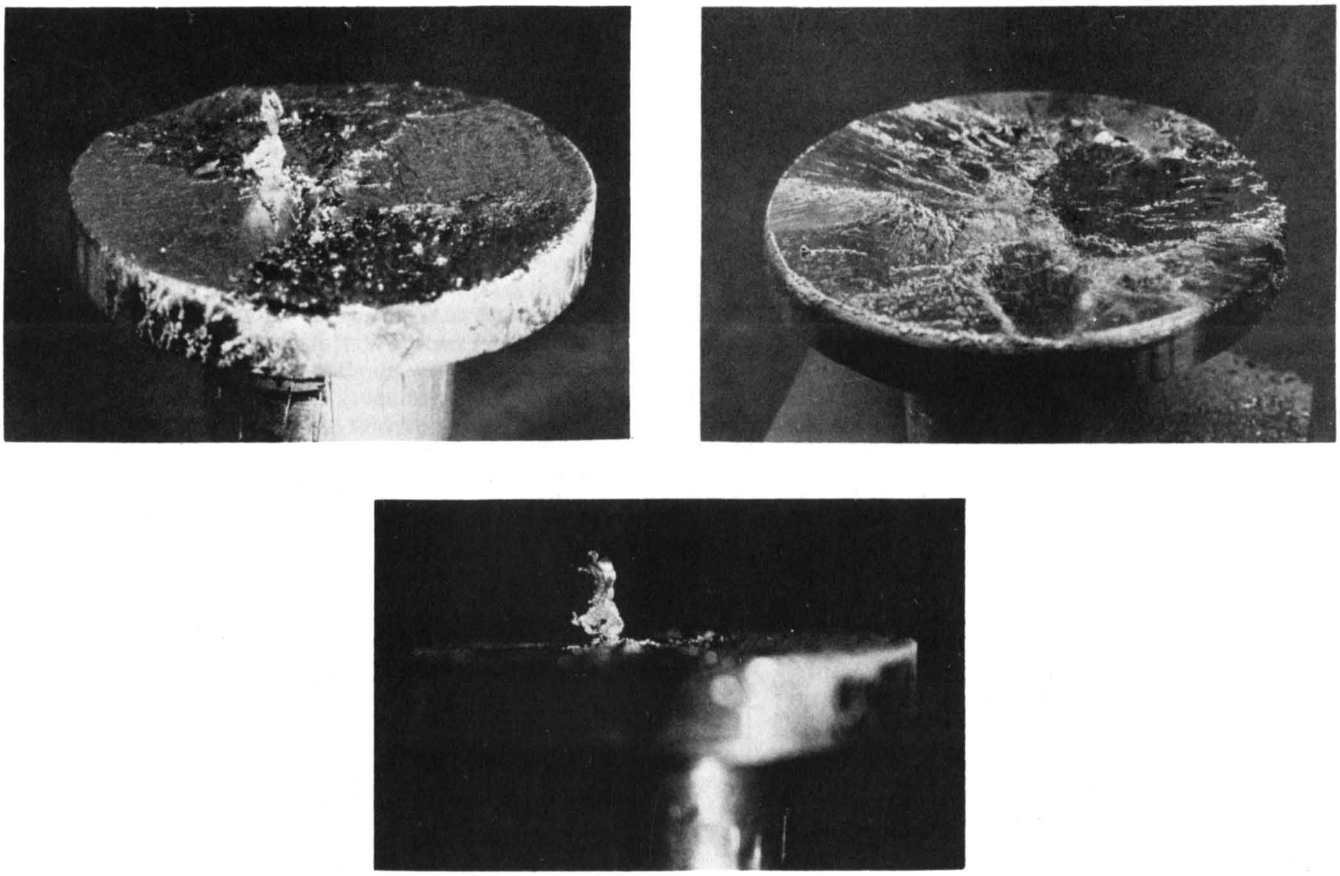

Fig. 11 Photograph of cathode (left) and anode (right) surfaces after experiment.

field emission is the cause of the observed current. This type of data presentation is called a Fowler-Nordheim plot. If, indeed, field emission is indicated, one of two probable breakdown processes is likely to occur.

The first of these occurs entirely at the emission cathode. Although the magnitude of the emission current is usually small--that is, microamperes or less--the regions from which the current originates are also small. Thus the current density can be extremely high when the emission current increases at high voltage. The current density can, in fact, become so large that the emission regions at the cathode are vaporized by Joule heating leading to the breakdown of the gap.

The second process involves interaction of the cathode emission with the opposing anode surface area. With high voltage across the gap, it can easily be appreciated that electrons originating at the cathode will arrive at the anode with considerably more energy than they had when first emitted. Therefore, it should not be surprising that the anode can, under certain conditions, be heated and vaporized by the cathode emission leading to breakdown of the gap before the cathode emitting areas themselves are vaporized.

By these two processes, then, emission can interact either at the cathode surface or at the anode surface to produce breakdown. The conditions which determine whether anode or cathode interaction is involved have been analyzed(2-4) for emitters at the cathode having simple shapes. The results of this analysis show that the decisive factors which determines anode or cathode dominance are the detailed shape of the cathode emitter, the gap length, and the thermal properties of the electrode metal.

If we consider, by way of example, a cylindrical emitter having a hemispherical cap, the factor by which an average electric field is enhanced solely to the geometry of that emitter has been shown to be(5, 6)

$$\beta = \frac{h}{R} + 2$$

where h is the height of the emitter and R is the radius of the circular cross section. A calculation of the conditions which would produce anode and cathode type breakdown is shown in Fig. 12 for this type of emitter. The figure represents a plot of a critical value of field enhancement factor, β, as a function of emitter height for a gap length of 0.19 cm, the gap used in the present experiments. The result shows that if the enhancement factor is higher than a critical value, breakdown will be dominated by the cathode. If, however, β is small, the anode process occurs. Experimentally we can determine an approximate value of β by measuring the slope of the Fowler-Nordheim plot. The details of how this is done are well documented(7) and are not vital to our present discussion. The value of h appropriate to a given experimental condition, however, cannot usually be obtained from the data and so is generally an unknown factor. From Fig. 12 it is seen that the critical value of β changes very slowly with h. We find in fact that we can generalize by saying that in order for the anode process to dominate, the β factor must lie below 500 no matter what the emitter height may be, since this is the maximum value of β attainable. Under this condition the emitter is assumed to be so long that it completely spans the gap.

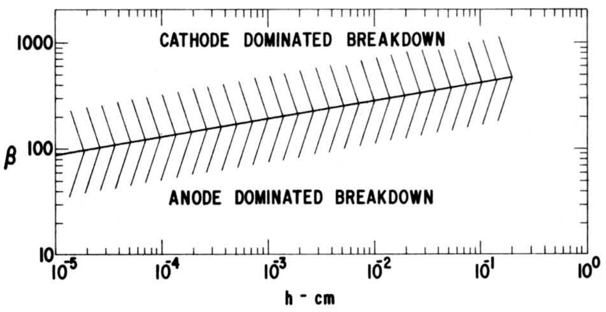

Fig. 12 Critical β value distinguishing anode and cathode dominated breakdown as a function of emitter height for a fixed 0.19 cm gap.

We now turn to data from the experiment. During the course of this work many Fowler-Nordheim plots were made. Some of these were of very irregular shape and not consistent with what one might expect of a cathode surface which is producing current by a purely field emission process. Others, however are quite respectable. We cite as examples those of Figs. 13(a) and (b). Both figures show the results of emission measurements as the voltage was first raised in steps indicated by the solid points, then decreased as shown by the open points. The log of the emission current divided by the square of the voltage has been plotted as a function of reciprocal voltage.

In Fig. 13(a) the emission was somewhat unstable as the voltage was raised and the gap finally suffered a breakdown at about 5.4 kV (1/kV = 0.185). This produced a large increase in the emission which was much more stable than that seen before so that a reasonable straight emission curve was found as the voltage was decreased. In Fig. 13(b) the emission was stable for both increasing and decreasing voltages and yielded a straight line characteristic. The slopes of the straight lines passing through the data points can, as we have suggested earlier, be measured to yield the factor, β, by which the microscopic geometry of the emitter enhances the applied electric field. It is this factor which essentially determines the local field at the emitter and thus strongly influences the applied voltage at which breakdown will occur, provided that the assumption of the field emission

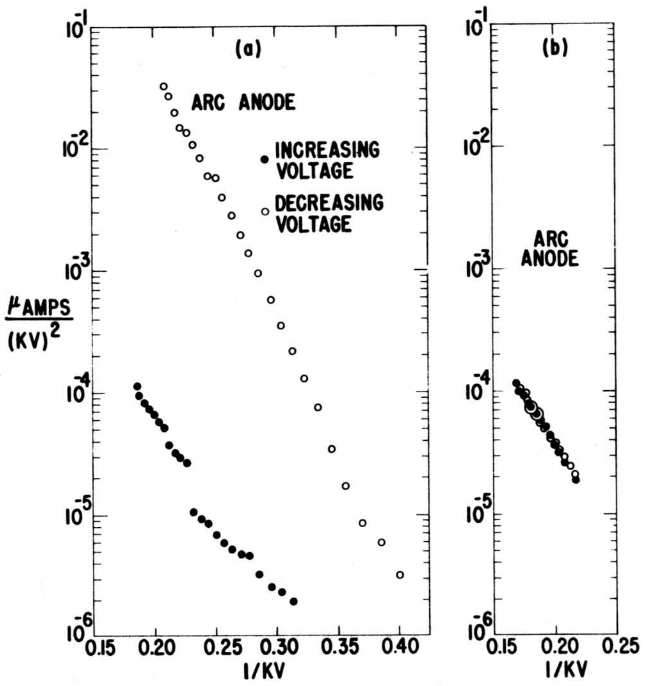

Fig. 13 Example of straight line Fowler-Nordheim plots obtained after arcing.

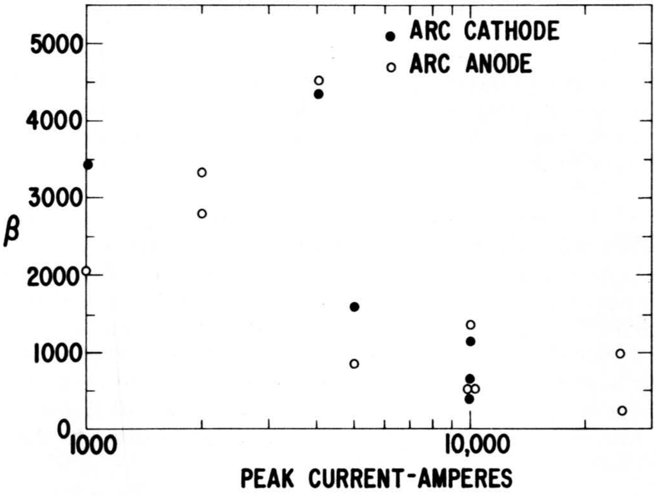

Fig. 14 Field enhancement factors computed from emission measurements following arcs at various currents.

process is valid. For a given gap length a dominant emitter having a high β factor will initiate breakdown at a low voltage. If, however, the β of the dominant emitter is low, the gap will sustain a relatively high voltage.

From the Fowler-Nordheim plots obtained during this work those showing straight line data were selected. Field enhancement factors were then computed for each and the result was plotted in Fig. 14. The experiment, as mentioned earlier, was carried out at various levels of arc current. The computed β's are plotted as a function of the particular arc current with which they were associated. We find generally that at currents below 1000 amp relatively few of the Fowler-Nordheim plots showed good straight-line characteristics. Those few however, yielded high β values in the range of 2000 to 5000. As the arc current was increased, relatively more of the plots clustered about straight lines. Despite the relatively few points on Fig. 14, a trend seems quite clear. The value of β computed from the Fowler-Nordheim curve is decidedly smaller at high current; that is, if field emission breakdown dominates, one would anticipate a higher breakdown voltage for contacts which had been subjected to arcing at high current. This result is supported by a somewhat more general observation; early in the measurement when the arc currents were below 5000 amp, about 5 kV was required to produce moderate levels of emission across the gap. After the higher current arcs at 10,000 and 25,000 amp, however, about 20 kV was required to produce the same emission levels. From a field emission view we would conclude that the gap has undergone a marked dielectric improvement after its exposure to high current. Whether this improvement is due to the cumulative effect of total watt-seconds of arc or due to the actual magnitude of current cannot at this point be determined. A significant point, however, is the fact that according to the β factor criterion the gap did not deteriorate at high current where extensive new cathode tracking and anode melting certainly occur with each arc. Since Fig. 14 contains a mix of data from both arc cathode and anode surfaces, the conclusion applies to both electrodes.

We might note at this juncture that while the decline of β after high current arcs suggests a significant improvement in breakdown voltage toward the end of the experiment, the measurements of actual pulse breakdown voltage in the last section show no substantial change following the high current arcs. These two ideas are in direct conflict if field emission is assumed to provide the breakdown mechanism.

By comparing Figs. 12 and 14 it is seen that most of the β factors computed are high enough that we can expect breakdown to be dominated by processes entirely at the cathode. Under conditions of a cathode type of breakdown we can estimate the level of voltage at which breakdown will occur, provided that β is known. Experimentally it has been found that the maximum local field that a copper emitter can withstand is about 10^8 V/cm. The field at the tip of an emitter having an enhancement factor β is

$$E = \frac{\beta V}{d} ,$$

where V is the applied voltage and d is the gap length. Since breakdown is expected when E reaches 10^8 V/cm, the value of voltage at which breakdown will occur is

$$V = \frac{10^8 d}{\beta} .$$

Since β is computed from the slope of the Fowler-Nordheim curve the above can also be written as

$$V = 0.353 \text{ (slope)}.$$

This line is plotted in Fig. 15. In order to obtain this result the assumption was made that the surface work function was 4.5 eV. Also plotted in Fig. 15 are data points obtained from experimental trials where the measurement of emission current was followed directly by a measurement of pulse breakdown voltage on the same electrode surface. From the emission measurement we should be able to estimate a breakdown voltage from the slope of the data. The corresponding breakdown measurement should corroborate this estimate. Each point on Fig. 15 represents paired slope and breakdown measurements. The trials plotted in this figure represent only those for which the emission data were well represented by straight lines. If simple field emission were the dominant breakdown process, we should expect these points to lie along the computed line of Fig. 15. Despite the fact that only the "best" trials are represented, the agreement with computed breakdown is poor or nonexistent.

If breakdown were controlled by vaporization at the anode we would anticipate a disparity between estimated and observed breakdown. However, in such a case, anode vaporization would have to occur before vaporization of the cathode. Thus anode collapse should occur at a lower voltage than that for cathodic breakdown. We note that each of the points in Fig. 15 lies above the cathode estimate so that under the assumption of field emission, participation at the anode can be disregarded as a dominant effect, as was concluded earlier from another argument.

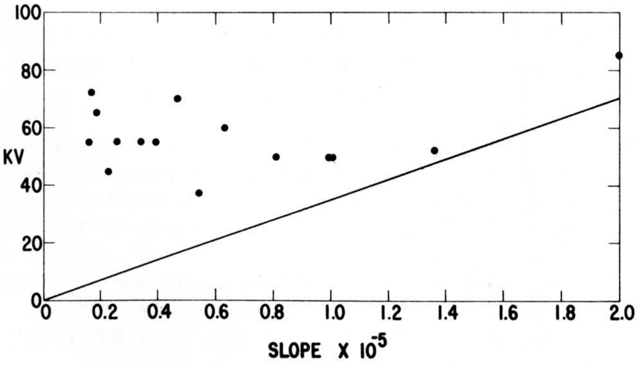

Fig. 15 Measured pulse breakdown voltage and corresponding emission data slopes compared with field-emission predicted breakdown voltage.

We should point out there that the estimate of breakdown voltage from the slope of a Fowler-Nordheim plot is usually based upon the assumption that the voltage actually producing breakdown is DC. Since our breakdown measurements are pulse measurements, we must consider the possibility that breakdown will occur at a different voltage with a pulse than with DC. To help resolve this question comparative breakdown measurements were made using both pulse and DC high voltage. The results showed that there was indeed a higher pulse voltage required for gap breakdown than in the case of DC. The ratio of pulse to DC voltage however, lies between 1.3 and 1.5, a factor which appears to be considerably smaller than that required to account for the disparity in Fig. 15. This ratio, incidentally, is in good agreement with the results of Kalyatskii and Kassirov(8) for copper electrodes and comparable rise rates of voltage.

In the author's opinion the conflict suggested by Fig. 15 is not readily resolved. If field emission is dominant as suggested by some rather good Fowler-Nordheim plots, why do actual breakdown voltages exceed by such large factors the estimated values? It is possible, of course, that breakdown or partial breakdown actually does occur on the rise of the pulse, but it does not result in the complete collapse of the gap; that is, the breakdown is simply undetected.

Other data, however, suggest that simple field emission is not dominant. We have frequently seen, for example, Fowler-Nordheim plots which are not straight. This is especially true at low current. It is the usual practice to disregard such data since they are believed to reflect a very unstable emission condition which is random in time and not reproducible. Some of the results in this experiment are, however, reproducible. After the first 2000 amp arc we obtained the data of Fig. 16(a) from the arc cathode surface. We note particularly that at A for increasing voltage there begins a significant change in the slope of the curve. This is in essence reproduced at B for decreasing voltage. Moreover, following a sequence of 100 pulses, the plot in Fig. 16(b) was obtained. While the points for the decreasing voltage vary somewhat from the corresponding region of Fig. 16(a), the remainder of the data and especially that labeled A are nearly identical in each figure. This, then, is an example of reproducible emission data which show strong departure from the result normally expected of pure field emission.

We conclude this section by summarizing as follows. Fowler-Nordheim plots obtained in connection with low currents early in the experiment often showed strong departures from a result that can be interpreted as pure field emission. Moreover, those plots which are straight and, which can be interpreted

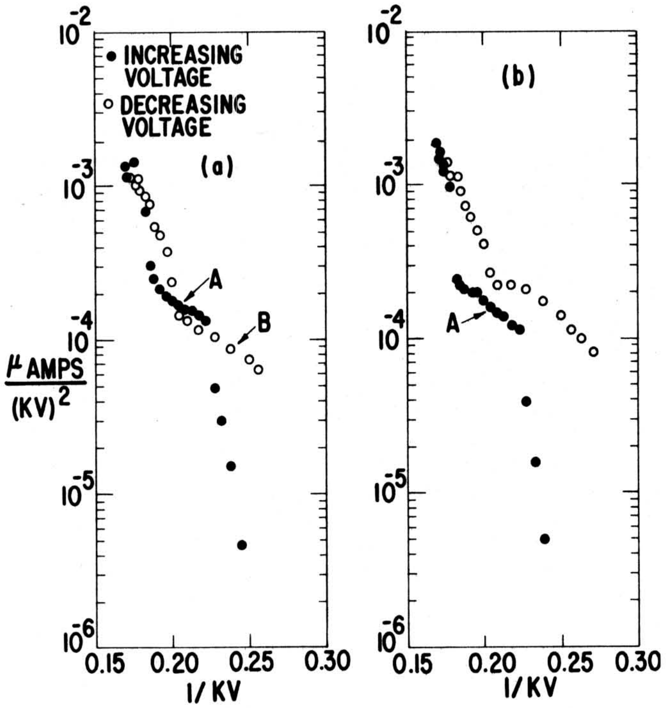

Fig. 16 Illustration of the persistence of abrupt deviations in emission data: (a) before, and (b) after 100 pulse breakdown events with this electrode as anode to the breakdown events.

as field emission, fail to show the expected correlation with actual breakdown voltage measurements even where one accounts for the effect of fast rising pulse voltage. As the experiment progressed to higher current, good Fowler-Nordheim plots became more frequent and their slopes yielded smaller field enhancement factors. We are thus led to conclude that if a straight line Fowler-Nordheim plot can, in the present experiment, be interpreted as being due to legitimate field emitters, the high current arc has a salutory effect on the dielectric capability of the gap despite the extensive cathode tracking and anode melting incurred by the electrodes from each arc.

IV. CONCLUSION

Since currents of 5000 amp or more are required to wipe the electrodes clean of prior surface defects, breakdown between electrodes can be determined by the prior history of the electrodes and may be little affected by present arcing. We anticipate, however, that extensive use at low current at both arcing polarities would, in time, remove inherited defects.

The breakdown studies show that, although some degradation of breakdown voltage occurred on both anode and cathode surfaces due to arcing, this effect was not a strong function of current. That effect may well have been produced by accumulated watt-seconds of arcing. Further, the anode fared no worse than the cathode surface even after arc currents at which anode melting must have occurred.

An attempt to correlate the pulse breakdown measurements and the emission measurements by prediction of breakdown voltage from the slopes of Fowler-Nordheim plots was not successful. From such field emission measurements which could be analyzed, however, it appears that emitters present on electrodes after high current arcs have smaller field enhancement factors than those observed after low current arcs. The high current arc, even when accompanied by extensive cathode tracking and anode melting, does not generate stable high β emitters. It appears that the greatest problem in connection with static breakdown after high current arcs is the formation of partial or complete electrode bridges due to electrode melting.

In concluding, it is appropriate to make some comment regarding observed β values for the relatively straight Fowler-Nordheim plots throughout this experiment. The factor, β, by which the field is enhanced for the simple geometry of a cylindrical whisker, is approximately given by the ratio of height to cross-sectional radius of that emitter. This relationship is expected to be approximately true even for somewhat distorted emitter shapes. While metallic emitters having estimated enhancement factors of 20 to 50 have been directly observed under the electron microscope, metallic emitters which would produce β factors of a few hundred or more have not been observed. In the present report we have estimated β values of several hundreds and even a few thousands. Such high β factors even when determined from straight line Fowler-Nordheim plots stretch the imagination and lead one to suspect that the concept of field emission from metallic emitters simply does not fit experimental observations. Other experiments now underway have suggested that small insulating particles on the electrode surfaces may be critically involved in producing emission and breakdown between the electrodes under study. This possibility is now being actively pursued.

REFERENCES

1. H.C. Miller and G.A. Farrall, "Polarity Effect in Vacuum Breakdown Electrode Conditioning," J. Appl. Phys. 36, 1338-1344 (1965).

2. F.M. Charbonnier, "High Current Density Field Emission and the Transition to Vacuum Breakdown," Paper at Intern. Symp. on Insulation of High Voltages in Vacuum, MIT, Oct. 19-21, 1964.

3. P.A. Chatterton, "Further Calculations on Field Emission Initiated Vacuum Breakdown," Proc. Phys. Soc. (Great Britain), 89, 178-180 (1966).

4. T. Utsumi, "Cathode- and Anode-Induced Electrical Breakdown in Vacuum," J. Appl. Phys. 38, 2989-2997 (1967).

5. G.E. Vibrans, "Field Emission in Vacuum Voltage Breakdown," Tech. Rept. 353, Lincoln Lab., MIT (1964).

6. H.C. Miller, "Change in Field Intensification Factor β of an Electrode Projection (Whisker) at Short Gap Lengths," General Electric TIS Report.

7. G.A. Farrall and T.P. Owen, "Correlation of Electrical Breakdown and Centers of Strong Electron Emission on a Zone Refined Iron Cathode in Vacuum," General Electric TIS Report 69-C-309.

8. I.I. Kalyatskii and G.M. Kassirov, "Effect of Electrode Material on Electrical Pulse Strength of a Vacuum Gap," Soviet Phys. Tech. Phys. 9, 274-276 (1964).