GENERAL ELECTRIC

GENERAL ELECTRIC COMPANY
CORPORATE RESEARCH AND DEVELOPMENT
Schenectady, N.Y.

# BREAKDOWN PHENOMENA OF SURFACES IN VACUUM SUBJECTED TO ARCING

by

G.A. Farrall
Physics and Electrical Engineering Laboratory

Report No. 72CRD242 August 1972

TECHNICAL INFORMATION SERIES

CLASS 1

GENERAL ELECTRIC

General Electric Company
Corporate Research and Development
Schenectady, New York

# TECHNICAL INFORMATION SERIES

AUTHOR
Farrall, GA

SUBJECT
vacuum breakdown

NO.
72CRD242

DATE
August 1972

TITLE
## Breakdown Phenomena of Surfaces in Vacuum Subjected to Arcing

GE CLASS
1

NO. PAGES
9

ORIGINATING COMPONENT
Physics and Electrical Engineering Laboratory

CORPORATE
RESEARCH AND DEVELOPMENT
SCHENECTADY N.Y.

SUMMARY

This report discusses a variety of effects related to electrical breakdown between electrodes in vacuum subjected to arcing use Two regimes are considered The first concerns breakdown under essentially static conditions where electrodes have been eroded by the arc and where the electrode surfaces have deposited upon them the products of this erosion. The second regime concerns the time-dependent breakdown phenomena associated with the decaying residue of the arc in the gap volume. We note that, while a variety of effects resulting from the arc can materially affect the conditions of breakdown, vacuum devices show remarkable breakdown characteristics especially with respect to their ability to withstand high voltage at short times following interruption of an arc.

KEY WORDS

vacuum arcs, vacuum breakdown, arcs, breakdown

INFORMATION PREPARED FOR

Additional Hard Copies Available From
Corporate Research & Development Distribution
P.O. Box 43 Bldg. 5, Schenectady, N Y, 2301

Microfiche Copies Available From
Technical Information Exchange
P.O. Box 43 Bldg. 5, Schenectady, N Y, 230

# BREAKDOWN PHENOMENA OF SURFACES IN VACUUM SUBJECTED TO ARCING

G. A. Farrall

## I. INTRODUCTION

The title which I have been asked to speak upon is a very general one which I assume is designed to allow the speaker some latitute in his detailed choice of topic. At these symposia* we speak at length concerning the ability of clean, well-conditioned electrode surfaces to withstand high voltage in vacuum. Vacuum switchgear, however, have major constraints placed upon them that many other devices do not. One of these constraints is the arc. I would, therefore, like to focus my attention upon breakdown phenomena of surfaces in vacuum subjected to arcing. I begin with a brief historical comparison.

In 1913, W D. Coolidge(1) introduced the first stable, thermionically emitting, high vacuum x-ray tube. Thirteen years later he summarized(2) the then present state of the x-ray tube art in terms of maximum operating voltage. In a tube having spun copper anode and cathode surfaces separated by about 2 cm, continuous operation at 300 kV and, under favorable conditions, 350 kV was achieved. This voltage withstand capability in vacuum has not been substantially exceeded even today This is but one of the many reasons why the Coolidge X-ray tube program must be regarded as highly successful.

At about the same time that high-voltage x-ray tubes were being developed, Sorensen and Mendenhall (Ref. 3) at the California Institute of Technology began a program of study aimed at investigating the circuit interrupting properties of vacuum devices This program was continued at the General Electric Research Laboratories in the late twenties (4) Despite the fact that vacuum switches held great promise, the industrial program failed to produce a commercially acceptable device.

The success of the x-ray tube and the disappointments of early vacuum interrupters make an interesting comparison because critical phases of the work were carried out not only at the same time but also at the same Laboratory The differences in the outcome of the two programs is due in part to the nature of the two devices In the x-ray tube operating conditions are static. Carefully prepared surfaces which are subjected to high-voltage stresses remain essentially in their original state throughout their useful life. Moreover, the vacuum in a sealed x-ray tube will tend to improve with use. The vacuum switch, on the other hand, is a dynamic device where original surfaces undergo marked and widely varying changes due to the action of arc. Further, the rapid outgassing of surfaces due to arcing in a sealed device caused the vacuum conditions to deteriorate with successive operations

The problems associated with rapid outgassing of internal surfaces have since been solved by the combined application of modern processing techniques and the availability of relatively gas free materials Internal surfaces of an interrupting device, however, have additional constraints placed upon them that are not usually imposed upon a static device like an x-ray tube. These constraints are formidable, even today, and result in a diminished dielectric capability of interrupting devices compared with their static counterparts We should keep clearly in mind however that this comment is made within the context of comparing one form of vacuum device with another form of vacuum device Vacuum is, in many respects, an unexcelled interrupting medium.

In the following sections of this report we shall consider in detail the variety of effects which determine the dielectric capabilities of a gap after arcing It is convenient to divide this discussion into two parts The first of these considers the steady state electrode surface conditions existing after current zero (excluding any transient recovery phenomena) and the effect of these conditions upon breakdown. The second section discusses the dynamic, time dependent phenomena just after arc extinction and their effects upon voltage withstand capability

## II. STEADY-STATE BREAKDOWN PHENOMENA ON ARCED SURFACES

Electrode surface conditions, even after arcing at low current, have a profound effect on breakdown voltage. The magnitude of the effect can be estimated from the earlier work of Farrall and Miller (5, 6) For these experiments, copper electrodes were partially conditioned by a series of high-voltage pulse breakdown events then subjected to arcing at peak currents of 550 amp. For a 1 mm gap the pulse breakdown voltage before arcing was about 30 kV The first pulse breakdown after arcing was 11 to 15 kV For a 4 mm gap the partially conditioned breakdown voltage before arcing exceeded 100 kV After arcing, breakdown occurred at about 40 kV Thus the effect of arcing at moderate current was to reduce the pulse breakdown voltage to less than half of its partially conditioned value.

Similar degradation of breakdown voltage by arcing occurred regardless of whether the cathode during the application of pulse voltage was situated on the electrode used as cathode during arcing or on the electrode used as anode during the arc.

---

*This report presented as talk to Fifth International Symp. on Discharges and Electrical Insulation in Vacuum, Aug. 30-Sept. 1, 1972

Manuscript received August 23, 1972

These particular experiments were carried out using arc currents for which the dominant phenomena during the arc occur at the cathode surface To determine the possible reasons for the degradation of dielectric strength, it will be instructive to consider particularly those cathode processes which directly influence electrode surface conditions.

In vacuum the very existence of the arc depends upon the erosion of electrode metal vapor to supply the medium in which the arc burns. Erosion occurs under the action of one or more cathode spots which represent the root or attachment of the arc at the cathode surface. Because all of the arc current must pass through these spots and because the spots are small in size, the current density in these regions is extremely high, in the range $10^5$ to $10^9$ amp/cm$^2$.(7, 8) The spots appear as tiny highly luminous spheres which move rapidly and randomly over the cathode surface during the discharge. Their number in a given discharge depends upon the electrode metal and becomes larger in proportion to the instantaneous value of arc current.(9, 10) As a consequence of the erosion produced by the spots, cathode tracks are left on the electrode surface.

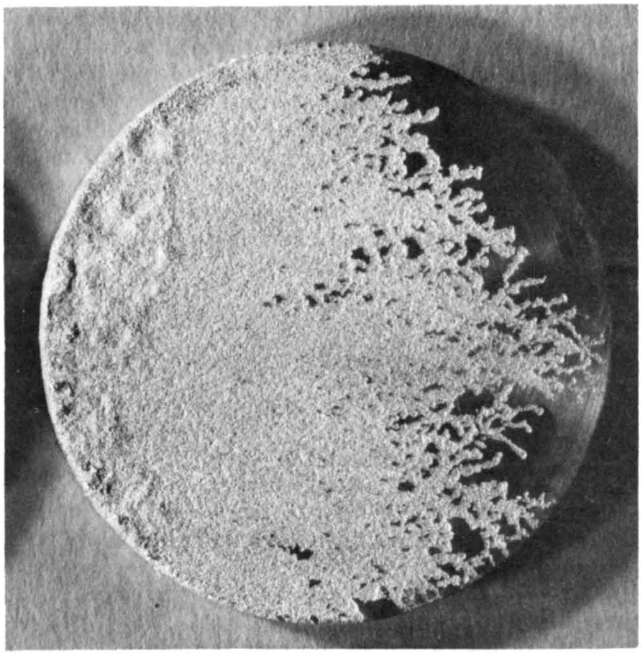


Fig. 1 Copper surface used for a few hundred trials at currents of 500 to 3000 amp. Each trial had arc lasting most of a 60 Hz half-cycle period.

If the arc current is small and of limited duration, the surface area over which tracking is visible on the cathode will be small, but on succeeding arc trials, erosion will tend to occur in noneroded regions. After extended use, a given electrode will, therefore, be completely covered with cathode tracks. Figure 1 shows a copper surface which had been used for a few hundred trials at currents ranging from 500 to 3000 amp, each trial consisting of an arc lasting most of a 60 Hz 1/2-cycle period. Much of the surface has been tracked and we would anticipate that with further use, the entire front surface would be covered. The surface finish left by tracking will depend in part upon the electrode metal and the cleanliness at the surface Reece(9) points out that surface texture tends to be coarse for metals on which the arc voltage is low. Further, certain of our own observations suggest that finer tracking is obtained for surfaces bearing oxide films

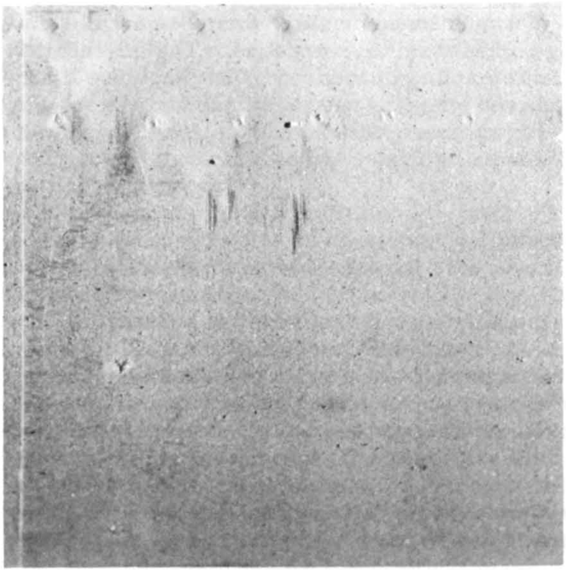
Cathode surface texture can also be influenced by gas occluded within the bulk electrode metal if there are gas pockets close to the electrode surface. A cathode spot traveling in the vicinity of such a pocket can literally cause a small explosion which roughens the surface and scatters small metal particles into the discharge.

Observations of this kind have been made by Cobine and Vanderslice.(11) They found that erosion rates were always higher for electrodes containing occluded gases due to the ejection of large globules of metal during arcing This conclusion was also more recently verified by Kantsel', Kurakina, Potokin, Rakhovskii, and Tkachev (12) Cobine and Vanderslice illustrate the effect by showing deposits of metal collected on the internal surfaces of shields surrounding the discharge during arcing. We reproduce that illustration here

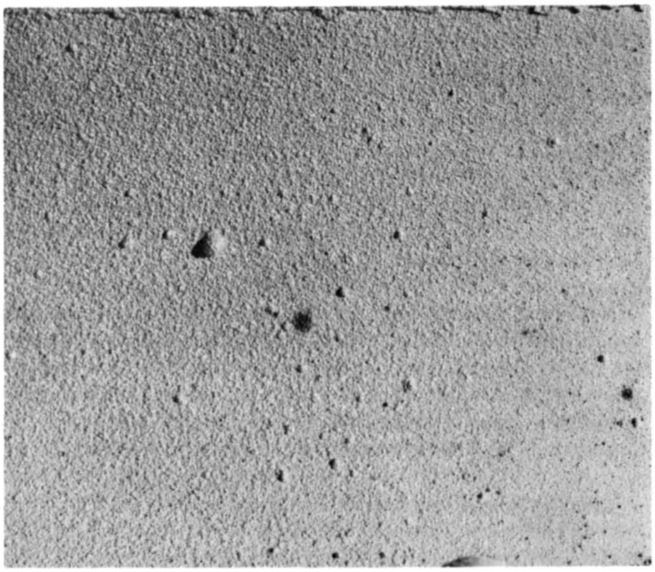
In Fig. 2(a) the deposits are relatively fine and were produced by erosion of metal from gas-free electrodes. In 2(b), the deposits contain globules of varying size, some of which are 2 to 3 mm in diameter Such deposits from cathode erosion will, of course, not only occur on surrounding shield surfaces, but upon the anode surface as well.

In 1963, Udris(13) studied the distribution of particle sizes produced by low current (60 amp max) arcs for a wide variety of metals. Several interesting conclusions were reached. No minimum particle size was found. Further, the smaller particle sizes always occurred in greater abundance than the larger ones Particle size was generally large for metals like cadmium and lead, and small for the more refractory metals like molybdenum and tungsten. Maximum particle sizes differed for various metals but generally ranged from 30μ to 80μ

In an elegant experiment employing centrifugal force to either aid or suppress ejection of particles from the cathode, Klyarfel'd, Neretina, and Druchinina(14) have also shown that large particles are likely to account for a significant portion of metal eroded from cathodes having low melting point. They also show that although large particles are far less abundent from cathodes like copper; they nevertheless do appear as a part of erosion products



(a)



(b)

Fig. 2 Metal deposits collected on internal surfaces of shields surrounding discharge during arcing. (a) Fine deposits produced by erosion of metal from gas-free electrodes (b) Deposits containing globules of varying size--some 2 to 3 mm diam.

The work of Kantsel' and co-workers already mentioned,(12) comments upon particle ejection during cathode erosion. Their study utilized relatively gas free metals and did not include metals having melting points less than that of copper Erosion measurements were made at currents up to about 700 amp. The deposits resulting from the cathode erosion from these metals were nearly free of large particles The English translation of this article appears not to be literally correct. Rakhovskii, in a recent private communication, pointed out that no particles were found. In any event, as we now shall see, the presence of particles and their size have an important bearing on the breakdown properties of the gap

Experiments were performed by Olendzkaya(15) using steel electrodes with and without contamination by steel particles Particle sizes in the range 0 5 mm to 9 mm reduced the breakdown voltage of a 10 mm gap from greater than 100 kV (the experimental voltage limit) to 60 kV Further experiments were performed by Poshekhonov and Pogorelskii(16) using molybdenum electrodes and molybdenum particles in the size range 20μ to 80μ The 80μ particles showed a reduction of about 10 kV in breakdown voltage for gaps ranging from 2 to 6 mm. Similar results were much more recently obtained by Martynov (17) These experiments leave little doubt that metal particles can significantly degrade the dielectric performance of a vacuum gap and that greater degradation is produced by large particles

Certainly particles produced by the arc will have varying degrees of adhesion to the surface upon which they rest. Breakdown might, therefore, occur via the impact of particles at an electrode surface as described by Cranberg(18) and by Slivkov (19) Martynov(17) has pointed out that this process is especially applicable to cases in which particle sizes under 10μ are present. The debris produced by arcing contains an abundance of particles in this size range The Cranberg process is considered by Poshekhonov and Pogorelskii(16) to be valid for larger particles (in the 20μ to 80μ range) as well.

Olendzkaya(15) has demonstrated that for large particles breakdown occurs between a particle in transit and the electrode surface which it approaches This is believed to precipitate breakdown across the whole gap Chatterton and Biradar(20) conclude that this same process probably accounts for their experimental observations of particle effects Martynov(17) has expressed the view that particle micro-discharges account for breakdown events even in the 20μ to 80μ particle size range studied by Poshekhonov and Pogorelskii.

Whatever the detailed breakdown mechanism may be, it is clear that the presence of metallic particles in the gap can significantly affect breakdown voltage. It may even be that the roughening of the cathode surface due to cathode tracks is a minor effect on breakdown compared with the contamination of the electrode surfaces produced by particles eroded from the cathode during the arc

For high-power vacuum interrupters, currents in the 10 ka and higher range are of interest. At this level the cathode effects we have described will be much more pronounced. Particles will be much more abundant and exist in a wider range of size even for gas-free metals.

It is clear that high-power interrupters operate under conditions where the state of the electrode surface is very much less than ideal. Arcing polarity is random on successive operations so that at one time one electrode may be arc cathode; at another time the same electrode might be arc anode. Thus both electrodes are likely to have cathode spot erosion, and deposits of vapor and particles Further, an interrupter, each time it is operated, is subjected to severe mechanical shock which can act to dislodge loose particles from any region of the device. These may ultimately reappear on critical internal surfaces.

Although particle exchange processes are undoubtedly important in interrupting devices, other effects may also be significant. Protrusions on the electrode surfaces could arise from several different phenomena. A switching device is called upon to withstand voltage after contacts have been opened from an initially closed position. In the process of opening there may have been a large arc current or perhaps almost no current at all. The latter condition would favor the survival of protrusions produced by mechanical stresses in the contacting surfaces in the manner suggested by Tomaschke and Alpert.(21)

We have already indicated the probable presence of particles on the electrode surfaces due to previous arcing. The impact of these particles accelerated across the gap by an applied voltage can produce craters with splash rims which themselves may form emitting surface protrusions as suggested by Little and Smith.(22) The presence of metal vapor produced by the arc might also produce protrusions from the vapor phase as indicated by Juttner (23) Added to these effects is that of simple mechanical deformation of the surface either by cathode tracking or by deposition of large particles If these surface irregularities are large compared with the micron-sized defects we normally expect for cathode emitters, it is possible for the grosser defect to enhance the smaller one. Schottky,(24) for example, shows the field enhancement of a hemispherical boss on a plane surface is 3. Each of these effects could influence the role played by protrusions on arced surfaces.

We should note before concluding this discussion of breakdown under static conditions certain possible effects concerning gap length. For nonarced surfaces the literature suggests that, for clean electrodes at short gaps, breakdown most likely occurs by Joule heating of an emitting protrusion at the cathode surface. At long gaps, however, breakdown is more likely to be precipitated by local heating at the anode surface by cathode emission.(25)

Gap lengths in power vacuum interrupters are long--frequently greater than 10 mm. In searching for various possible causes for breakdown in such devices we might be tempted to think only in terms of long gap effects such as the anode interaction we have just mentioned or some form of particle exchange. This can be erroneous. The degradation of breakdown voltage produced by arcing quite likely extends the range of maximum gap lengths we would consider as short for nonarced surfaces by a factor of at least 2 or 3.

Further, the consideration of cathode- or anode-dominated breakdown must take into account not only gap length but also rate of rise of applied voltage.(26) Fast rates of rise favor a cathode type of breakdown, whereas slow rise rates favor breakdown via an anode process. Thus while we have discussed at length the effects of particle contamination upon breakdown, the wide variety of conditions under which a vacuum interrupter is used lead us to an inevitable conclusion--that at some time in its life, a vacuum interrupter will be exposed to conditions which will favor electrical breakdown by almost any proposed mechanisms suggested in the 50 years of literature on the subject.

## III. ARC RECOVERY PHENOMENA

In addition to the static effects of the arc upon breakdown, there are other phenomena associated with the arc which make the gap breakdown voltage dependent upon time. These effects are primarily associated with phenomena in the gap volume.

Immediately following the extinction of an arc, the volume between and around the electrodes is filled with a residue consisting of desorbed gas, neutral electrode vapor, metal ions, and electrons Part of this residue consists of high-energy ions in the range 20 to 60 eV as indicated from experiments by Plyutto, Ryzhkov, and Kapin,(27) by Tyulina,(28) and by Davis and Miller (29) A striking feature of these experiments is that the ion energies substantially exceed the voltage drop across the stable discharge. Of more direct interest in connection with interrupting devices is the fact that these high-speed components move out of the gap volume very rapidly and contribute to the fast recovery of vacuum interrupters.

In an experiment involving the force extinction of copper vacuum arcs, Kimblin(30) reports more moderate average ion energies (≈22 eV) based on the measurement of the decay of post-arc current with time. Most recently, Miller(31) has performed experiments on DC copper arcs forced to zero by an auxiliary circuit. He measured ion energies in the time interval surrounding the instant of extinction and found that a large burst of low-energy ions (~20 eV) was apparently produced as a consequence of extinction processes. It now appears likely that the low-energy ions reported by Farrall(32) are part of the extinction burst described by Miller

Several years ago, Reece(33) suggested that post-arc currents in some of his experiments were due to the presence of gaseous rather than metallic ions in the residual plasma. In this connection, Holmes, Broadhead, and Edels(34) found that post-arc current magnitude showed a significant increase under a high background gas condition ($2 \times 10^{-3}$ torr) It is possible that at high peak currents outgassing of internal surfaces will produce a significant contribution to residual ion density Miller(31) has shown that even for small currents easily measured concentrations of neutral masses 2 and 28 are present after arc extinction.

We should, at this point, interject a word of caution regarding gas released during the arc. Large amounts of ambient gas will be released in a vacuum device which has been poorly processed. As a reminder of this we can think back to the late 1920's and the then unsuccessful attempts to produce an acceptable vacuum switch. Reece and Smithers(35) have clearly pointed out the need for extreme rigor in processing in order to avoid excessive outgassing during the arc. Processing may, therefore, influence not only the density of neutral gas species present in the gap after current zero, but also the degree to which gaseous ions populate the residual plasma.

In the presence of a residual plasma, voltage applied to the electrodes will tend to extract electrons at the anode such that the main body of the plasma cloud assumes a quasi-steady state potential which is close to that of the anode. This readjustment of the plasma occurs typically in times much less than a microsecond. The plasma thus acts as a physical extension of the anode so that most of the applied voltage appears across a thin space-charge layer adjacent to the cathode surface. As a consequence, the field at the cathode surface, for a given applied voltage, can be significantly higher than would be the case were the plasma not present.

Experimental studies of breakdown under conditions such as these, that is, breakdown between a plasma and an electrode surface, have been rather extensive.

Fearn,(36) for example, has reviewed related theories and experiments with possible application to MHD devices. He concludes that the field at the plasma-cathode boundary can reach $\sim 2 \times 10^6$ V/cm, a field which, when combined with surface defects and inclusions, could produce electrical breakdown by field emission. Calculations of a similar nature have also been made by Owen.(37)

Other studies such as those by Hancox,(38) Maskrey and Dugdale,(39) and Pfeil and Griffiths(40) show that breakdown between a plasma and a surface is most frequently associated with surface defects such as insulating inclusions Breakdown between a plasma and surface projection would also seem to be a likely process and is in fact the basis for a mode of breakdown described by Fursei and Vorontsov-Vel'yaminov (41) Strong arguments for such a process during the arc are made by Sena, Pranevychius, and Fursey.(42) These authors show that the stability of DC arcs on mercury and gallium can be increased by inducing ripples to appear on the cathode surface and decreased by applying a centrifugal force to oppose deformation of the surface. The authors conclude that the existence of the arc itself depends upon the ease with which the plasma space charge field can induce the formation of liquid protrusions. It is therefore quite reasonable that such a process is also applicable in the early recovery time regime when solid protrusions may already exist or when protrusions can alternatively be formed from existing molten pools produced during the arc

Plasma effects undoubtedly dominate the breakdown of a gap during the very early recovery period. As recovery of the gap proceeds, the plasma density diminishes rapidly due to the movement of residual ions. The time dependence of this ion decay is believed by Tyulina and Musin(43) to determine the time required to achieve full recovery in gaps having refractory electrodes Certainly as the residual plasma decays, the sheath thickness at the cathode will expand,(32, 33) thus reducing the intensity of the cathode field. The importance of the plasma effect should, however, diminish rapidly especially if the residual plasma consists mainly of high-energy ions

Ions may also play another role in the recovery of a gap following an arc Miller(31) has found experimental evidence that residual gas density decays faster in the presence of ions than would be the case if ions were excluded. The effect is particularly strong for hydrogen.

There is some uncertainty as full recovery is approached as to just what phenomena are still active. In some cases it seems likely that slowly moving neutral metal vapor would limit the time required for the gap to achieve full recovery A theoretical model based on neutral vapor density decay proposed by Rich and Farrall(44) appears to account for a variety of experimental results in cases where the arc current is a few hundreds of amperes and the extinction of the arc current occurs in less than a microsecond. The computations in this model were made specifically for silver electrodes For this metal, best fit between theory and experimental was obtained by assuming that when metal vapor struck a bounding surface such as an electrode or an internal shield during recovery, it remained adhering to that surface. Experiments by Zalucki, Seidel, and Kutzner(45) done under closely similar conditions, however, suggest that this assumption is not always valid. For some metals the vapor incident on a surface is reflected back into the gap volume. They further comment that during the arc, the cathode jet may play upon the anode producing secondary particles These must also be taken into account during the recovery period.

The phenomena mentioned thus far are essentially related to low current arcs--that is, arcs of a few hundreds of amperes Vacuum interrupters, however, are subjected to currents in the tens of thousands of amperes Certainly we can expect that the process we have discussed will occur in larger measure under these conditions, but other effects will also appear

If the current is high, melting at the anode surface is likely In addition to the effect of producing large particle sizes in the erosion products, melting can leave a hot molten pool on the electrode surface after current zero. This pool is slow to cool and can act as a source of residual metal vapor after the arc is extinguished.(46, 47) This slowly decaying source of vapor can prolong the time required to achieve full recovery

An additional effect of melting may also occur. In the usual case the cathode during the voltage rise across a gap following arc extinction is situated on the electrode which was anode during the arc With anode melting during the discharge, the high voltage is applied with a cathode situated on an electrode which has, in part, a liquid pool. The effects of high voltage upon liquid metal pools have been extensively studied. Many years ago, Tonks(48) and Frankel,(49) in order to account for the breakdown measurements of Beams(50) on a liquid mercury surface, developed approximate theories to describe the rupture of liquid metal pools under high fields. It was found that mercury would rupture at impressed fields of $10^6$ V/cm in microseconds time. Bartashyus, Pranevichyus, and Fursei(51) have measured rupture fields for both mercury and gallium and found them to be in good agreement with theory Pranevichyus and Bartashyus (Ref. 52) have investigated field rupture of liquid surfaces using a novel apparatus in which centrifugal force could be applied to the liquid cathode surface to suppress surface rupture by high electric fields Significant increases in rupture field was found with increasing centrifugal force.

In the time period immediately after arc extinction, the residual plasma and its effective enhancement of the field across the space charge sheath will lie adjacent to anode melting that might have occurred during the arc Thus the space-charge field enhancement and anode melting are quite likely to act in concert to reduce gap breakdown voltage Thus melting is an important consideration in the recovery of a gap.

Several studies of anode melting have been made. Kimblin(53) and Mitchell(47) have both found that the conditions which most readily promote anode melting are the following:

1 Small anode diameter
2 Long gap length
3 High current
4. Time.

To this list we should also add the findings of Rich,(46) who has shown that melting appears more readily in electrode configurations which have edges and sharp corners and in which the electromagnetic forces tend to concentrate the discharge. In another paper, Rich, Prescott, and Cobine(54) have illustrated the importance of the thermal characteristics of the electrode material.

Because of the many parameters involved, one might seek to avoid melting in one of several different ways For any given combination of circumstances, however, there is a limit of current above which melting cannot be avoided. Exceeding this limit will not only influence the time dependent recovery of the gap but also add to the constraints of static breakdown capability following complete recovery

In this section on recovery effects we have drawn from the literature to describe the conditions which can exist in a vacuum gap following extinction of arc current. At high power levels we can anticipate a significant influence on recovery performance by such effects as electrode melting, plasma field distortion, desorbed gas, metallic and gaseous ions, and neutral metal vapor

## IV CONCLUSION

In the preceding paragraphs we have attempted to illustrate some of the conditions both static and dynamic which limit the voltage capability of an interrupting device. We have also attempted to suggest some of the physical processes which accompany these effects. If the processes that could limit the voltage capability of a vacuum device were examined one at a time, one might easily acquire an adverse and very wrong impression of the vacuum medium.

We have noted that vacuum devices which have been subject to arcing require longer gap lengths to withstand given voltage levels than nonarced vacuum devices The fact of the matter is that even with this "penalty," the gap lengths used on vacuum interrupting devices is still short compared with other interrupting media subjected to the same conditions of current and voltage. We have also noted that during the recovery period, a number of different phenomena act either separately or in concert to limit the rate at which voltage can be reapplied to the gap after arcing. Despite these limitations recovery in a vacuum gap is fast--faster than any other switching medium.

Vacuum has many other virtues which have been listed in the published literature(55-58) so there is no need here to detail them. There is, however, one characteristic that I would especially like to mention. When a sealed interrupter is new, it will break down at some average voltage level following an arc Further, the ambient operating pressure will fall within certain typical limits The interesting characteristic of such devices is that following a period of moderate use which involves arcing operations, the breakdown characteristics of the device improve and the background pressure declines. Thus, to quote a colleague, J A. Rich, "a vacuum interrupter, like fine wine, ripens with age."

This conditioning capability of the vacuum interrupter is also observable in a somewhat different way If the gap should fail to withstand voltage, the breakdown process itself tends to remove the cause of the failure so that the device has an improved voltage capability the next time voltage appears. This self-healing property of vacuum devices is unique.(59)

Unquestionably, vacuum devices which are intelligently applied perform remarkably well. It is my belief that, through the application of experimental techniques which permit study of breakdown phenomena on the same microscopic scale upon which these phenomena occur, vacuum devices can be made even better

## REFERENCES

1 W D. Coolidge, "A Powerful Röentgen Ray Tube with a Pure Electron Discharge," Phys Rev (2nd ser ), II, 409-430 (Dec. 1913).

2 W D. Coolidge, "Cathode-Ray and Röentgen-Ray Work in Progress," The Amer. J Roentgenology Radium Therapy XIX, 313-321 (April 1928)

3 R. W Sorensen and H. E. Mendenhall, "Vacuum Switching Experiments at California Institute of Technology," AIEE Trans 45, 1102-1105 (Sept. 1926).

4. J D. Cobine, "Research and Development Leading to High Power Vacuum Interrupters--A Historical Review," IEEE Trans Power App. Syst. No. 65, 201 217 (April 1963)

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

6. G. A. Farrall and H. C. Miller, "Influence of Gap Length Upon the Polarity Effect in Vacuum Breakdown Electrode Conditioning," J Appl. Phys. 36, 2966 (Sept. 1965)

7 K. D. Froome, "The Rate of Growth of Current and the Behavior of the Cathode Spot in Transient Arc Discharges," Proc Phys. Soc., London 60, 424-435 (May 1948)

8. C. C. Sanger and P E. Seeker, "Arc Cathode Current Density Measurements," J Phys. D: Appl. Phys 4, 1940-1945 (1971)

9. M. P Reece, "The Vacuum Switch, Part 1 Properties of the Vacuum Arc," Proc. IEE 110, 793-802 (April 1963).

10. B. E. Djakov and R. Holmes, "Cathode Spot Division in Vacuum Arcs with Solid Metal Cathodes," J Phys. D (GB) 4, 504-509 (April 1971).

11 J D. Cobine and T A. Vanderslice, "Electrode Erosion and Gas Evolution of Vacuum Arcs," IEEE Trans Communication and Electronics, No. 66, 240-245 (May 1963)

12 V V Kantsel', T S. Kurakina, V S. Potokin, V I. Rakhovskii, and L. G. Tkachev, "Thermophysical Parameters of a Material and Electrode Erosion in a High-Current Vacuum Discharge," Sov Phys.-Tech. Phys 13, 814-817 (Dec 1968)

13. Y Y Udris, "Disintegration of Materials by an Arc Cathode Spot," Radio Eng. Electronic Phys 8, 1050-1056 (June 1963)

14. B. N Klyarfel'd, N A. Neretina, and N N Druzhinina, "Metal Sputtering by the Cathode Spot of a Vacuum Arc," Sov Phys -Tech. Phys 14, 796-799 (Dec. 1969)

15. N F Olendzkaya, "Vacuum Breakdown with Transfer of Conducting Particles Between Electrodes," Radio Eng. Electronic Phys 8, 423-429 (March 1963)

16. P V Poshekhonov and M. M. Pogorelskii, "Initiation of Vacuum Breakdown by Metallic Particles," Sov Phys -Tech. Phys 14, 811-815 (Dec 1969)

17 E. P Martynov, "Initiation of a Vacuum Discharge by Metal Particles on an Electrode," Sov Phys - Tech. Phys 16, 1364-1369 (Feb. 1972)

18. L. Cranberg, "The Initiation of Electrical Breakdown in Vacuum," J Appl. Phys 23, 518-522 (May 1952)

19. I. N Slivkov, "Mechanism for Electrical Discharge in Vacuum," Sov Phys. - Tech. Phys 2, 1928-1934 (Sept. 1957)

20. P A. Chatterton and P J Biradar, "Microparticle Processes Occurring Prior to Vacuum Breakdown," Z. Angew, Phys 30, 163-170 (1970)

21 H. E. Tomaschke and D. Alpert, "Role of Submicroscopic Projections in Electrical Breakdown," J Vac. Sci. Technol. 4, 192-198 (July/Aug. 1967)

22 R. P Little and S. T Smith, "Investigations Into the Source of Sharp Protrusions which Appear on Flat Cathode Surfaces as a Result of the Application of High Electric Fields," Proc. Intern. Symp. on Insulation of High Voltages in Vacuum, 41-49 (7-8 Sept. 1966), Cambridge, Mass

23. B. Juttner, W Rohrbeck, and H. Wolff, "Destruction and Production of Field Emission at Extensive Metal Surfaces," Beitr Plasma Phys (Germany), 10, 383-396 (1970)

24. W Schottky, "Cold and Hot Electron Discharges," Z Phys. 14, 63-106 (1923)

25. T Utsumi, "Cathode- and Anode-Induced Electrical Breakdown in Vacuum," J Appl. Phys 38, 2989-2996 (June 1967)

26. F M. Charbonnier, C. J Bennette, and L. W Swanson, "Electrical Breakdown Between Metal Electrodes in High Vacuum. I. Theory," J Appl. Phys 38, 627 633 (Feb. 1967)

27 A. A. Plyutto, V N Ryzhkov, and A. T Kapin, "High Speed Plasma Streams in Vacuum Arcs," Sov Phys. - Tech. Phys 20, 328 337 (Feb. 1965)

28 M. A. Tyulina, "Investigation of Plasma Propagation Rate When Current is Switched Off in Vacuum," Sov Phys - Tech. Phys 11, 1421 1423 (April 1967)

29. W D. Davis and H. C. Miller, "Analysis of the Electrode Products Emitted by DC Arcs in a Vacuum Ambient," J Appl. Phys. 40, 2212-2221 (April 1969)

30. C. W Kimblin, "Vacuum Arc Ion Currents and Electrode Phenomena," Proc. IEEE 59, 546-555 (April 1971)

31 H. C. Miller, "Measurements on Particle Fluxes from DC Vacuum Arcs Subjected to Artificial Current Zeros," J Appl. Phys. 43, 2175-2181 (May 1972)

32 G. A. Farrall, "Decay of Residual Plasma in a Vacuum Gap After Forced Extinction of a 250 Ampere Arc," Proc. IEEE 56, 2137-2145 (Dec. 1968)

33. M. P Reece, "The Vacuum Switch, Part 2 Extinction of an AC Vacuum Arc," Proc. IEE 110, 803-811 (April 1963)

34. R. Holmes, J A. Broadhead, and H. Edels, "Post Arc Currents in Vacuum Gaps," Proc. 3rd Intern. Symp. on Discharges and Electrical Insulation in Vacuum, Paris, 342-346 (Sept. 16-18, 1968)

35. M. P Reece and B. W Smithers, "The Evolution and Adsorption of Gas in Vacuum Switches During Arcing," ERA Report 5127, 18 pp (Sept. 1965)

36. D. G. Fearn, "An Investigation of the Electrical Breakdown of a Plasma-Electrode System," Brit. J Appl. Phys (J Phys. D) 2, 527-533 (1969)

37 W D. Owen, "Electrical Breakdown Between a Plasma and an Electrode at a Negative Potential," Atomic Weapons Research Establishment Report 0 78/67, 11 pp (Nov 1967)

38 R. Hancox, "Importance of Insulating Inclusions in Arc Initiation," Brit. J Appl. Phys 11, 468-471 (Oct. 1960)

39 J T Maskrey and R. A. Dugdale, "The Role of Inclusions and Surface Contamination Arc Initiation at Low Pressures," Brit. J Appl. Phys 17, 1025-1034 (1966)

40 P C. L. Pfeil and L. B. Griffiths, "The Effect of Inclusions on the Arcing Behavior of Metals," J Nucl. Mater , 3, 244-248 (Oct. 1959)

41 G. N Fursei and P N Vorontsov-Vel'yaminov, "Qualitative Model of Initiation of a Vacuum Arc II. Field Emission Mechanism of Vacuum Arc Onset," Sov Phy Tech. Phys 12, 1377-1382 (April 1968)

42 L. A. Sena, L. I. Pranevichius, and G. N Fursey, "The Part Played by Microprotrusions in the Formation and Burning of Vacuum Arc," 10th Intern. Conf on Phenom. in Ionized Gases, Oxford, England (Sept. 13-18, 1971), p. 105.

43. M. A. Tyulina and A. K. Musin, "On Mechanism of Deionization of Vacuum Arc Plasma in Stage of Extinction," Proc. 3rd Intern. Symp. on Discharges and Electrical Insulation in Vacuum, Paris, 347-352 (Sept. 16-18, 1968)

44. J A. Rich and G. A. Farrall, "Vacuum Arc Recovery Phenomena," Proc. IEEE 52, 1293 1301 (Nov 1964)

45. Z Zalucki, S. Seidel, and J Kutzner, "Contribution to the Investigation of Dielectric Strength after Arc Extinction in Vacuum," Proc. 3rd Intern. Symp. on Discharges Electrical Insulation in Vacuum, Paris, 358-363 (Sept. 16-18, 1968)

46. J A. Rich, "A Means for Raising the Threshold Current for Anode Spot Formation in Metal-Vapor Arcs," Proc. IEEE 59, 539-545 (April 1971)

47 G. R. Mitchell, "High-Current Vacuum Arcs, Part 1 -An Experimental Study," Proc IEE (GB), 117, 2315-2326 (Dec. 1970)

48. L. Tonks, "Theory of Liquid Surface Rupture by a Uniform Electric Field," Phys Rev 48, 562-568 (Sept. 1935)

49 L. Frankel, "Liquid Surface Rupture by Uniform Electric Field," Phys Z. Suwietunion 8, 675-679 (1935)

50 J W Beams, "Field Electron Emission from Liquid Mercury," Phys Rev 44, 803 807 (Nov 1933)

51 I. Y Bartashyus, L. I. Pranevichyus, and G. N Fursei, "Electron Emission Bursts from a Liquid Gallium Cathode," Sov Phys Tech. Phys 16, 1535-1539 (March 1972)

52 L. Pranevichyus and I. Bartashyus, "Application of Liquid Cathodes to High Voltage Vacuum Breakdown," Proc. Intern. Conf. on Gas Discharges, London 441 443 (15-18 Sept. 1970)

53 C. W Kimblin, "Anode Voltage Drop and Anode Spot Formation in DC Vacuum Arcs," J Appl. Phys 40, 1744-1752 (March 1969)

54. J A. Rich, L. E. Prescott, and J D. Cobine, "Anode Phenomena in Metal-Vapor Arcs at High Current," J Appl. Phys. 42, 587 601 (Feb. 1971)

55. A. L. Stocater, R. H. Miller, and J C. Sofianek, "Heavy Duty Vacuum Recloser," Trans AIEE III, 81, 356-563 (Oct. 1962)

56. M. P Reece and N S. Ellis, "Good Prospects for Vacuum Interrupters in Circuit Breakers," Elec. Rev , Supp., 15-16 (18 June 1971)

57 R. Nakanishi, T Kikuta, and M. Nagai, "Vacuum Circuit Breaker," Meidensha Rev (Intern. Ed.) Ser 36, No. 1, 13-20 (1971)

58. H. Sugawara and T Takasuma, "Some Investigations of High Current Vacuum Arcs and the Development of 24 kV - 36 kV High Power Vacuum Circuit Breakers," IEEE Power Eng. Soc. Summer Meeting, San Francisco (July 9-14, 1972), 8 pp.

59. A. N Greenwood, D. R. Kurtz, and J C. Sofianek, "A Guide to the Application of Vacuum Circuit Breakers," IEE Winter Power Meeting, New York (Jan. 31-Feb. 5, 1971), 7 pp.