CRD

CORPORATE RESEARCH AND DEVELOPMENT • SCHENECTADY, NEW YORK

CONDUCTION AND BREAKDOWN IN VACUUM

by

G.A. Farrall
Electrical Systems and Technology Laboratory

Report No. 80CRD024 March 1980

TECHNICAL INFORMATION SERIES

CLASS 1

GENERAL ELECTRIC

GENERAL ELECTRIC

TECHNICAL INFORMATION SERIES

General Electric Company
Corporate Research and Development
Schenectady, New York

AUTHOR	SUBJECT	NO.
Farrall, GA	vacuum discharges	80CRD024
		DATE March 1980

TITLE	GE CLASS 1
Conduction and Breakdown in Vacuum	NO. PAGES 23

ORIGINATING COMPONENT	
Electrical Systems and Technology Laboratory	CORPORATE RESEARCH AND DEVELOPMENT SCHENECTADY, N.Y.

SUMMARY

This report is a review of the literature on electrical discharges in vacuum for 1978, and was originally written for the Digest of Literature on Dielectrics published under the auspices of the National Research Council. Topics discussed in connection with electrical breakdown in vacuum include field emission, photo-field emission, explosive emission, ion surface interactions, particle and impurity effects, magnetic field effects, and insulator flashover. Additional topics reviewed in connection with vacuum arcs are arc cathode and anode effects, the vacuum interrupter, and electrical breakdown in Tokamaks.

KEY WORDS

vacuum arcs, vacuum breakdown, field emission, insulators in vacuum, magnetic effects, arc cathode, arc anode, vacuum interrupter, Tokamaks

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)

CONDUCTION AND BREAKDOWN IN VACUUM

G.A. Farrall

INTRODUCTION

One of the areas of most active interest in connection with conduction in vacuum over the past year has been the behavior of vacuum arcs at high currents. The subject is of enormous practical interest to vacuum interrupter development and involves a variety of physical processes, the interactions of which provide fertile ground for novel experimental and theoretical investigations. The vital question concerns the Jeckyl and Hyde character of the vacuum arc anode junction. At low currents, the anode termination is diffuse and passive with the anode terminal acting largely as a charge collector over its entire exposed area. At high currents, the anode end of the arc may contract causing a high concentration of energy input to the electrode surface. This transition results in severe melting and violent ejection of anode metal. A variety of investigations on this subject are discussed in the section on the arc anode and include such subjects as the effects of axial magnetic fields, the visual appearance of the high current arc under different ignition conditions, the current flow pattern between cathode and anode at high current, and the ion flux distribution from the cathode to the anode.

This review as a whole calls upon several major sources in addition to the standard abstract services. Among these are the proceedings of the following conferences: Third International Conference on Plasma Surface Interactions in Controlled Fusion Devices in Abington-Oxfordshire, UK, 3-7 April; VIII International Symposium on Discharges and Electrical Insulation in Vacuum in Albuquerque, 5-7 September; Ninth International Conference on Electric Contact Phenomena in Chicago, 11-15 September; Fifth International Conference on Gas Discharges in Liverpool, UK, 11-14 September; Thirty-First Annual Gaseous Electronics Conference in Buffalo, 17-20 October; and The International Conference on Developments in Distribution Switchgear in London, UK, 20-22 November. Further, a large number of papers on field emission were available from a special issue of Surface Science[(1)] honoring the sixty-fifth birthday of E.W. Muller, who it is sad to note, passed away during the preparation of that issue.

The reader should be aware of certain other publications which represent extended works by individual authors. The thesis by Daalder[(2)] deals with various aspects of vacuum arcs and particularly with the energy balance at the arc cathode. A thesis by Foosnaes[(3)] investigates the energy balance at the cathode, anode, and surrounding shield surfaces for vacuum arcs with and without an imposed axial magnetic field. Chatterton has provided a comprehensive survey of vacuum breakdown phenomena as Chapter 2 in a revised edition of the Meek and Craggs text.[(4)] Reviews of special interest are those by van Oostrom[(5)] on surface analysis techniques and by Guenther and Bettis[(6)] on laser triggered high voltage switches.

In the discussions which follow, a variety of subtopics are discussed under one of two major categories: vacuum breakdown or vacuum arcs. For our present purposes, we use the term breakdown to represent the early stages of arc ignition between fixed contacts. This distinction is more of a convenience than a definition since a more or less steady state cold cathode arc is sometimes regarded as a rapid succession of breakdown events.

VACUUM BREAKDOWN

Field Emission

The first article in the special issue of Surface Science on Field Emission and Related Topics is an historical review by Drechsler[(7)] of the early work of E.W. Muller leading to the invention and development of the field emission and field ion microscopes. The article points out how the field emission microscope served to resolve the early discrepancy between the fields for which significant field emission current was expected on the basis of the Fowler-Nordheim theory and the fields for which emission currents were observed experimentally. The article further discusses Muller's adaptation of the field emission microscope and the field ion instruments to his pioneering studies of sputtering, adsorption, field desorption, field evaporation, surface reactions, work function, and field emission spectroscopy which collectively represent the foundation of surface studies today. Drechsler has, in relatively few words, drawn together the various aspects of present day surfaces studies into a cohesive whole.

One of the questions that arises in connection with the measurement of prebreakdown field emission current is the origin of random fluctuations in current magnitude when a constant voltage is applied to a vacuum gap. Such an effect is usually attributed to surface work function changes arising from the migration of adsorbed gas atoms on the emitter tip. This effect was recently studied by Yamamoto *et al.*[(8)] for

Manuscript received January 16, 1980

tungsten. The experiment consisted of monitoring the total emission current from the tip as well as that part of the current contributed from a (310) crystal face immediately following the cleaning of the tip by flash heating. The fractional current from the selected crystal face was amplified and subjected to frequency analysis at close intervals. Typically both the total current and the fractional current rise to a maximum value and then decay over a time period of several tens of minutes to a more or less stable current, lower than that observed immediately after flashing. The spectrum of the current fluctuations for the (310) crystal face, recorded in the range 0 to 500 Hz, shows two principal variations. The first is a spectrum amplitude which increases following emission peak, approaching a maximum at a point where the total emission current has its maximum rate of change and declines thereafter. The second effect occurs over a longer period of time and is seen as a slope of the power spectrum density as a function of frequency which becomes more negative with time. That is, the higher frequency components of the spectrum are strongly reduced. The authors interpret these results in the following way. After flashing, the initially clean emitter adsorbs background gases (mainly hydrogen) from the vacuum enclosure. The observed noise represents the statistical fluctuation in surface coverage as the transition is made from a clean surface to one which is covered by a monolayer. The maximum noise, observed during the maximum rate of change of emission current, corresponds to the maximum transition rate of moving atoms. Once a monolayer is formed, the emission becomes relatively stable. The initial monolayer is thought to be hydrogen. Over the longer term, substitution of the hydrogen by CO occurs. This conclusion is based upon field emission patterns obtained during this experiment as well as the results of prior experiments in which CO has been intentionally added to the system.

Current fluctuations on tungsten field emitters have been studied as a function of temperature by Swanson[9] over a frequency range up to 10 kHz. In obtaining data for certain of the adsorbate covered crystal faces, he found that clean surfaces themselves produced current fluctuations at threshold temperatures which depended upon the crystal face under study. For the planes (310), (112), and (100), these threshold temperatures were 300 K, 650 K and 1000 K, respectively. These fluctuations clouded the interpretation of noise of adsorbate origin. Swanson concluded that "the current fluctuations from the various planes on a clean tungsten field emitter generally support a mechanism involving the generation of mobile atoms on net plane terraces. At the conclusion of his paper, he warns that in such studies care in the choice of adsorbate and crystal plane must be exercised such that the threshold temperature for clean surface fluctuation is not exceeded.

In experiments designed to examine the modification of field emission current by external magnetic fields, Kennedy and Muir[15] have found two apparently separate effects. Tungsten emitters were maintained at liquid helium temperatures and subjected to magnetic fields of up to 5 tesla. For all emitters studied, a steady exponential decrease in emission current is seen when the field exceeds a threshold value. For fields just above the threshold, the reduction in emission showed cyclic changes superimposed upon the exponential form which first increase in amplitude then decrease as the field becomes larger. Those later variations suggest a resonance effect and differ greatly among the various emitters. To accentuate the cyclic variations, the authors subtracted the exponential decay of current with increasing field from the experimental curves using an empirically derived equation. The residual variations showed clearly that successive cyclic peaks occur at equal intervals of magnetic field change. The magnetic field intervals as well as the amplitude and complexity of the cyclic variations, however, appear to be characteristic of the individual emitters. The authors note that at a given applied electric field, the observed emission current is determined by the number of carriers incident upon the potential barrier within the emitter which have large momentum components normal to the surface. It is therefore suggested that earlier theoretical attempts to describe the influence of magnetic fields upon emission using a flat surface model are inadequate. Rather, if the needle contour is considered, a magnetic field parallel to the emitter axis would serve to reduce the radial momentum of charge carriers, thus reducing the contribution to the total current from all but the small area of the emitter tip. Further, resonances in the emission may be realized if the cyclotron resonance orbits within the conductor are appropriately related to the emitter radius.

In practice, field emission occurs from emitting points, yet the Fowler-Nordheim equation is formulated for a plane surface where the surface electric field, in the absence of image charge considerations for emitted electrons, is uniform. Rabinovich[18] has pointed out that that lack of uniformity at the emitter tip alters the shape of the surface potential barrier and becomes an important consideration for ultrasharp emitters having radii of the order of 10^{-7} cm. Because of this effect, the emission current density is generally higher than deduced from Fowler-Nordheim plots.

Another effect which causes the current density at the emitter tip to be higher than estimated from emission current plots is the difference in emission properties of various crystal planes. These planes generally have different work functions and therefore different emission current densities. Aside from the point to point differences in tip current density, this effect also tends to cause the emission current to be spread over a wider solid angle than would have been the case for the same tip contour without oriented crystal planes. This consideration led Heinrich *et al.*[19] to devise a method for etching field emission tips from a lead-silicon-copper metallic glass. Such a material is non-crystalline at room temperature and consequently has a uniform work function. Current from the tip is confined to a cone of half angle 0.15 radian with a total yield of about 5 μA. Tip radius was estimated to be 0.5 μm. The authors suggest that the mean current density of the tip is more than that of a tungsten tip at the same total current. One shortcoming of the tip material, however, is that an irreversible transformation to a crystalline state occurs at about 643 K. For this reason, bakeout temperatures of the experimental apparatus used in this work was limited to 523 K.

Work Function

Last year we referred to work by Michaelson who had demonstrated the periodicity of work function of polycystalline metals. Bakulin and Bredov[65] have shown a similar relationship through theoretical consideration of surface polarization waves.

The effect of metallic cluster size upon work function was examined theoretically by Kolesnikov and coworkers.[66] They obtained results for beryllium which are essentially in agreement with earlier work by Kulyupin (1975) and find that as cluster size is reduced below 5 nm, work function increases rapidly. They distinguish between two types of size effect. The first is related to the number of surface atoms of the cluster and varies over distances of the order of interatomic separation. The second results from an averaging of the first and varies with cluster size. It is the latter which is generally observed experimentally.

A related effect of cluster size upon work function is found in the work of Gaudart *et al.*[67] In a study of the work function of alkaline earth thin films, these investigators note that as the film thickness of metal deposited on a quartz substrate is increased, the work function passes through a pronounced minimum, which for calcium is 2.5 eV at a thickness of 5.5 nm, for strontium is 2.2 eV at a thickness of 7.5 nm, and for barium is 1.95 eV at a thickness of 1.5 nm. For thicknesses slightly above these critical values, the work functions rapidly increase to the values corresponding to the solid materials. Concurrent electron microscopy studies of these films using replica techniques showed that below the critical film thicknesses the deposited metal layers have a granular structure. For thickness within 1 nm of the critical value, the formation of aggregates or islands begins. With heavier films, the spaces between the islands of metal fill in, leaving a structure which is generally continuous with occasional voids. The minimum value of work function for each of these metals has thus been identified with the formation of material clusters. While it is difficult to compare this work with that of Kolesnikov *et al.*[66] because of the difference in metal studied, it seems clear that cluster size is a significant parameter in determining work function.

Photo-Field Emission

Photo-field emission is the process by which electrons are extracted from a "cold" (nonthermionic) surface through the combined effects of optical illumination and high electric field. Lee and Reifenberger[91] provide useful background comments on the subject as well as a discussion of their recent investigations. They point out two principal modes in which the effect is studied. In the first, the energy of the incident radiation is relatively small so that free electrons within the metal must still tunnel through the potential barrier at the metal surface in order for emission to occur. In this case, an experimental Fowler-Nordheim plot is a straight line, like that expected for normal field emission. The slope of the plot, however, will be determined by a work function which is equal to the difference between the field dependent barrier height and the incident photon energy. In the second mode, the incident photon energy exceeds the barrier height, at least at high fields. This condition yields a Fowler-Nordheim plot which may be linear at low fields but which passes through a maximum at high field and reverses the sign of the slope. Curves of this type have been the object of a recent analysis by Tarenko.[92]

Lee and Reifenberger have analyzed the shape of Fowler-Nordheim curves from photo-field emission experiments and concluded that the energy spectrum for a given total energy should be narrow. Initially they were unable to verify this conclusion experimentally. More recently they have found small cyclic variations in the photo current as the field was varied. It apparently was this effect that rendered the earlier energy distribution measurements invalid. The periodic field dependent photo currents were observed for the (510) region of a tungsten field emitter illuminated by a krypton ion laser having a photon energy of about 3.5 eV. The phase of the field periodic changes in photo current was found to be inversely proportional to the square root of the electric field. The authors suggest that the oscillations are related to quantum mechanical interference effects associated with the transmission of photo electrons across the surface barrier. They indicate that the inverse square root relationship with field "may arise from the field dependence of the width of the surface barrier." Surface contamination may also alter the oscillatory behavior.

Radon and Kleint[93] have also reported periodic current variations for photo-field emission from tungsten. This work, in fact, predates that of Lee and Reifenberger. Radon and Kleint used modulated monochromatic illumination from a mercury discharge and found a weak but reproducible dependence of the photo current periodicity upon photon energy. These authors suggest a model in which the potential barrier is altered by adsorbates such that partial reflections of electron waves occur.

Additional studies of photo-field emission have been carried out by Teisseyre *et al.*[94] on tungsten and barium covered tungsten using a He-Cd laser (3.82 eV or 2.81 eV) and a He-Ne laser (1.96 eV). They have examined polarization effects. The authors suggest that photo-field emission should play an important role in the cathode processes of a vacuum arc since the cathode spot is a bright source of illumination located in a region of high electric field.

Explosive Emission

Swanson and Schwind[100] have described experiments on a liquid metal emission tip for which the extraction of current at high electric field is believed to occur in an explosive emission mode. An alloy of gallium and indium containing 12% of the former is continuously fed through a tungsten capillary. Under the stress of a continuously applied field, the alloy is deformed into a tip of small radius resulting in a burst of emission which discharges the local capacitance. Upon recharging, the process repeats, producing a relaxation discharge for which bursts of current having peak values of 250 A are observed. Following an earlier analysis by Taylor (1964) of the balance between surface tension and field forces, the authors conclude that the maximum current expected on the basis of pure field emission is too small by several orders of magnitude. However, by taking into account the effects of Nottingham heating and Joule heating at the tip and by employing a work function of 3.0 eV instead of the literature value of 4.1 eV, the authors further suggest that the observed high levels of current can be attributed to emission in the explosive mode.

Several advantages are cited for the liquid metal emitter compared with solid ones. The liquid type is self-healing, has no limit on lifetime, has a faster-rise shorter-duration pulse, and has a time jitter less than 0.1 ns over a wide range of repetition rate.

Aside from whatever application liquid metal emitters may have as electron sources, they also exhibit an interesting luminous effect. During the emission burst, a small incandescent spot appears at the emitter tip, surrounded by a blue glow which extends several microns beyond the tip. The authors conclude that the blue glow is due to excited gallium atoms. In recent years, there has been a growing belief that electron emission in the explosive mode is the mechanism by which vacuum arcs exist. It seems reasonable that the incandescent spot at the liquid tip is an arc cathode spot and that the discharge is a vacuum arc for which current is limited only by the external circuit impedances.

Koval *et al.*[101] reiterate the view that explosive emission is closely related to the processes of the vacuum arc. They have made measurements of the erosion products from an emission tip operated in the explosive mode and compared their results with the vacuum arc experiments of Utsumi and English (1975) and Udris (1963). They note three areas of similarity: (1) the number of particles per coulomb of charge carried by the gap, (2) the distribution of particle sizes, and (3) a pronounced shift of the size distribution to smaller sizes with a decrease in current. These are taken as evidence of the close relationship between explosive emission and vacuum arc emission processes. The authors consider their results as preliminary.

While explosive emission is usually associated with discharges in vacuum, Babich *et al.*[102] cite experiments which suggest a relevance to discharges in air at pressures up to one atmosphere. Support for this view is taken from three considerations. First, the development of an avalanche in the gas is expected to produce an ion space charge region at the cathode capable of enhancing the surface field to the required level. Second, observations of spectral lines at the cathode during the developing discharge show the presence of doubly ionized species of cathode metal but few singly ionized atoms, indicating a hot plasma. Third, micrographs of the cathode after a discharge show craters ranging in size from one to ten microns, while the anode shows no cratering. It is concluded that explosive emission does occur in gas discharges, although the process plays a less important role in the discharge development than in vacuum.

Ion-Surface Interactions

A common method of cleaning a surface to be used in high voltage vacuum devices is the bombardment of that surface by heavy ions in a glow discharge. In some cases, the metals treated in this way develop conical structures which are sometimes associated with impurities. Whitton *et al.*[110] have investigated this effect and concluded that the cone or pyramid structures are crystallographic in origin and that impurities are not required for their growth. Copper of five nines purity (99.999%) was bombarded with 40 KeV argon ions for a total sample dose of 1023 ions/m^2 at room temperature. Both pits and pyramids were produced by this treatment, but is was noted that pyramids had formed only for crystal planes lying in the interval 12 to 15 degrees from the (100) direction, midway between the (100) and (110) planes. With a crystal cut specifically to expose this surface, ion bombardment produced an array of pyramids having crystallographic regularity. The formation of the pyramids is associated with surface defects. The process is suggested as having several practical uses among which is the fabrication of field emission or explosive emission cathodes. Similar pyramid formations have recently been noted by Rizk[111] for argon bombardment on a stainless steel. This work investigated surface microstructure changes produced by ion bombardment. The author concludes that a significant reduction in surface roughness can be effected in this way.

Particle Effects

Since the proposal by Cranberg in 1952 that vacuum breakdown could be initiated by particle impact, the behavior of particles under high fields in vacuum devices has been examined in numerous papers. Among the more important recent contributions are publications by Haug and Texier[121] and Boulloud and Texier.[122] In the first of these, a study was made of the effects of a pumping technique and baking upon generations of microparticles within a vacuum enclosure. Employing a special electrostatic device for particle detection, they find that a system which has been ion pumped and conditioned using ramps of high voltage so that no particles are detectable retains its apparent particle-free condition after being refilled with filtered air and reevacuated with an oil diffusion pump. The diffusion pump oil vapor, which was not trapped, did not contribute to particle generation.

It was also found that newly polished electrodes installed in the experimental tube yielded many particles. If, however, the tube was baked at 873 K for two hours after new electrodes were installed and after evacuation, no particles were found. The authors conclude that heating destroyed organic particles and/or caused particles to adhere more strongly to their rest surface. The publication by Boulloud and Texier draws the same conclusion and points to other instances in the literature which support this view.

There are other uncertainties connected with the study of particles. Generally their shape and even their composition are unknown. Measurements from outside the vacuum enclosure indicate only particle velocity and total charge, and these show that the charge carried by a "natural" particle is greater than would be computed for a spherical shape. The factor by which measured charge exceeds that deduced on the basis of a sphere is termed the overcharge factor by Texier. Texier and Haug[123] find that the overcharge never increases with increasing applied voltage. To account for this result, they consider such factors as particle density, shape, and charge loss, but arrive at no firm conclusion regarding the origin of the overcharge. In connection with particle shape, Shtepa[126] has analyzed the motion of an elongated ellipsoid of revolution in vacuum under the influence of an electrostatic field. Under certain assumptions, the results of this work allow earlier analyses for spherical particles to be extended to the ellipsoidal case.

In a related paper Winterberg[127] discusses the high velocity reached by filamentary particles in vacuum diodes under high electric fields. He suggest that the filament is pulled out of an anode surface by the field and is the focal point of a breakdown across the gap. If the particle radius is sufficiently small, the bulk of the filament, despite the discharge, will retain its shape through the action of the high local magnetic field of the discharge current. This condition permits the particle to attain a higher than normal charge and accounts for high particle velocities.

Impurity Effects

In recent years increasing attention has been focussed upon the role played by electrode impurities in electrical breakdown. Hurley and Dooley[137] associate breakdown with semiconducting inclusions. Similarly, Allan and Latham[138] have examined electron emission from microscopic sites on broad area electrodes using a 180° electrostatic deflection electron energy analyzer and have compared these results with those obtained from a reference tungsten emitter. They conclude that the observed emission is reasonably interpreted in terms of an emitting area having a semiconducting overlayer.

Further work on contaminated cathodes has been carried out by Juttner.[140] In these experiments, small spherical electrodes were formed by melting the ends of wires 20 μm to 100 μm in diameter n vacuum under electron beam bombardment. Cathodes of tungsten, molybdenum, iron, and copper were prepared in this way. The first two of these metals were formed at sufficiently high temperatures that the resulting spheres were clean. For the latter two metals, however, some impurities, possibly carbon and sulfur, survived melting temperatures. Juttner compares the erosion produced by breakdown discharges for the clean and impurity bearing surfaces. He finds in the case of a clean sphere (molybdenum) that cathode erosion occurs on single crystal faces and is not preferentially situated at the grain boundaries. On the other hand, the erosion patterns on the copper and iron spheres occur principally on the grain boundaries. It is concluded that grain boundaries are more likely to accumulate a higher impurity concentration than the exposed crystal surface. Juttner also finds that initial discharges on contaminated samples occur at very low voltages and are characteristic of microdischarges but anode involvement is precluded by the electrode geometry. A parallel is drawn between these low voltage discharges and vacuum arcs drawn between contaminated surfaces for which erosion is slight and cathode spot velocities are high.

Magnetic Field and the Anode

The effect of a transverse magnetic field upon the breakdown and emission characteristics has been studied by Petrosov and Cherkasskii.[146] They find that the prebreakdown emission current to the anode is strongly suppressed when the Larmor radius for the electrons becomes less than the gap length. A corresponding increase in breakdown voltage is also noted. Although this paper contains interpretive errors regarding emission current density and to a certain extent reiterates conclusions drawn in the 1958 work of Pivovar *et al.,* the data illustrate the dramatic changes that occur in emission and breakdown characteristics with increasing field strength.

The increase in breakdown voltage with transverse magnetic field noted above occurs because the interaction of the prebreakdown emission current with the anode surface is suppressed. Without the field, emission sites produce electron beams which strike the anode and may produce vaporization or dislodge a small mass of metal. Ionization of this anode material can lead to electrical breakdown. Poshekhonov *et al.*[148] have explored the development of breakdown in a gap for which the anode is bombarded by a beam from an electron gun. They find that if the beam intensity is kept below 10^{10} W/m^2 with gap voltage applied, breakdown occurs at a reproducible delay time measured from the application of beam power. This mode of breakdown is identified with the evaporation of anode metal. Above 10^{10} W/m^2, a pulse of current passes through the gap before the transition to breakdown occurs. As the beam power is increased, the time period between the application of the beam and the current pulse becomes shorter while the peak current becomes higher. At still higher beam powers, breakdown becomes coincident with the pulse. It is suggested that the anomalous behavior at beam intensities higher than 10^{10} W/m^2 is related to the formation of the breakdown in a gaseous atmosphere desorbed from the anode surface by beam bombardment.

Similar observations of prebreakdown current pulses in an electron beam tube were reported by Gaponov *et al.*[149] In this work, it was found that a substantial increase in breakdown voltage could be obtained for unconditioned surfaces by placing a grid, positively biased with respect to the anode, in front of the anode. The authors suggest that the grid is effective in reducing charge exchange between anode and cathode. Experimentally it is found that an increasing grid potential reduces the magnitude of the prebreakdown current pulse and delays the appearance of the pulse. At a working bias level, the current pulse is totally suppressed.

Insulators

Miller and Furno[179,180] discuss two approaches to improved insulator design. In the first, alumina ceramic is coated with a mixture of manganese and titanium, while in the second a 95% alumina is made with 4% manganese and 1% titanium in the bulk. Both approaches are compatible with alumina brazing procedures, are not damaged permanently if a breakdown occurs, and offer an improvement in dielectric strength (20% for the 4% Mn, 1% Ti mixture). The improved dielectric characteristic is attributed in part to the lower resistiviy of the insulator and to a reduced secondary electron emission at the surface.

A case in which discharge damage causes deterioration in secondary emission properties is discussed by Stringfield *et al.*[181] who investigated flashover propagation speeds on dielectric cathodes of an electron beam accelerator. They find a propagation speed for alumina to be about 2×10^{11} m/s while that for alumina coated with Cr_2O_3 was 1.3×10^{11} m/s. The Cr_2O_3 coating was used to obtain a surface for which the secondary electron yield would always be less than unity. Once a filamentary conduction path had been established on the coating in the course of a developing discharge, however, the coating was removed, exposing a surface for which σ would exceed unity. Thereafter there was little difference in dielectric behavior in the coated and uncoated insulators.

In recent work carried out by Chatterton and Davies,[182] the secondary emission coefficient, σ, was determined *in situ* for three different insulators before and after measurements of flashover voltage. They find an increasing flashover voltage in successive trials with a corresponding decrease in the secondary emission characteristic over the energy range 250 to 2500 eV. They further report a decrease in σ in local regions of the insulator which show discharge tracking. The authors attribute the reduction in σ to the presence of a discontinuous metal film on the insulator deposited there during the discharge erosion from the electrodes.

A similar reduction in secondary emission coefficient was noted by Lavarec *et al.*[183] on surfaces of niobium, oxidized niobium, tantalum, and gold for primary electron beam energies in the range 200 eV to 3 KeV. They attribute the changes in σ to modification of adsorbed layers by the primary beam. They conclude the effect is not of thermal origin. The calculation of secondary electron emission coefficients for twenty insulating materials is the subject of a paper by Kanaya *et al.*[184] who obtain results in good agreement with experiment.

The temporal development of dc flashover on alumina has been investigated by Cross[187] using subnanosecond streak photography. Experiments were performed in a vessel having a background pressure of 10^{-3} Pa. Photographs are obtained which show a luminous region, starting at the cathode, growing toward the anode at approximately 4×10^7 m/s. This event is followed by intense luminous clouds expanding from both the anode and the cathode at rates of 4.8×10^7 m/s and 2.4×10^7 m/s respectively. The gap is bridged within 0.15 ns. The following sequence of events in the flashover of the insulator is suggested. An initial positive charge on the insulator surface produced by secondary electron emission serves to enhance the field at the cathode junction of the insulator increasing electron emission current. With further increase in gap voltage, a spot on the insulator near the cathode junction becomes still more positive, producing a cathode emission burst which exceeds the more or less steady electron losses to the anode. This burst causes light emission from the cathode and masks the positive charge on the insulator with an electron cloud. The cloud, lying initially closer to the cathode, causes subsequently emitted electrons to arrive at the insulator closer to the anode. Ultimately the burst strikes the anode. A consequence of the electron bombardment of the solid is the desorption of gas accompanied by excitation and ionization. The final step in the flashover process is a discharge through the channel of desorbed gas which now lies adjacent to the insulator. It is this last stage that provides the luminosity (recorded in the streak photographs) which proceeds from both anode and cathode surfaces. This mechanism is similar to that proposed by Avdienko and Malev[186] in that both require desorbed gas for the development of the discharge. The mechanism outlined by Cross is nearly identical to that which was more recently proposed by Anderson and Brainard.[188]

VACUUM ARCS

The Arc Cathode

The current density at the arc cathode spot has been a subject of intense experimental and theoretical interest for decades, since a knowledge of this quantity is essential in establishing the arc emission mechanism. Eckhardt[196] has investigated this question for anchored cathode spots in a dc mercury vacuum arc. She finds that the current carried by individual spots varies continuously from about 0.6 A at a current of 40 A to 2.5 A at a total current of 300 A. Current density varies over this same current range from about 4×10^9 A/m^2 to 1.5×10^9 A/m^2, the latter value corresponding to the highest current. These results are in good agreement with previous studies.

Juttner *et al.*[200] studied the propagation of the cathode spot over clean solid surfaces in vacuum. Streak photographs for arcs on copper in the current range 10 A and 75 A show fluctuations in intensity which are viewed by the authors as extinctions and reignitions of cathode spots. Viewing spot motion through a mesh anode and correlating the streak photographs with arc voltage fluctuations, the authors conclude that the displacement of the spot with time follows the random walk relation in which the step of movement, Δx, for a given time interval, Δt, is proportional to the square root of Δt. The interval Δt represents the time required for the spot to erode the thin layer of liquid metal at the spot crater rim. The quantity Δx is taken to be the cathode crater radius.

This view is expanded upon in a latter work by Juttner[201] which discusses various aspects of crater formation and erosion. By comparing crater sizes as a function of arc current for nanosecond discharges with those for dc arcs reported by Daalder (1974) and by correlating cathode spot movement for dc arcs on copper with a random walk process in previous work [Juttner, Freund, Pursch (1976)], Juttner has concluded that nanosecond discharges and dc arcs are sustained by the same cathode mechanisms. In particular, dc arcs in vacuum for currents less than 100 A exist as a rapid succession of nanosecond discharge events in steps having a length equal to successive crater radii. This view requires that after a discharge the cathode craters lie in a connected string, a condition which is not always seen experimentally. Juttner does in fact report cases for which the crater pattern of a single discharge occurs in disconnected segments. He accounts for this effect by proposing that metal droplets ejected from an active crater strike the cathode surface at a distance from the parent crater which can be large compared to the crater radius. The impact of such a droplet with the cathode provides the necessary conditions for discharge ignition there.

The view that a vacuum arc sustains itself as a rapid succession of discharges is widespread and carries with it the notion of cathode emission fluctuations and instability. It is well recognized that when a dc vacuum arc is initiated at low current, the discharge will burn for a finite time then spontaneously extinguish. The duration of the arc varies statistically with arc current, cathode material and circuit constants as well as a number of other parameters. In ac circuits, this effect is seen as an instability and sudden extinction of the arc at the end of a half cycle period of arcing where current is low. This form of instability is called "chopping." The currents at which chopping occurs tend to be high for cathode metals which have high melting points and lower for the less refractory metals. The melting point, or more properly, the vapor pressure characteristics of the cathode metal determine the ease with which the arc cathode spot can supply the metal vapor atmosphere needed to maintain the arc. Hassler *et al.*[202] report measurements of chopping currents for copper, tungsten, and composites of those two metals. They find that the chopping currents for copper are somewhat lower than has been found in earlier literature. For a tungsten matrix impregnated with 12% copper and another having 24% copper, the former has a lower chopping current than the latter. That is, the metal containing the lower percentage of copper sustains a more stable arc. The authors suggest that this result follows from the lower losses of surface heat through conduction in the bulk metal of the electrode. This condition enhances the vaporization of copper at the cathode spot and sustains a more stable arc.

Certain characteristics of cold cathode arcs at atmospheric pressure are fundamentally the same as for the vacuum case. This is particularly true of cathode spot stability. Gray and Pharney[203] describe measurements of arc durations for palladium, silver, palladium-silver and gold contacts in air for currents ranging from 0.1 A to 1.5 A in a 50 volt dc circuit. At a current of 0.5 A, it was found that, on the average, arc durations early in the use of contacts were higher for surfaces with a rough finish. After approximately 3000 trials of "make and break" operations, the average arc duration for all surface finishes becomes similar and lower than the initial values. The authors suggest that the 3000 initial operations have served to completely replace the original surface microstructure so that all surfaces regardless of their initial preparation become the same. The paper further shows that the statistical distribution of arc durations in a succession of trials changes from one in which the mode of the distribution is zero to one which is log-normal in form as the current is increased. The authors identify the current at which this transition occurs as the minimum arc current. Data suggest that below this minimum arc current, the statistical duration of the arc is controlled by the volume of the molten metal bridge which is formed at contact parting.

Guile and Hitchock[204] have called upon some of their earlier work to compare certain erosion characteristics of moving arcs at atmospheric pressure with published data on vacuum arcs. They note that for atmospheric-air arcs on copper, the cathode crater diameters are usually less than 1 μm and individual emitting sites carry currents of 10 to 15 mA, while for vacuum arcs crater diameters can be 10 times larger and emission sites may carry 100 A. The authors call attention to the fact that the high pressure arc in its normal rapid motion across the cathode surface has an erosion rate that is roughly proportional to the first power of the arc current. In a slowly moving mode, however, the erosion rate undergoes a dramatic increase. A parallel is drawn between this enhanced erosion mode and the high-current, anode-melting mode of a vacuum arc for which erosion rate also is greatly increased. It should be kept in mind by the reader, however, that this parallel between high pressure and vacuum arc erosion appears not to reflect a fundamental similarity since the phenomena giving rise to the observed effects are probably quite different in the two cases. Another aspect of vacuum arc erosion may provide a better comparison. It is well recognized that vacuum arcs will move very rapidly over oxidized surfaces and show very low erosion rates. However, after the surface has been eroded by many arcs and the oxide is removed, the propagation velocity becomes markedly reduced and the erosion rate increases significantly. This behavior appears to be more closely related to the fast and slow cathode spot modes at high pressure.

Under the influence of a transverse magnetic field, cold cathode arcs at low pressure tend to move in a direction which is opposite to that predicted from vxB forces. Recently Robson[206] measured retrograde velocities of about 500 m/s in a field of 1 tesla for arc currents of 5 A and 10 A. He suggests that the influence of electrode separation on reverse motion has not been appreciated and concludes that this parameter is properly accounted for in the 1953 proposal of Robson and von Engel. According to this view the arc cathode spot moves in response not only to the imposed field but also to a component introduced by the current flow to the spot. Because of the bending of the arc positive column (which occurs more readily at low pressure), the self field can exceed the external field, driving the spot retrograde.

The movement of cathode spots on oxide films has been examined by Hitchcock *et al.*[210] At atmospheric pressure with 40 A arcs on copper electrodes spaced 3 mm apart, the spot velocity over the surface is found to depend upon the strength of a transverse magnetic field according to the approximate relation $U \propto B^{0.6}$ For fields up to about 0.1 tesla, spot velocity varied up to about 55 m/s. Oxide film thicknesses between 2.5 nm and 110 nm were investigated and over this range did not have a large effect on spot velocity.

The authors also investigated spot movement over a pressure range of a few torr to 200 torr on copper using a fixed field of 0.075 T. The gap length was 1.5 mm and the current 12 A. For a film thickness of 2.5 nm, which corresponds to that obtained upon exposure of copper to air, a reduction to zero velocity was noted as pressure approached 100 torr. Below that pressure, the arc was stationary until a pressure of 25 torr was reached, at which point movement became retrograde. At a few torr, the measured retrograde velocity was about 45 m/s and showed much greater scatter in values than was observed for forward motion.

A new theory of vacuum arc cold cathode spot operation has been developed by Harris.[211] The analysis employs no adjustable input parameters and yields a quantitative description of cathode spot properties which can be compared with experiment. A sample calculation for copper is cited. Harris finds that a single Kesaev cell carries a current of 80 A and operates at a voltage of 10.2 V. Computed current density is 1.3×10^{11} A/m^2, the ratio of electron to ion current, 8.8, the average degree of ionization 1.77, and the ion energy, 45 eV. Each of these figures compares favorably with experimental measurement. The electric field at the cathode is found to be 2.5×10^9 V/m.

Dalder[212] has developed a model for the active cathode spot which considers the sustained arc as a succession of self-extinguishing ignition events. Upon initial ignition of a cathode spot, the current density within the bulk metal of the electrode tends to be high. Joule heating of the metal is therefore also high, causing evaporization and ionization of metal atoms. This ion flux enters the region just above the erosion area to maintain a plasma cloud which extends laterally for a much greater distance than the size of the ion source area. As the erosion of electrode material continues, a crater forms and enlarges so that the current density in the emission zone becomes smaller. With further reduction in current density, the rate of ion production falls reducing the ion density above the emission zone. A new ignition site is formed by the expanding plasma region, which then recycles in the same way as the previous spot. Daalder estimates the probable limits of ion current flow to the cathode to lie between 10% and 20% of the total arc current with the lower percentage being more likely.

A discussion of the cathode spot emission properties and the influence of polarization effects in the dense vapor above the cathode emission zone has been given by Leycuras.[214] He suggests that the presence of a high concentration of metal atoms above the cathode surface constitutes a dielectric fluid which can be polarized in the cathode field. He supports this view with experimental data from a high pressure, high temperature mercury vessel. The effect of such polarization is to reduce the surface work function and thereby strongly alter the cathode emission process. He indicates that the effect should be taken into account in theoretical descriptions of cathode emission processes.

The Arc Anode

In a low current vacuum arc, positive ions generated at the arc cathode move into the interelectrode volume neutralizing the space charge associated with the electron flow and maintaining the arc voltage at a low value. Typically the flux of ions from the cathode is anisotropic and has a maximum along the discharge axis. This aspect of the discharge has been shown by a number of investigations in the past and most recently in a study by Kutzner.[221] The directional character of the ion flux and its moderating effect on arc voltage is illustrated in an experiment by Schwartz *et al.*[222] who found large voltage fluctuations in the arc voltage of a discharge for which the anode was a ring coaxial with the axis of the cathode. It is likely in this circumstance that the anode lies outside the region of highest ion flux so that effective space charge neutralization does not occur.

At high current, the flux of ions reaching the anode in a gap between conventional butt-type contacts is insufficient to neutralize the anode space charge, causing an increase in anode drop. It is felt by some that the increased voltage in the anode region causes a higher input of energy to the anode surface which ultimately leads to anode melting. The past literature on this subject contains several papers aimed at determining the threshold conditions which lead to anode spot formation for parameters such as electrode metal, gap length, arc current, and discharge duration. A new paper by Boxman *et al.*[225] investigates power frequency effects for arcs triggered between electrodes of copper and of nickel. Threshold currents, indicated by a sudden rise in arc voltage during an approximately sinusoidal current waveform, were found to be higher for higher power frequencies. Several possible mechanisms for this effect are discussed.

One method for improving the distribution of ions in the vicinity of the arc anode is the use of an axial magnetic field across the discharge gap. An indication of the effectiveness of this approach is the consequent reduction in arc voltage. Measurements of vacuum arc voltage as a function of axial magnetic field have been carried out by Gundlach[226] for molybdenum and for copper electrodes. He found that for an arc current of about 100 A, the arc voltage increases as the square root of field strength up to the maximum field studied, 0.25 tesla. For higher currents (up to 25 kA for copper and 30 kA for molybdenum), he finds that as the field is increased from zero, the arc voltage (initially higher than for the 100 A case) decreases to a minimum having a value and a corresponding field which depend upon current. For fields beyond the minimum, arc voltages at the various currents increase, asymptotically approaching the curve for the 100 A arc. This result is largely in agreement with the 1975 results of Rondeel who examined the same metals over the same field range. However, Rondeel found that the voltage curves at various currents for copper at high fields failed to converge completely and remained separate and distinct over the full field range studied. Gundlach attributes this difference to a skin effect voltage drop in the body of the contact of the Rondeel work. Gundlach also presents measurements of arc drop as a function of gap length for various magnetic fields, as well as measurements of radial cathode spot velocity. He presents a simple model of the discharge for the region lying outside the cathode spot based upon his results.

Foosnaes[3] discusses a wide variety of experiments on 500 A vacuum arcs of 30 to 35 ms duration in axial magnetic fields varying from 0 to 0.35 tesla. His investigations were carried out in a demountable test cell and included studies of (1) the energy delivered to the anode, cathode, and surrounding electrically floating shield as a function of gap length, arc voltage and floating shield potential; (2) changes in mass at anode, cathode, and shield; (3) ion currents and energy distributions; and (4) radiation losses. Foosnaes describes the general behavior of the arc from his own work and that of Kimblin and Voshall (1973) and of Rondeel (1975). With increasing field the cathode spots are less random in their motion, each becoming associated with a plasma column extending to the anode. In the high field range, the arc drop increases with field because the plasma columns become similar in their characteristics to the positive columns in high pressure arcs. Among the conclusions drawn from this work are the following: (1) the equivalent voltage drop of the energy dissipated at the anode is 1.7 to 1.9 times that at the cathode over the range of fields studied, (2) the energy collected by the shield surrounding the arc depends upon shield configuration and field but is higher with the field than without it (an unexpected result); (3) cathode erosion increases with increasing field, apparently because of the retarded cathode spot movement; (4) the ion current to the shield is saturated over the field range and therefore remains constant; and (5) ion energies are not significantly altered by the field.

Agarwal and Holmes[227] have studied axial magnetic field effects in triggered, high-current arcs between 75 mm diameter copper electrodes at a gap of 15 mm. Arc currents from 2.7 kA to 8.7 kA were used in conjunction with fields up to 0.2 tesla. Current flow patterns during the arc were mapped by a magnetic probe. Two discharge modes are described. With no axial field, the triggering event generates a ring of cathode spots which expand as a ring with increasing time. The flow lines of current vary their inclination with the electrode axis to follow the expanding spot ring. When no axial field is present, some of the spots of the expanding perimeter remain within, tending to give an internally uniform distribution of spots. For this case, the flow lines tend to remain parallel with the electrode axis. It is the cathode in these two cases that undergoes the greatest change since the flow terminates at the cathode spots. The anode ends of the flow are similar with and without the field.

A more recent paper by Sherman *et al.*[228] shows data similar to that just mentioned and provides additional information on the arc voltage during the expansion of the ring of cathode spots. Currents in the range 3 kA to about 9 kA were studied without an axial field. Arc drop was found to be dependent upon current, gap length, and time, and measurements were well described by a simple relationship derived by the authors. A comparison is also made with the results of Mitchell (1970) for drawn arcs.

High current arcs drawn under the influence of axial magnetic fields have been studied by Heberlein and Gorman[230] using 100 mm copper, butt-type contacts. They note that with contacts parted at an instantaneous current on an ac current wave with no axial field, the bridge rupture at contact parting forms an arc column which expands to become diffuse within one millisecond. If parting is delayed to an instantaneous current of 7 kA to 15 kA, the bridge rupture forms a column with diffuse boundaries which expand linearly with increasing current. With continuing current increase above 16 kA, the expanding column constricts and remains so until the current drops below 10 kA. The work describes the appearance of the high current arc under conditions where both the instantaneous current and the gap length change with time and includes comments on the conditions under which anode and cathode jets are formed. The presence of an axial field tends to delay intense anode activity to higher currents and longer gap lengths. The paper stresses the importance of the instantaneous current at contact parting upon the subsequent appearance of the discharge. Results are summarized in "appearance" diagrams in which the principal coordinates are current and gap length.

While the more fundamental studies of axial field effects are conducted by employing external coils, a greater simplicity is achieved for practical vacuum interrupters by designing the electrodes themselves with current flow patterns which will produce the required field. An example of such a development is given in a paper by Okumura *et al.*[233] The authors discuss a design in which the arc drop can be as low as 52 V for a 40 kA (rms) arc current. Contact erosion is said to be of the order of 100 μg per coulomb of charge transferred by the arc—a figure characteristic of low current vacuum arcs.

The axially symmetric magnetic field which is frequently favored as a means for reducing the tendency for anode spot formation at high current and long gap lengths has been modified by Pertsev *et al.*[234] to include a radial component. This condition is achieved simply by incorporating a field producing coil coaxially in one electrode only. The authors report interruption of 60 kA peak current for 10 cm diameter copper electrodes in a system which develops a peak recovery voltage of 13 kV to 19 kV at an initial rise rate corresponding to 15 kHz. Gap length was 1.4 cm. Measurements of arc voltage as a function of current indicate a total arc drop which is generally low, approximately 60 volts at 60 kA. The radial field component is viewed as providing a mechanism by which the arc anode root can spread more easily over the electrode surface, reducing temperature increases there.

We have heretofore considered the enhancement of current interruption by suppression of anode spot formation using an axial magnetic field. Under certain conditions, a transverse magnetic field can also improve current interruption. The use of a crossed electric and magnetic field configuration to modulate the arc drop of a vacuum arc has been studied by Dethlefsen and Mylius[235] following closely the work of Gilmour and Lockwood (1972, 1975). A central cathode with trigger is coaxially arranged below an annular anode around which is a field producing coil. When a vacuum discharge is triggered and a coil energized, the arc voltage undergoes a marked increase. For a constant voltage source, this increase drives the arc current to a low value. Desirable cathode metals for this application would have low atomc weight as well as a high melting temperature.

Vacuum Interrupter

The high vacuum conditions which are required for the interruption of high currents or the withstand of high voltage must be maintained within a vacuum interrupter regardless of whether the device receives frequent use or is idle most of the time. The question of the gas content within the interrupter envelope and the changes in these gases that may occur with varying use and time is therefore an important one. Arthur and Zunick[239] have measured residual gases in a commercial device with acceleration of time effects simulated by elevated temperature. They conclude that most of the residual gas is evolved from the bulk of the material within the interrupter envelope and that gas permeation from the atmosphere is small for interrupters having ceramic envelopes. In the discussion of this paper, these conclusions are questioned by Dethlefsen[240] who noted particularly that permeation of hydrogen through the thin wall of the interrupter bellows is probably not negligible.

Juttner *et al.*[241] have investigated the effects of arcing upon gas content and conclude that if chemically active gases such as O_2, CO, and N_2 are contained within the bulk of the contact, the gases released by arcing become immediately bound to the eroded metal and therefore are not observed as residual gases. They further conclude that if the electrodes are conditioned by preliminary arcing, "the gas content of many contact materials can essentially exceed the values mentioned in the literature without any negative effect to the performance of vacuum interrupters."

The ability of a pair of opposing electrodes to withstand high voltage after they have been parted from an initially closed position depends upon a number of parameters. Some of these have been investigated by Frolich[248] for conditions typical of vacuum interrupter operation. Breakdown voltages as well as field emission currents were measured for both 50 Hz high voltages and waveforms having rise rates in the range 0.2 to 50 kV/μs. It was concluded that breakdown between copper contacts after interruption of a small current was limited mainly by residual cold weld structures at the surfaces formed during contact parting. Arcing tends to smooth the surface especially at high current. When the interrupter is arced at currents exceeding 10 kA, the ac breakdown voltage becomes smaller, presumably by particle effects. Similar results are obtained by Juttner[249] in a study of various contact metals in a current range up to 20 kA. A paper by Rushton *et al.*[251] also is closely related. This work was discussed in last year's review on the basis of a University of Liverpool Report.

While contact surface effects determine in large part the voltage withstand capability after interruption of current, a time varying component of dielectric strength immediately following arc extinction is imposed by the decay residual arc plasmas in the interelectrode space. Certain of the processes which come into play during this period are discussed by Farrall.[252] Among these is the generation of a space charge field formed at the new cathode surface by the impressed reverse voltage acting upon the plasma residue. This field can become sufficiently intense under some conditions to promote breakdown at the new cathode surface. It is concluded that this breakdown mechanism can be dominant for some electrode metals during early recovery. Later, however, recovery is more likely to be controlled by the relatively slow decay of neutral vapor. The effect of neutral vapor density upon dielectric recovery of vacuum interrupters has been considered by Gorman.[253] A semiemperical analytical expression was obtained; this expression is reported to have predictive value in assessing recovery strengths of different gap lengths for widely varying arcing conditions.

Recovery in vacuum is strongly influenced by the degree to which neutral vapor will adhere to surfaces surrounding the arcing volume upon initial impact. Particles that rebound from these surfaces may reenter the gap volume and slow the recovery. Harris[254] discusses an analysis of particle surface energy accommodation within the framework of a model which in its initial phase is mathematically equivalent to a transient in an RCL electrical circuit. Results are obtained which show that under vacuum arc conditions impact of a metal atom at a metal surface has a high probability of condensation.

In an experiment designed to explore the use of vacuum interrupters in dc circuits, Anderson and Carroll[261] have examined in detail the recovery characteristics of an interrupter following rapid commutation of arc current. They showed that the single interrupter used could interrupt a 10 kA current forced to zero at a rate of about 1 kA/μs and withstand a positive going recovery voltage of 100 kV rising at the rate of about 2 kV/μs. At a current of 10 kA for the experimental conditions prevailing, one would expect modest melting at the arc anode.

In related work, Shimada *et al.*[262] have studied the use of axial field type vacuum interrupters for Tokamak power switching. They propose an array of eight interrupters: two in series, and four in parallel for a 92 kA, 25 kV dc circuit.

Tokamak Discharges

Vacuum arc related effects have recently become of acute interest in connection with the operation of Tokamaks. Discharges between the Tokamak plasma and the containing metal walls introduce metallic impurities which render plasma radiation losses unacceptably high. There are a number of current papers on this subject[307-317] from which we select the work of McCracken and Goodall[307] for discussion. It is pointed out that after a few weeks of operation and discharge cleaning, more than one-half of the ohmic power loss from the Tokamak can be accounted for by radiation from metallic impurities. Measurements of the thicknesses of metal films deposited during the operation of the machine indicate that metal mass being deposited far exceeds that expected on the basis of a sputtering process. The ignition of arcs between various internal surfaces and the normal Tokamak plasma is suggested as a more probable source of metal vapor. Clear evidence for this view is visible in micrographs of cathode spot erosion tracks on metal surfaces typical of those found for vacuum arcs. From the micrographs, it is seen that the arcs move in a retrograde direction. The authors conclude that if the high concentration of metallic impurities is present in Tokamaks, generally "the impurity problem in contemporary and next generation devices has to be reconsidered." The type of discharge from the plasma to the wall is referred to as a "unipolar arc." That terminology is not new and can be found in a 1963 paper by Maskrey and Dugdale. The problem of unipolar arcs, in fact, is the same as discussed in that work, where the ignition of an arc from a plasma to a bounding metal wall was frequently found to be associated with nonmetallic inclusions in the wall surface. The problem of unwanted arcs in the Tokamak is also found in connection with MHD channels.[318-320]

BIBLIOGRAPHY

An asterisk (*) precedes papers not explicitly discussed in the text.

The topical outline follows that of the text.

INTRODUCTION

1. P.H. Cutler and T.T. Tsong, Editors, *Surface Science (Special Issue) on Field Emission and Related Topics*, North Holland, Amsterdam (1978).
2. J.E. Daalder, *Cathode Erosion of Metal Vapour Arcs in Vacuum*, Thesis, Eindhoven Un. Technol., (1978) 158 pp.

*3. J.A. Foosnaes, *The Vacuum Arc in an Axial Magnetic Field*, Thesis, Norwegian Int. Technol., (1978) 85 pp.

*4. J.M. Meek and J.D. Craggs, *Electrical Breakdown of Gases*, John Wiley (1978), 878 pp.

*5. A. van Oostrom, "Review of Surface Analysis Techniques," pp C1-1 to C1-37 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum*, Albuquerque, New Mexico, U.S.A. (1978).

*6. A.H. Guenther and J.R. Bettis, "The Laser Triggering of High-Voltage Switches," J. Phys. D: Appl. Phys. *11*, 1577-1613 (1978).

VACUUM BREAKDOWN

Field Emission

7. M. Drechsler, "Erwin Muller and the Early Development of Field Emission Microscopy," Surf. Sci. *70* 1-18 (1978).
8. S. Yamamoto, N. Saitou, and S. Fukuhara, "Field Emission Current Instability Induced by Migrating Atoms on W(310) Surface," Surf. Sci. *71*, 191-198 (1978).
9. L.W. Swanson, "Current Fluctuations from Various Crystal Faces of a Clean Tungsten Field Emitter," Surf. Sci. *70*, 165-180 (1978).

*10. Ch. Kleint, R. Meclewski, and R. Blaszczyszyn, "Coverage Dependence of FE Flicker Noises," Surf. Sci. *70*, 151-164 (1978).

*11. Ch. Kleint, R. Meclewski, and R. Blaszczyszyn, "Temperature Dependence of the Noise Spectral Density Functions of Potassium Adsorbed on Tungsten (112) Planes," Acta Phys. Pol. A *A52*, 499-510 (1977).

*12. R. Meclewski, R. Blaszczyszyn, and Ch. Kleint, "Flicker-Noise Investigations of Potassium Adlayers on (112) Tungsten Planes," Acta Phys. Pol. A *A52*, 499-510 (1977).

*13. H. Roux, A. Piquet, G. Pralong, R. Uzan, and M. Drechsler, "Adsorption, Diffusion and Self-Diffusion on Tungsten Surfaces with Adsorbed Palladium," Surf. Sci. *71*, 375-386 (1978).

*14. N. Saitou, S. Yamamoto, and H. Okano, "Power Spectral Density of Field Emission Current Fluctuation," J. Vac. Soc. Japan. *21*, 86-91 (1978).

15. P.J. Kennedy and A.V. Muir, "Modification of Field-Emission Currents from Tungsten by External Magnetic Fields," Solid State Commun. *27*, 279-281 (1978).

*16. M. Landolt and M. Campagna, "Electron Spin Polarization in Field Emission," Surf. Sci. *70*, 197-210 (1978).

*17. J. Schmit and R.H. Good, Jr. "Polarization Effects in Penetration of a Barrier with a Magnetic Field Applied," Phys. Rev. B *16*, 1197-2000 (1978).

18. A. Rabinovich, "Estimation of the Field Emission Current Density Drawn from Ultra Sharp Field Emitters," Surf. Sci. *70*, 181-185 (1978).

19. H. Heinrich, T. Haag, and J. Geiger, "A Metallic Glass Tip - a Promising Field Electron Emission Source," J. Phys. D: Appl. Phys. *11*, 2439-2442 (1978).

*20. I. Brodie, "The Visibility of Atomic Objects in the Field Electron Emission Microscope," Surf. Sci. *70*, 186-196 (1978).

*21. R. Meclewski and R. Blaszczyszyn, "Field-Emission from Individual Planes of Potassium Single Crystals," Acta Univ. Wratislav. No. 380, 139-143 (1977).

*22. A.J. Melmed, J.J. Carroll, and J. Smit, "FEM-FIM Study of Fowler-Nordheim Slope Variation with Crystal Plane Size," Acta Univ. Wratislav. No. 380, 29-35 (1977).

*23. J.F. Hainfeld, "Understanding and Using Field Emission Sources," pp 591-604 in *Proc. 10th Ann. Scanning Electron Microscopy Symp.*, Chicago, U.S.A. (1977).

*24. I.V. Strigushchenko, "Field-Electron Emission from Cerium Dioxide Whisker Crystals," Sov. Phys. Solid State *19*, 1118-1119 (1977).

*25. I.D. Ventova and G.I. Fursfi, "Remoulding of the Vertex of a Fine-Tip Microcrystal into a Polyhedron I," Sov. Phys. Tech. Phys. *22*, 506-508 (1977).

*26. I.D. Ventova, G.I. Fursei, and S.A. Polezhaev, "Formation of Microscopic Protuberances at the Vertex of a Sharp Metal Tip in a Strong Electric Field. Critical Remoulding II," Sov. Phys. Tech. Phys. *22*, 509-512 (1977).

*27. V.G. Pavlov, A.A. Rabinovich, and V.N. Prednik, "Temperature Dependence of the Minimum Electric Field Required for the Formation of Microscopic Protuberances," Sov. Phys. Tech. Phys. *22*, 239-241 (1977).

*28. I.D. Ventova and G.N. Fursei, "Thermal Smoothing after Critical Remolding III," Sov. Phys. Tech. Phys. *22*, 513-514 (1977).

*29. G.J. Edwards and P.R. Pearce, "A Comparison of AC and DC Electrochemical Etching Techniques for the Fabrication of Tungsten Whiskers," J. Phys. D: Appl. Phys. *11*, 761-764 (1978).

*30. G.H.N. Riddle, "Method of Oxygen Processing a Field Emission Cathode," RCA Tech. Not. No. TN 1192, 1-2, 28 Sept. 1977.

*31. W.A. Thompson, "Preparing High Emission Cathodes," IBM Tech. Disclosure Bull. 19, 4045 (1977).
*32. P.V. Poshekhonev, V.M. Gennad' yev, and N.P. Ovsyannikov, "Methods of Improving the Activation Efficiency of Single Crystal Whisker Field-Emission Cathodes," Radio. Eng. and Electron. Phys. *21*, 91-95 (1976).
*33. F. Okuyama, M. Aoyagi, T. Kitai, and Ishikawa, "Field Electron Emission from Dense Array of Microneedles of Tungsten," J. Vac. Sci. Technol. *15*, 98-102 (1978).
*34. P. Moretti and G. Masnard, "Electron Microscope Study of Dendritic Growths on the Anode during Prebreakdown Conditions in an Organic Residual Vapor," J. Polym. Sci. Polym. Phys. Ed. *15*, 1989-1998 (1977).
*35. J.J. Cuomo and J.M.E. Harper, "Carbon Whisker Formation," IBM Tech. Disclosure Bull. 20, 775-776 (1977).
*36. H. Bross, "The Final States in Photoemission and Field Emission," Z. Phys. B *28*, 173-182 (1977).
*37. S.G. Christov, "Recent Tests and New Applications of the Unified Theory of Electron Emission," Surf. Sci. *70*, 32-51 (1978).
*38. M. Isaacson and R. Gomer, "Extended Range Field Emission Spectroscopy," Appl. Phys. *15*, 253-256 (1978).
*39. N. Kar, "Effect of Ordered Overlayer on Field Emission from a Substrate," Surf. Sci. *70*, 101-113 (1978).
*40. A. Modinos, "Field Emission Spectroscopy of Transition Metals," Surf. Sci. *70*, 52-91 (1978).
*41. R. Gomer, "Applications of Field Emission to Chemisorption," Surf. Sci. *70*, 19-31 (1978).
*42. A.E. Heylen, A.H. Hitchcock, and A.E. Guile, "An Electron Field Emission," pp 308-311, in *Proc. 5th Int. Conf. on Gas Discharges*, Liverpool, U.K. (1978).

T-F Emission

*43. E.A. Litvinov and A.A. Starobinets, "Maximum Field-Emission Current," Sov. Phys. Tech. Phys. *22*, 1215-1216 (1977).
*44. S. Zaima, M. Sasc, H. Adachi, and Y. Shibata, "Measurements of Energy Spread of Thermal Field-Emitted Electron Flow from Tungsten," J. Phys. D: Appl. Phys. *11*, 179-180 (1978).
*45. J.K. Wysocki, "Simplified Current Density Formula at the T-F Emission in the Intermediate Region," Acta Univ. Wratislav. No. 380, 99-105 (1977).
*46. J.M. Shannon, "Thermionic-Field Emission Through Silicon Schottky Barriers at Room Temperature," Solid-State Electron *20*, 869-872 (1977).
*47. H.H. Busta and H.A. Waggener, "Thermally Assisted Field Emission Near Precipitates in PN Junctions," pp 184-186, in *Proc. Electrochem. Soc. Spring Meeting*, Philadelphia, USA (1977).

Field Ion Microscopy

*48. H.C. Eaton and R.J. Bayuzick, "Observation of Grain-Boundary Migration Using Field Ion Microscopy," Appl. Phys. Lett. *33*, 115-117 (1978).
*49. M. Doyama, T. Nishida, M. Obara, and S. Tanigawa, "Atomistic Images in Field Ion Microscopy at High Temperatures," Japan. J. Appl. Phys. *17*, 805-810 (1978).
*50. H.C. Eaton and R.J. Bayuzick, "Field-Induced Stresses in Field Emitters," Surf. Sci. *70*, 408-426 (1978).
*51. R. Smith and J.M. Walls, "Ion Trajectories in the Field-Ion Microscope," J. Phys. D: Appl. Phys. *11*, 409-419 (1978).
*52. R.G. Forbes, "Negative Work-Function Correction at a Positively-Charged Surface," J. Phys. D: Appl. Phys. *11*, L161-L164 (1978).
*53. T.T. Tsong, "Field Ion Image Formation," Surf. Sci. *70*, 211-233 (1978).
*54. J. Duffell and R.G. Forbes, "Field Ion Image Contrast: The Gas Distribution Hypothesis Re-examined," J. Phys. D: Appl. Phys. *11*, L123-L125 (1978).
*55. K. Faulian and E. Bauer, "Field Ion Microscopy of Halogens on Tungsten," Surf. Sci. *70*, 271-285 (1978).
*56. K. Sendecka and R. Meclewski, "Field Desorption of Potassium from (001), (011) and (112) Tungsten Planes," Surf. Sci. *70*, 255-264 (1978).
*57. K.D. Rendulic, "The Potential Above Field Adsorbed Gas Atoms," Surf. Sci. *70*, 234-238 (1978).
*58. R.G. Forbes, "Field Evaporation Theory: The Atomic-Jug Formalism," Surf. Sci. *70*, 239-254 (1978).
*59. S.V. Krishnaswamy and S.B. McLane, "Highly Charged Ions in Field Evaporating 4d-Transition Metals," Surf. Sci. *70*, 265-270 (1978).
*60. S. Kapur, "Field Ionization of Ozone," Surf. Sci. *70*, 403-407 (1978).
*61. B.H.C. Niu, J.R. Beacham, and P.J. Bryant, "Photon Assisted Field Ionization," J. Chem. Phys. *67*, 2039-2042 (1977).
*62. Z. Knor, "Field Emission and Field Ionization Studies and Their Impact on the Formulation of Elementary Steps in the Heterogeneous Activation of Gas Molecules by Transition Metal Surfaces," Surf. Sci. *70*, 286-291 (1978).
*63. S. Nakamura and T. Kuroda, "Atom-Probe FIM Studies of B-SiC Whiskers," Surf. Sci. *70*, 452-458 (1978).

*64. A.R. Waugh, "An Imaging Atom Probe Using a Single Time-Gated Chennel Plate," J. Phys. E: Sci. Instr. *11,* 49-52 (1978).

Work Function

65. E.A. Bakulin and M.M. Bredov, "Plasmon Energy and Work Function of Metals," Sov. Phys. Solid State *19*, 518-519 (1977).

66. V.V. Kolesnikov, E.V. Polozhentsev, V.P. Sachenko, and A.P. Kovtun, "Size Fluctuations of the Work Function in Small Metallic Clusters," Sov. Phys. Solid State *19*, 883-884 (1977).

67. L. Gaudart, P. Renucci, and R. Rivoira, "Work Functions and Structures of Alkaline-Earth Thin Films," J. Appl. Phys. *49*, 4105-4110 (1978).

*68. U. Bauder, K. Alex, and E. Fromm, "Photoelectric Measurements on Vapor Deposited Tantalum Films," Thin Solid Films *46*, 229-237 (1977).

*69. N.A. Surplice and W. Brearley, "The Effect of Carbon Monoxide on the Work Function of Evaporated Films of Titanium and Erbium," Surf. Sci. *72,* 84-94 (1978).

*70. O. Nishikawa and A.R. Saadat, "Field Ion Image Qualities of Ga, In and Sn on W and Work Functions," Surf. Sci. *70,* 292-301 (1978).

*71. Y. Fukuda, W.T. Elam, and R.L. Park, "Absolute 2p 3/2 Core Binding Energies and Work Functions of 3d Transition-Metal Surfaces," Phys. Rev. B *16,* 3322-3329 (1977).

*72. K. Senzaki and Y. Kumashiro, "Field Emission Studies of TiC Single Crystal," Bull. Electrotech. Lab. *41,* 593-599 (1977). In Japanese.

*73. R.A. Collins and C.A. Kiwanga, "Tellurium Adsorption on Single Crystal Faces of Molybdenum and Tungsten Field Emitters," Surf. Sci. *71,* 185-190 (1978).

*74. Y.I. Kostikov, N.V. Volkov, Y.K. Guskov, and Z.N. Kononova, "Field Emission of Tungsten Covered with Tellurium and Caesium Films," Sov. Phys. Tech. Phys. *22*, 375-377 (1977).

*75. E.F. Chnikovskii, Y.F. Derkach, and E.D. Kovtun, "Investigation of the Admission and Adsorption Properties of Tantalum and Molybdenum (For Admission 'read' Thermionic Emission)," Bull. Acad. Sci. USSR Phys. Ser. 40, 1-3 (1976).

*76. E. Bauer, H. Poppa, G. Todd, and P.R. Davis, "The Adsorption and Early Stages of Condensation of Ag and Au on W Single-Crystal Surfaces," J. Appl. Phys. *48*, 3733-3787 (1977).

*77. J.P. Jones and E.W. Roberts, "Field Emission Microscopy of Gold on (110), (100) and (211) Tungsten Surfaces," Thin Solid Films *48*, 215-228 (1978).

*78. S.A. Lindgren and L. Wallden, "Structure and Electronic Properties of Cs Adsorbed on Cu (111)," Solid State Commun. *25*, 13-15 (1978).

*79. A. Cieszynska, M. Blaszkiewiez, E. Gierowska-Pluta, and S. Surma, "Field Ion Microscopy of the Cu/W System. An Initial Study," Acta Phys. Pol. A *A52,* 885-891 (1977).

*80. E. Bauer, H. Poppa, P.R. Davis, and Y. Viswanath, "The Co-Adsorption of Copper and Oxygen on a Tungsten (1000) Surface," Surf. Sci. *71,* 503-518 (1978).

*81. J. Kessler and F. Thieme, "Chemisorption of Co on Differently Prepared Cu (111) Surfaces," Surf. Sci. *67,* 405-415 (1977).

*82. J.M. Derochette, "Adsorption of Nitrogen on Iridium Influence of Steps on the Surface Potential Studied by Field Emission," Phys. Stat. Sol. a *45*, 163-169 (1978).

*83. E. Bauer and T. Engel, "Adsorption of Oxygen on W (110). II The High Coverage Range," Surf. Sci. *71,* 695-718 (1978).

*84. R.A. Shigeishi, "The Adsorption of Methane on Tungsten (100) and (111)," Surf. Sci. *72,* 61-76 (1978).

*85. M. Grunze, F. Bozso, G. Ertl, and M. Weiss, "Interaction of Ammonia with Fe (111) and Fe (100) Surfaces," Appl. Surf. Sci. *1*, 241-265 (1978).

*86. M.I. Urbakh, "Effect of Adsorption on Field Emission and Photoemission," Bull. Acad. Sci. USSR, Phys. Ser. 40, 44-48 (1976).

*87. V.V. Betsa, V.N. Zhikharev, and Y.V. Popik, "Mechanism of Adsorption of Oxygen and Hydrogen on Surface of Solids," Izv. VUZ Fiz. No. 9, 84-89 (1977). In Russian.

*88. B.S. Kulvarskaya, "Concerning the Problem of Estimating the Influence of Surface and Bulk Effect on the Magnitude of the Work Function of Cathode Materials Made of Oxides," Bull. Acad. Sci. USSR, Phys. Ser. 40, 30-35 (1976).

*89. Z.P. But, I.S. Miroshnichenko, and A.F. Yatsenko, "Adsorption Peculiarities of Barium Oxide on Silicon Field Cathodes," Ukr. Fiz. Zh. *23,* 978-982 (1978). In Russian.

*90. J.L. Taylor and W.H. Weinberg, "Method of Continuously Measuring Work Function Changes," J. Vac. Sci. Technol. *15*, 1811-1814 (1978).

91. M.J.G. Lee and R. Reifenberger, "Periodic Field-Dependent Photo-current from a Tungsten Field Emitter," Surf. Sci. *70*, 114-130 (1978).

92. E. Taranko, "The Influence of the Surface Potential Barrier on Photofield Emission from Metals," Acta Phys. Pol. *A53*, 761-764 (1978).

93. T. Radon and C. Kleint, "Periodic Current Deviations in Photo Field-Emission from Tungsten and Their Wavelength Dependence," Ann. Phys. *34*, 239-252 (1977). In German.

94. Y. Teisseyre, R. Haug, and R. Coelho, "Influence of Light and Its Polarization on Field Emission of Metal Tips," pp. PD3-1 to PD3-5 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).

*95. C. Kleint, "Photo Field-Emission from Tantalum," Acta Univ. Wratislav. No. 380, 44-48 (1978).

*96. C. Kleint, "Photo Field Emission Spectroscopy of the Tantalum Bond Structure," Surf. Sci. *70*, 131-150 (1978).

*97. B.P. Bundza and B.V. Stetsenko, "Potential Distribution in a Photofield Emission Cathode and Model for Its Operation," Bull. Acad. Sci. USSR, Phys. Ser. 40, 32-36 (1976).

*98. C. Ghosh and B.P. Varma, "The High Field Enhancement of Photoemission in Multi-Alkali Photo-cathodes," Thin Solid Films *46*, 151-155 (1977).

*99. I.I. Kantorovich, "Nonlinear Surface Photoelectric Effect in Metals Subjected to Intense Light," Sov. Phys. Tech. Phys. *22,* 397-399 (1977).

Explosive Emission

100. L.W. Swanson and G.A. Schwind, "Electron Emission from a Liquid Metal," J. Appl. Phys. *49*, 5655-5662 (1978).

101. B.A. Koval, D.I. Pruskourovsky, and E.B. Yankelvitch, "On the Drop Fraction of the Cathode Erosion at the Explosive Electron Emission," pp. B5-1 to B5-6 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).

102. L.P. Babich, I.A. Berezin, T.V. Laiko, M.D. Tarasov, L.V. Tarasova, and R.S. Chikina, "Explosive Emission in Nano-second Gas Discharges," Sov. Phys. Tech. Phys. *22,* 113-115 (1977).

*103. R.B. Baksht, B.A. Kablamboyev, G.T. Razdobarin, and N.A. Ratakhin, "Measurements of Plasma Parameters in Diode with Explosive Electron Emission by Thomson Scattering Method," pp. B6-1 to B6-6 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).

*104. G.P. Bazhenov, S.P. Bougaev, S.M. Chesnokov, O.B. Ladyzhenski, and E.A. Litvinov, "Formation of Explosive Emission Current Flashes," pp. B4-1 to B4-7 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).

*105. G.P. Bazhonov, O.B. Ladyzhenskii, E.A. Litvinov, and S.M. Chesnokov, "Emission Surface of the Cathode Plasma in Explosive Electron Emission," Sov. Phys. Tech. Phys. *22,* 1212-1215 (1977).

*106. V.I. Koshelev and M.N. Timofeev, "Collective Ion Acceleration in a Vacuum Diode," Sov. Phys. Tech. Phys. *22*, 579-581 (1977).

*107. E.A. Litvinov, G.A. Mesyats, D.I. Proskurovsky, and E.B. Vankelvitch, "Processes at Cathode Operating in Regime of Electron Explosive Emission," pp. 657-658 in *Proc. XIII Int. Conf. on Phenom. in Ionized Gases,* Leipzig, East Germany (1977).

*108. E.A. Litvinov, G.A. Mesyats, and A.A. Starobinets, "Application of the Electron Explosive Emission Model to the Cathode Processes of Vacuum Discharges," pp. D3-1 to D3-5 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).

*109. G.A. Mesyats, D.I. Proskourovsky, and V.F. Puchkarev, "On Effects Resulting in Appearance of New Emission Centers at Explosive Electron Emission," pp. C4-1 to C4-8 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).

Ion-Surface Interactions

110. J.L. Whitton, L. Tanovic, and J.S. Williams, "The Production of Regular Pyramids on Argon Ion Bombarded Surfaces of Copper Crystals," Applications of Surf. Sci. *1*, 408-13 (1978).

111. A. Rizk, "The Effects of Ion Bombarding Ground Surfaces of Stainless Steel (EN58B) in a DC Glow Discharge in AR and $Ar+O_2$," Vacuum *28*, 241-244 (1978).

*112. R.E. Hurley and J.H. Holliday, "Electrode Surface Effects in the High Voltage Glow Discharge," Vacuum *28*, 453-458 (1978).

*113. U. Littmark and W.O. Hofer, "The Influence of Surface Structures on Sputtering: Angular Distribution and Yield from Facated Surfaces," J. Materials Sci. *13*, 2577-2586 (1978).

*114. K.R. Pollitt, J.C. Robb, and D.W. Thomas, "Mechanism of Sputtering of Solid Surfaces by Ion Impact," Nature *272*, 436-437 (1978).

*115. A.A. Predvoditelev and V.N. Opekunov, Surface Erosion of Materials Under Action of Ion Bombardment," Fiz. and Khim. Obrab. Mater. No. 5, 44-61 (1977). In Russian.

*116. R.S.V. Watkins and E.M. Williams, "An Appraisal of Glow Discharge Treatment of Copper Surfaces by the Techniques of Electron Stimulated Desorption," Vacuum *28*, 459-465 (1978).

*117. N. Winagrad and B.J. Garrison, "Angular Distributions of Ejected Particles from Ion-Bombarded Clean and Reacted Single-Crystal Surfaces," Phys. Rev. Lett. *41*, 1120-1123 (1978).

*118. M. Suzuki, "Photoionic Emission from Metal Surface," Solid State Commun. *25*, 1091-1092 (1978).

Vacuum Processing

*119. J.F. Hull, "Delayed Gassing in Electron Tubes," pp 451-454 in *Proc. Int. Electron Devices Meeting,* Washington, DC, USA (1977).

*120. D.I. Nosova, A.A. Nosov, and P.V. Poshekhonov, "An Annealing Temperature Cycle Which Has an Effect on the Relief and Field Emission Properties of Electrodes," Radio Eng. and Electron. Phys. *22*, 138-140 (1977).

Particle Effects

121. R. Haug and C. Texier, "Influence of Pumping Technique and Electrode Heating on Microparticles," pp. PD1-1 to PD1-6 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).

122. A. Boulloud and C. Texier, "On the Observation of Microparticles Flying Through an Electrically Stressed Vacuum Gap," J. Phys. D: Appl. Phys. *11*, L37-L38 (1978).

123. C. Texier and R. Haug, "Variations of the Overcharge Factor of Microparticles," pp PD2-1 to PD2-4 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).

*124. C. Texier, "Electrical Discharges in Vacuum: Impact of Micron Sized Spherical Iron Microparticles on Mechanically Polished Electrodes. I Mechanical Effects of Impact," Rev. Phys. Appl. *13*, 13-22 (1978). In French.

*125. C. Texier, "Electrical Discharges in Vacuum: Impact of Micron-Sized Spherical Iron Microparticles on Mechanically Polished Electrodes. II Influence of the Contact Potential on Charge Transfer Between Microparticles and Electrodes," Rev. Phys. Appl. *13,* 165-170 (1978). In French.

126. N.I. Shtepa, "Effect of Particle Shape on Motion in Vacuum Electrostatic Fields," Sov. Phys. Tech. Phys. *22*, 256-257 (1977).

127. F. Winterberg, "Acceleration of Filamentary Macroparticles to Very Large Velocities in High Voltage Diodes," Z. Naturf. *33a*, 439-441 (1978).

*128. A.S. Brah, S. Mohindra, and R.V. Latham, "Microparticle Bouncing Behavior from Oxidized and Atomically Clean Electrode Surfaces," pp. C6-1 to C6-9 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).

*129. R.V. Latham, "Initiation of Electrical Breakdown in Vacuum," Phys. Technol. *9*, 20-25 (1978).

*130. A.S. Denholm, W.A. Frutiger, and S.V. Nabol, "Large Area Single Gap Electron Accelerators and Their Voltage Performance," pp F5-1 to F5-12 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).

*131. G.L. Griffith, D.A. Eastham, and F.J. Kiulin, "The Appearance of Microparticles in Accelerator Tubes," pp F6-1 to F6-10 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).

*132. M.S. Aksenov, L.M. Baskin, W.M. Zhukov, G.N. Fursey, N.F. Fedorov, and O.P. Sharkova, "Critical Field Emission Currents Initiating Vacuum Breakdown for Metals Cooled Up to Liquid-Helium Temperatures," pp 655-656 in *Proc. XIII Int. Conf. on Phenom. in Ionized Gases,* Leipzig, East Germany (1977).

*133. B. Juttner, "Minimum Conditions for Cathode Erosion by Electrical Discharges in UHV," pp 659-660 in *Proc. XIII Int. Conf. on Phenom. in Ionized Gases,* Leipzig, East Germany (1977).

*134. W. Rohrbeck and B. Juttner, "On the Behavior of Carbon Fibre Cathodes in Vacuum Discharges," pp 661-662 in *Proc. XIII Int. Conf. on Phenom. in Ionized Gases,* Leipzig, East Germany (1977).

*135. B. Schmidt, "Influence of Electrode Curvature on Breakdown Voltage of High Vacuum Gaps," pp B2-1 to B2-13 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).

*136. A.K. Vijh, "The Influence of the Thermal Pressure of Conditioned Metal Electrodes on the Electrical Strength of the Vacuum Gap," IEEE Trans. Electr. Insul. *EI-13,* 129-130 (1978).

Impurity Effects

137. R.E. Hurley and P.J. Dooley, "Vacuum Breakdown from Electroluminescent Impurities on Metallic Cathode Surfaces," Vacuum *28,* 147-149 (1978).

138. N.K. Allen and R.V. Latham, "A Comparison of the Electron Energy Spectra Obtained from High-Emission Sites on Broad-Area High-Voltage Electrodes of Copper, Titanium and Stainless Steel," pp B3-1 to B3-13 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).

139. N.K. Allen and R.V. Latham, "The Energy Spectra of High-B Electron Emission Sites on Broad-Area Copper Electrodes," J. Phys. D: Appl. Phys. *11*, L55-L57 (1978).

140. B. Juttner, "Erosion Phenomena on Contaminated Cathodes Caused by Electrical Discharges in Ultra High Vacuum," Akad. der Wissensch. der DDR. Preprint 78-3 (1978).

*141. D.A. Eastham and R. Thorn, "Ion Exchange Currents in Vacuum Accelerator Tubes," J. Phys. D: Appl. Phys. *11*, 1149-1156 (1978).

*142. D.A. Eastham and R. Thorn, "Microdischarges in D.C. Accelerator Tubes," pp D8-1 to D8-7 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).

*143. Y.E. Kreindel, N.N. Koval, and P.M. Shchanin, "Pulse Space Discharge in Vacuum," pp F2-1 to F2-7 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).

*144. A.S. Pokrovskaya-Soboleva, A.L. Shapiro, V.I. Razgoulyaeva, and T.S. Borisova, "The Dependence of Breakdown Voltage on Adsorbed Gases," pp 667-668 in *Proc. XIII Int. Conf. on Phenom. in Ionized Gases,* Leipzig, East Germany (1977).

*145. A.L. Shapiro, A.S. Pokrovskaya-Soboleva, V.I. Razgouljaeva, L.K. Mazyrova, and L.N. Zutchenko," Phenomena Taking Place at the Electrode Surface in Vacuum Gap at High Voltages," pp 669-670 in *Proc. XIII Int. Conf. on Phenom. in Ionized Gases,* Leipzig, East Germany (1977).

Magnetic Field and the Anode

146. V.A. Petrosov and N.V. Cherkasskii, "Effect of a Transverse Magnetic Field on the Breakdown in a High-Vacuum Discharge Gap," Sov. Phys. Tech. Phys. *22*, 565-569 (1977).

*147. K.D. Bergeron, J.W. Povkey, M.S. DiCapua, and D.G. Pellinen, "Magnetic Insulation of High Voltages in Vacuum: Comparison of Experiment with Simulations," pp E2-1 to E2-16 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).

148. P.V. Poshekhonov, A.M. Ryzhkov, and V.I. Solovev, "Mechanism for Vacuum Breakdown Initiated by Electron-Beam Bombardment of the Anode," Sov. Phys. Tech. Phys. *22*, 551-555 (1977).

149. V.A. Gaponov, V.E. Nekhaev, and V.E. Teryaev, "Breakdown Strength of a Large Vacuum Gap with an Anode Grid," Sov. Phys. Tech. Phys. *22*, 410-415 (1978).

*150. H.J. Fitting, H. Glaefeke, and W. Wild, "Electron Penetration and Energy Transfer in Solid Targets," Phys. Stat. Sol. a *43*, 185-190 (1977).

X-Ray

*151. J.C. Cheng, L.G. Multhauf, and G.R. Trip, "Fiber Array Technique for Subnanosecond X-Ray Framing Camera," pp 218-222 in *Proc. 12th Int. Congr. on High Speed Photography,* Toronto (1978).

*152. H. Dietz, "Temperature Distribution in X-Ray Rotating Anodes. I. Physical Principles," Siemens Forsch.-and Entwicklungsber. *7*, 18, -23 (1978).

*153. D.A. Gogonov, N.I. Komyak, V.B. Elkind, and A.A. Schultz, "Design and Characteristics of Soft X-Ray Sealed Gas Electraluminescence Detector," Nucl. Instrum. and Methods *154,* 485-488 (1978).

*154. V.I. Grebennikov, O.B. Sokolov, and E.A. Turov, "Response of Metal Electrons to Local Fields of Holes Arising in X-Ray Processes," Phys. Stat. Sol. b *84,* 773-784 (1977).

*155. R. Nowothy, "Measurement of the KVp of X-Ray Tubes with Si PIN Photodiodes," Biomed. Tech. *23*, 118 (1978). In German.

Electrostatics

*156. A. Anis, A. Zeitoun, M. El-Ragheb, and M. El-Dosovki, "Field Calculations Around Non-Standard Electrodes Using Regression and Their Spherical Equivalence," IEEE Trans. Pwr. Power Appar. Syst. *PAS-96,* 1721-1730 (1977).

*157. K.J. Binns and P.J. Lawrenson, *Analysis and Computation of Electric and Magnetic Field Problems,* 2nd Ed., Pergamon, Oxford (1978), 352 pp.

*158. R. Cade, "The Kelvin Transformation for a Torus," J. Appl. Phys. *49,* 5722-5727 (1978).

*159. Y.L. Chow, "The Application of Optimization Techniques to the Method of Images," pp 686-689 in *Proc. IEEE Int. Symp. on Circuits and Syst.,* New York, USA (1978).

*160. J. Deuse, J.L. Lilien, and L. Vandermeeren, "Methods for the Numerical Calculation of Electric Fields: Their Possibilities and Limitations," Bull. Sci. Assoc. Ing. Electr. Inst. Electrotech. Montefiore *90*, 202-212 (1977).

*161. G. Fichera, "Asymptotic Behavior of the Electric Field Near the Singular Points of the Conductor Surface," Atti Accad. Naz. Lincei Rend. Cl. Sci. Fis. Mat. and Nat. *60*, 13-20 (1976).

*162. A.A. Halacsy, "Discussion of Calculation of the Potential Equation Around a Charge or a Current in the Presence of Three Dielectric Media Using the Image Method," IEEE Trans. Electr. Insul. *EI-13*, 392 (1978).

*163. R.A. Hurd, "On Meixner's Edge Condition for Dielectric Wedges," Can. J. Phys. *55*, 1970-71 (1977).

*164. V.F. Kravchenko, V.I. Polevoi, A.M. Andrusenko, and A.V. Kobyakova, "Analysis of Electrostatic Fields in Periodic Structures of Complex Form," Izv. VUZ Radioelektron, *20,* 3-11 (1977). In Russian.

*165. V.D. Makelskii and L.D. Osnovich, "The Maximum Electrostatic Field Intensity for Electrodes with Rounded Edges," Izv. VUZ Energ. No. 11, 26-31 (1977). In Russian.

*166. J.A. Morrison, "Charge Singularity at the Vertex of a Slender Cone of General Cross-Section," SIAM J. Appl. Math. 33, 127-132 (1977).

*167. P.K. Mukherjee and C.K. Ray, "Computation of Fields In and Around Insulators by Fictitious Point Changes," IEEE Trans. Electr. Insul. *EI-13,* 28-31 (1978).

*168. A. Nicolaide, "Computation of Potential Fields by a Method of Images," Rev. Roum. Sci. Tech. Ser. Electrotech. and Energ. *22*, 483-490 (1977).
*169. E.D. Pergamentseva, "Electrostatic Field of Cylindrical Conductor Between Parallel Conducting Planes or Within a Dihedral Angle Formed by Conducting Walls," Sov. Phys. Tech. Phys. *22*, 16-19 (1977).
*170. J.H. Pickles, "Monte Carlo Field Calculations," Proc. IEEE *124,* 1271-1276 (1977).
*171. W. Schnider and H. Baggenstos, "Computation of Electrical Field Around Stranded Conductors Using Orthogonal Functions," Arch. Elektrotech. *60,* 41-45 (1978). In German.
*172. P.P. Silvester, D.A. Lowther, C.J. Carpenter, and E.A. Wyatt, "Exterior Finite Elements for 2-Dimensional Field Problems with Open Boundaries," Proc. IEE *124*, 1267-1270 (1977).
*173. T. Sumetani and K. Hasebe, "Method for Solving Electrostatic Problems Having a Simple Dielectric Boundary," Am. J. Phys. *45*, 918-921 (1977).
*174. K.D. Srivastava, "Electric Field Computations for Rotationally Symmetric Electrodes," paper A77 737-0, *IEEE Power Eng. Soc. Summer Meeting.* Mexico City, Mexico (1977), 8 pp.
*175. V.M. Volokobinskii and V.G. Kryvkov, "Reducing the Electric Field Intensity Near to the Edge of an Electrode," Izv. VUZ Energ. No. 9, 117-120 (1978). In Russian.
*176. R. Wilkins and J.J. Little, "Solution of Electrostatic Field Problems Using Sander's Function," Proc. IEE *125,* 909-914 (1978).
*177. V.I. Demachev, I.I. Sergeev, and L.N. Afanasev, "Device for Measuring Powerful Pulsed Electric Fields," Instrum. and Exp. Tech. *19*, 1533-1535 (1976).
*178. Y.K. Yeskov and A.M. Sopozhnikov, "Mechanisms of Generation and Perception of Electric Fields by Honey Bees," Biophysics *21*, 1124-1130 (1976).
179. H.C. Miller and E.J. Furno, "Improving the Voltage Holdoff of Alumina Insulators by Mn/Ti Treatments," pp D6-1 to D6-8 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).
180. H.C. Miller and E.J. Furno, "The Effect of Mn/Ti Surface Treatment on Voltage-Holdoff Performance of Alumina Insulators in Vacuum," J. Appl. Phys. *49*, 5416-5420 (1978).
181. R.M. Stringfield, Jr., W.O. Doggett, and W.H. Bennett, "Flashover Speed and Surface Characteristics of Dielectric Cathodes in a Relativistic Electron Beam Accelerator," pp D5-1 to D5-15 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).
182. P.A. Chatterton and D.K. Davies, "Secondary Electron Emission Characteristics of Insulator Surfaces Before and After Impulse Flashover," pp D2-1 to D2-11 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).
183. M. Lavarec, G. Boquet, and A. Septier, "Lowering of the Secondary Electron Emission Coefficient of Real Surfaces Due to the Primary Electron Bombardment," pp C3-1 to C3-11 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).
184. K. Kanaya, S. Ono, and F. Ishigaki, "Secondary Electron Emission from Insulators," J. Phys. D: Appl. Phys. *11*, 2425-2437 (1978).
*185. A.A. Avdienko, "Surface Breakdown of Solid Dielectrics in Vacuum. I. Characteristics for Breakdown of Insulators Along the Vacuum Surface," Sov. Phys. Tech. Phys. *22*, 982-985 (1977).
186. A.A. Avdienko and M.D. Malev, "Surface Breakdown of Solid Dielectrics in Vacuum. II. Mechanism for Surface Breakdown," Sov. Phys. Tech. Phys. *22*, 986-991 (1977).
187. J.D. Cross, "High Speed Photography of Surface Flashover," IEEE Trans. Electr. Insul. *EI-13,* 145-148 (1978).
188. R.A. Anderson and J.P. Brainard, "Surface Flashover Model Based on Electron-Stimulated Desorption," pp D4-1 to D4-15 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).
*189. V.A. Arutskiy and V.N. Koschienko, "Vacuum Breakdown Along a Dielectric Surface with an Accumulated Charge," pp 665-666 in *Proc. XIII Int. Conf. on Phenom. in Ionized Gases,* Leipzig, East Germany (1977).
*190. S.Y. Belomytsev, S.P. Bougaev, V.I. Koshelev, G.A. Mesyats, G.S. Popova, V.M. Sveshnikov, K.N. Sukhushin, and M.N. Timofeev, "On Characteristics of the Hollow Electron Beam Formed in Diodes with Magnetic Insulation," pp E3-1 to E3-8 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).
*191. Y. Ohki, M. Sakai, and K. Yahagi, "Impulse Surface Flashover Along a Polycarbonate Plate with a Back Electrode in Vacuum," Japan. J. Appl. Phys. *17*, 1739-1743 (1978).
*192. M. Shatzkes, 'Injection into Insulators in the Presence of Space Charge," J. Appl. Phys. *49*, 4868-4872 (1978).
*193. A. Sievota, S. Zoledziowski, J. Golinski, and J.H. Calderwood, "Electro-Optical Studies of Discharges in Artificial Voids," p 185-188 in *Proc. 5th Int. Conf. on Gas Discharge,* Liverpool, U.K (1978).

*194. A. Tslaf, "Criterion of Surface Stability to Arc Discharge," IEEE Trans. Electr. Insul. *EI-12,* 354-360 (1977).

*195. J.P. VanDevender and D.H. McDaniel, "Advanced Power Flow Technologies for High Current ICF Accelerators," pp E1-1 to E1-17 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).

VACUUM ARCS

The Arc Cathode

196. G. Eckhardt, "Current Densities in Anchored Cathode Spots of a DC Mercury Vacuum Arc," pp 671-672 in *Proc. XIII Int. Conf. on Phenom. in Ionized Gases,* Leipzig, East Germany (1977).

*197. G. Eckhardt, "Power Flux to the Cathode of a dc Mercury Vacuum Arc," p 66 in *Proc. 31st Gaseous Electronics Conf.,* Buffalo, NY, USA (1978). (Abstract only.)

*198. V.I. Rakhovskii, "Measuring High Current Densities in the Cathode Spot of an Arc Discharge," Meas. Tech. *20,* 111-113 (1977).

*199. G.P. Smith, D.P. Malone, R. Dollinger, and A.S. Gilmour, "Cathode Current Densities and Current per Cell in a Copper Cathode Vacuum Arc," p 65 in *Proc. 31st Gaseous Electronics Conf.,* Buffalo, NY, USA (1978). (Abstract only.)

200. B. Juttner, E. Freund, and R. Pursch, "Experiments on Cathode Spot Motion of Electrical Arcs Between Clean Electrodes in UHV," Acad.

201. B. Juttner, "Erosion Craters and Arc Cathode Spots in Vacuum," Acad. der Wissensch. der DDR. Preprint 78-14 (1978).

202. H. Hassler, H. Kippenberg, and H. Schreiner, "The Structural Effect of Sintered Contact Materials for Vacuum Switches on the Magnitude and Distribution of the Chopping Current," p 39-43 in *Proc. 9th Int. Conf. on Electr. Contact Phenom.,* Chicago, IL, USA (1978).

203. E.W. Gray and J.R. Pharney, "Statistical Behavior of Break Arc Durations and the Minimum Arc Sustaining Current," IEEE Trans. Comp. Hybrids and Manufacturing Technol. *CHMT-2,* 12-15 (1978). See also pp 57-61 in *Proc. 9th Int. Conf. on Electr. Contact Phenom.,* Chicago IL, USA (1978).

204. A.E. Guile and A.H. Hitchcock, "The Erosion of Copper Cathodes from Vacuum to Atmospheric-Pressure Arcs," J. Appl. Phys. *49,* 4275-4276 (1978).

*205. D.T. Tuma, C.L. Chen, and D.K. Davies, "Erosion Products from the Cathode Spot Region of a Copper Vacuum Arc," J. Appl. Phys. *49,* 3821-3931 (1978).

206. A.E. Robson, "The Motion of a Low-Pressure Arc in a Strong Magnetic Field," J. Phys. D: Appl. Phys. *11,* 1917-1923 (1978).

*207. I.I. Aksenov and A.A. Andreev, "Motion of the Cathode Spot in a Vacuum Arc in an Inhomogeneous Magnetic Field," Pis'ma V. Zh. Tekh. Fiz. *3,* 1212-1215 (1977). In Russian.

*208. V.I. Alferov, O.N. Vitkovskaya, and G.I. Shcherbakov, "Retrograde Motion of the Current in a Discharge in a Transverse Magnetic Field," Sov. Phys. Tech. Phys. *22,* 57-62 (1977).

*209. M.S.I. Rageh, D.V. Morgan, and A.E. Guile, "Charge Storage and the Effect of Ultraviolet Radiation on Aluminum Oxide Films," J. Phys. D: Appl. Phys. *10,* 2269-2275 (1977).

210. A.H. Hitchcock, M.S.I. Rageh, A.E. Guile, and D.V. Mogan, "Effects of Cathode Oxide Films on Forward and Retrograde Motion of Arcs," pp 293-296 in *Proc. 5th Int. Conf. on Gas Discharges,* Liverpool, U.K. (1978).

211. L.P. Harris, "Mathematical Model for Cathode Spot Operation," pp F1-1 to F1-18 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).

212. J.E. Daalder, "A Cathode Spot Model and Its Energy Balance for Metal Vapour Arcs," J. Phys. D: Appl. Phys. *11,* 1667-1682 (1978).

*213. M.P. Zektser, "Effect of Joule Heat Liberation in a Metal Cathode on the Temperature of the Cathode Arc Spot," High Temp. *15,* 190-193 (1977).

214. A. Leycuras, "Observation of High-Temperature Electron Injection in Dense Argon and Mercury: Application to Cathode Spots," J. Phys. D: Appl. Phys. *11,* 2249-2256 (1978).

*215. I.I. Beilis, "Cathode Spots on Metallic Electrodes of a Vacuum Arc Discharge," High Temp. *15,* 818-824 (1977).

*216. H. Hantzche, "Cathode Processes in Vacuum Arcs," pp 121-138 in *Proc. XIII Int. Conf. on Phenom. in Ionized Gases,* Leipzig, East Germany (1977).

*217. G.A. Lyubimov, "Dynamics of Cathode Vapor Jets," Sov. Phys. Tech. Phys. *22,* 172-177 (1977).

*218. T. Kubona, "The Evaporation Rate from the Cathode Spot on Base Metal Electrodes in Vacuum Arcs," J. Appl. Phys. *49,* 5790-5793 (1978).

*219. T. Kubona, "A Theory for the Cathode Mechanism in Low-Current Vacuum Arcs, with Application to the Calculation of Erosion Rate," J. Appl. Phys. *49,* 3863-3869 (1978).

*220. V.M. Kulyapin, N.I. Galkin, O.E. Rybakov, and A.I. Pechenkin, "Theory of Cathodic Processes of the Arc Discharge," Izv. VUZ Elektromekh. No. 1, 52-55 (1978). In Russian.

The Arc Anode

221. J. Kutzner, "Angular Distribution of Ion Current in DC Copper Vacuum Arc," pp A1-1 to A1-15 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).

222. P.R. Schwartz, R. Dollinger, A.S. Gilmour, and D.P. Malone, "Cathode Material Study with a Hollow Anode," p 64 in *Proc. 21st Annual Gaseous Electronics Conf.,* Buffalo, NY, USA (1978). (Abstract only.)

*223. M. Rosenfeld, R. Dollinger, and C.N. Manikopoulos, "Microwave Diagnostics of a Vacuum Arc Plasma," p 63 in *Proc. 21st Annual Gaseous Electronics Conf.,* Buffalo, NY, USA (1978). (Abstract only.)

*224. W. Crampton, F.N. Yao, J.L. Lee, R. Dollinger, D.P. Malone, and D.M. Benenson, "Neutral Temperatures and Densities in a Copper Vacuum Arc with a Ring Anode," p 63 in Proc. *21st Annual Gaseous Electronics Conf.,* Buffalo, NY, USA (1978). (Abstract only.)

225. R.L. Boxman, J.H. Harris, and A. Bless, "Time Dependence of Anode Spot Formation Threshold Current in Vacuum Arcs," IEEE Trans. Plasma Sci. *PS-6,* 233-237 (1978).

226. H.C.W. Gundlach, "Interaction Between a Vacuum Arc and an Axial Magnetic Field," pp A2-1 to A2-11 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).

227. M.S. Agarwal and R. Holmes, "Current Distribution in High Current Vacuum Arcs with Superimposed Axial Magnetic Fields," pp 277-280 in *Proc. 5th Int. Conf. on Gas Discharges,* Liverpool, UK (1978).

228. J.C. Sherman, R. Webster, J.E. Jenkins, and R. Holmes, "The Voltage, Self-Generated Magnetic Field and Current Distribution in a High-Current Vacuum Arc," J. Phys. D: Appl. Phys. *11,* pp 379-388 (1978).

*229. C.W. Kimblin, "Anode Spot Ion Currents and the Interaction with Axial Magnetic Fields," pp 675-676 in *Proc. XIII Int. Conf. on Phenom. in Ionized Gases,* Leipzig, East Germany (1977).

230. J.V.R. Heberlein and J.G. Gorman, "Instabilities of Columnar Metal Vapor Arcs at Current Levels up to 67 kA," p 178 in *Proc. IEEE Int. Conf. on Plasma Sci.,* Troy, NY, USA (1977). (Abstract only.)

*231. J.V.R. Heberlein and J.G. Gorman, "The Columnar Metal Vapor Arc Under the Influence of an Axial Magnetic Field," pp 281-284 in *Proc. 5th Int. Conf. on Gas Discharges,* Liverpool, UK (1978).

*232. J.A. Rich and C.P. Goody, "Diffuse Vacuum Arcs," p 179 in Proc. IEEE Int. Conf. on Plasma Sci., Troy NY, USA (1977). (Abstract only.)

233. H. Okumura, T. Tsutsumi, S. Yanabu, S. Sohma, and M. Ohkawa, "Development of High Power Vacuum Circuit Breakers Having Axial Magnetic Field Type Electrodes," pp 78-81 in *Proc. Int. Conf. on Developments in Distrib. Switchgear,* London, UK (1978).

234. A.A. Pertsev, L.G. Guseva, and A.E. Kulikov, "High-Current Vacuum Arc in a Magnetic Field," Sov. Phys. Tech. Phys. *22,* 1227-1229 (1977).

235. R. Dethlefsen and J. Mylius, "DC Switching and Impedance Modulation of the Vacuum Arc Through Magnetic Control," pp E5-1 to E5-15 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).

*236. M.G. Drouet, R. Haug, and M. Goldman, "Voltage Fluctuations in Low Current Atmosperhic D.C. Arcs," p 64 in *Proc. 21st Annual Gaseous Electronics Conf.,* Buffalo, NY, USA (1978).

*237. A.A. Samokhin, "On the Behavior of the Surface Temperature and Reflection Coefficient of a Metal Under the Action of Intense Optical Radiation," Sov. Phys. Lebedv Inst. Rep. No. 12, 10-14 (1976).

*238. V.D. Dhait, "A Model for Formation of Anodal Spots on Hot Electrodes in a Weakly Ionized Molecular Gas Plasma Stream," High Temp. *15,* 418-425 (1977).

Vacuum Interrupter

239. M.E. Arthur and M.J. Zuhick, "Useful Life of Vacuum Interrupters," IEEE Trans. Power Appar. Syst. *PAS-97,* 1-7 (1978).

240. R. Dethlefsen, "Discussion of Useful Life of Vacuum Interrupters," Ibid. p 6.

241. B. Juttner, H. Dursch, and P. Siemroth, "Gas Release Caused by Arcs in Vacuum Interrupters," Wiss.-techn. Mitt. IPH, Berlin, 5-8 (1978). In German.

*242. P. Pech and B Juttner, "On the Ignition of Glow Discharge in Vacuum Interrupters," Wiss.-techn. Mitt. IPH, Berlin 21-24 (1978). In German.

*243. B. Juttner, L. Roth, and E. Freund, "Pressure Measurement in Sealed Vacuum Interrupters by Magnetron Discharge," Wiss.-techn. Mitt. IPH, Berlin, 25-27 (1978). In German.

*244. J. Kusserow and H.J. Haupt, "Technology and Long-Term Pressure Behavior of Vacuum Interrupters," Wiss.-techn. Mitt. IPH, Berlin, 28-32 (1978). In German.

*245. P. Pech and B. Juttner, "Gas Release in Resting Vacuum Interrupters," Wiss.-techn. Mitt. IPH, Berlin, 33-36 (1978). In German.

*246. T. Mori, K. Fukui, K. Matsumoto, N. Kawana, M. Kashimura, K. Furuya, and T. Kikuchi, "Separation of Surface and Bulk Gases in Contact Materials of Vacuum Switches — Determination of Gases and Effect on Vacuum Breakdown," pp 45-50 in *Proc. Int. Conf. on Electr. Cont. Phenom.,* Chicago, IL, USA (1978).

*247. K. Matsumoto, T. Mori, K. Fukui, N. Kawana, M. Kashimura, K. Furuya, and T. Kikuchi, "Separation of Surface and Bulk Gases in Contact Materials of Vacuum Switches — Determination of Gases and Effect on Vacuum Breakdown," IEEE Trans. Comp. Hybrids and Manufacturing Technol. *CHMT-2,* 4-8 (1978).

248. K. Frolich, "On the Steady State Breakdown Voltage of a Vacuum Interrupter," pp E6-1 to E6-14 in *Proc. VIII Int. Symp. on Disch. and Electr. Insul. in Vacuum,* Albuquerque, New Mexico, USA (1978).

249. B. Juttner, "Field Emission Centers Formed by Arcs on the Cathodes of Vacuum Interrupters," Wis.-techn. Mitt. IPH, Berlin, 15-20 (1978). In German.

*250. B. Juttner, P. Pech, K.-H. Ibsch, and E. Freund, "Conditioning of Vacuum Switch Contacts by DC Arcs," Wiss.-techn. Mitt. IPH, Berlin, 9-14 (1978). In German.

*251. G.J. Rushton, C. Christopoulos, and P.A. Chatterton, "The Use of an Anode Probe Hole Technique to Study Conditioning Processes Between Arced Copper Electrodes in Vacuum," IEEE Trans. Electr. Insul. *EI-13,* 355-365 (1978).

252. G.A. Farrall, "Recovery of Dielectric Strength After Current Interruption in Vacuum," IEEE Trans. Plasma Sci. *PS-6,* 360-369 (1978).

253. J.G. Gorman, "The Dielectric Recovery Strength of Vacuum Gaps Following High Current AC Arcing," p 176 in *Proc. IEEE Int. Conf. on Plasma Sci.,* Troy, NY, USA (1977). (Abstract only.)

254. L.P. Harris, "A Simple Classical Analysis for Particle-Surface Energy Accommodation," p 66 in *Proc. 21st Snnual Gaseous Electronics Conf.,* Buffalo (1978). (Abstract only.)

*255. R.S. Akhmetzyanov, F.M. Gaisin, G.Y. Dautov, E.I. Krivohosova, and K.M. Shavaliev, "Investigation of Electrical Breakdown of Arc Plasma Flow-Cold Electrode Gap," Fiz. and Khim. Obrab. Mater. No. 6, 30-34 (1977). In Russian.

*256. F.G. Baksht, G.A. Dyvzhev, V.B. Kaplan, A.A. Kostin, A.M. Martsinovoskii, and V.G. Yurev, "Quenching of Low Voltage Arc at Low Caesium Pressure," Sov. Phys. Tech. Phys. *22,* 152-159 (1977).

*257. V.A. Vozdvizhenskii and M.E. Danivlov, "Insulation characteristics of Vacuum Arc Quenching Chambers," Elektrichestvo No. 6, 67-70 (1977). In Russian.

*258. S.A. Kratko and I.G. Nekrashevich, "Transition from a Normal Glow Discharge to an Arc," Sov. Phys. Tech. Phys. *22,* 478-480 (1977).

*259. G.L. Payne, J.D. Perez, T.E. Sharp, and B.A. Watson, "Recombination Effects in an Expanding Laser-Produced Plasma," J. Appl. Phys. *49,* 4688-4693 (1978).

*260. S.G. Artyshev, N.N. Degtyarenko, A.N. Polyanichev, and V.S. Fetisov, "Expansion of a Two-Component Plasmoid in a Vacuum," Sov. Phys. J. *21,* 186-190 (1978).

261. J.M. Anderson and J.J. Carroll, "Applicability of a Vacuum Interrupter as the Basic Switch Element in HVDC Breakers," IEEE Trans. Power Appar. Syst. *PAS-97,* 1893-1900 (1978).

262. R. Shimada, K. Tani, H. Kishimoto, S. Tamura, S. Yanabu, S. Yamashita, H. Ikeda, and T. Sasaki, "Development of High Current DC Circuit Breaker for Large Tokamak Fusion Device," paper A78 594-4, *IEEE Power Eng. Soc. Summer Meeting,* Los Angeles (1978) 9 pp.

*263. R.W. Warren, "Vacuum Interrupters Used for the Interruption of High DC Currents," pp 1774-1778 in *Proc. 7th Symposium on Engineering Problems of Fusion Res.,* Knoxville, TN, USA (1977).

*264. L. Demetor, J. Benford, and V. Bailey, "Fast Switching of Magnetically Stored Energy into External Loads," p 231 in *Proc. IEEE Int. Conf. on Plasma Sci.,* Troy, NY, USA (1977).

*265. J.G. Gorman, J.V.R. Heberlein, C.W. Kimblin, and P.G. Slade, "Vacuum Arc Experiments Associated with Fusion Switch Development," p 235 in *Proc. IEEE Int. Conf. on Plasma Sci.,* Troy, NY, USA (1977).

*266. M. Vajta, "High-Voltage DC Circuit Breakers," Electrotechnika *70,* 359-373 (1977). In Hungarian.

*267. P. Wildi and E.L. Woods, "High Current Switches in the Doublet III Poloidal Field Circuit," pp 1753-1756 in *Proc. 7th Symp. on Engineering Problems of Fusion Res.,* Knoxville, TN, USA (1977).

*268. W.O. Eckhardt, G.A. Hofmann, E.T. Bernhardt, R.-C. Kunze, and D. Dorst, "LMPV Circuit Breakers: Operation of a 15 kA Unit with Wendelstein VII A, and Laboratory Tests of the Next Breaker Generation," pp 1767-1771 in *Proc. 7th Symp. on Engineering Problems of Fusion Res.,* Knoxville, TN, USA (1977).

*269. W.O. Eckhardt, "Liquid-Metal Plasma Valves for High-Power Conversion and Switching," p 177 in *Proc. IEEE Int. Conf. on Plasma Sci.,* Troy, NY, USA (1977).

*270. T.G. Galkina, O.A. Gusev, A.G. Nechaev, and E.P. Pavolv, "Fast Acting Vacuum Commutator with Connection by Liquid-Metal Contacts," Instrum. and Exp. Tech. *20,* 506-508 (1977).

*271. M.A. Lutz, "Gridded Cross Field Tube," IEEE Trans. Plasma Sci. *PS-5,* 273-277 (1977).

*272. H.M. Pollock, "The Force of Adhesion Between Solid Surfaces in Contact," Appl. Phys. Lett. *33*, 798-799 (1978).

*273. H.M. Pollock, "Contact Adhesion Between Solids in Vacuum: II Deformation and Interfacial Energy," J. Phys. D: Appl. Phys. *11*, 39-54 (1978).

*274. Y. Yoshioka and K. Mano, "Theoretical Calculation of the Transient Temperature Rise and the Welding Limit Current of Point Contact Due to Momentary Current Flow," IEEE Trans. Comp. Hybrids and Manufacturing Technol. *CHMT-1* 90-94 (1978).

*275. E.I. Kim, D.V. Kim, V.T. Omelchenko, S.N. Kharin, S.S. Domalevskii, Y.M. Dolinskii, F.G. Biryvkova, A.E. Pudy, and S.P. Gorodnichev, "Mathematical Modeling of Thermal Processes in Electrical Contacts," Izv. VUZ Electromekh. No. 1, 5-28 (1978). In Russian.

*276. R.E. Cuthrell and L.K. Jones, "Surface Contaminant Characterization Using Potential-Current Curves," IEEE Trans. Comp. Hybrids and Manufacturing Technol. *CHMT-1,* 167-171 (1978).

*277. H. Kongsjorden, J. Kulsetas, and J. Sletbak, "Direct Detection of A-Spots in Current Carrying Contact by Means of IR-Microscopy," pp 477-482 in *Proc. 9th Int. Conf. on Electr. Contact Phenom.,* Chicago, IL, USA (1978).

*278. T. Tamai and K. Tsuchiya, "Direct Observation for the Effect of Electric Current on Contact Interface," pp 469-475 in *Proc. 9th Int. Conf. on Electr. Contact Phenom.,* Chicago, IL, USA (1978).

*279. F. Llewellyn-Jones, "Phenomena of Opening Contact Electrodes in Vacuum — The Micro-Arc," pp 249-254 in *Proc. 9th Int. Conf. on Electr. Contact Phenom.,* Chicago, IL, USA (1978).

*280. H. Bettge, F. Battiwala, H. Kopplin, K. Muller, and G. Sinnecker, "New Vacuum-Type Circuit-Breaker for Medium Voltage Distribution Systems," pp 24-27 in *Proc. Int. Conf. on Developments in Distrib. Switchgear,* London, UK (1978).

*281. R.W. Blower, K.J. Cornick, and M.P. Reece, "The Use of Vacuum Switchgear for the Control of Motors and Transformers in Industrial Systems," pp 5-10 in *Proc. Int. Conf. on Developments in Distrib. Switchgear,* London, UK (1978).

*282. P. Claus, "Vacuum Tube Provides a Long Life Circuit Breaker," Eltek. Aktvell Elektron. A *20*, 38-39 (1977). In Swedish.

*283. R. Feibig and H. Gunther, "Vacuum Circuit Breaker 12 kV/1250A/16kA for Testing of Supplies," Elektrie *31*, 628-632 (1977). In German.

*284. R. Fiebig and H. Gunther, "Medium-Voltage Vacuum Switches," Elektrie *32*, 360-361 (1978). In German.

*285. R. Fiebig and H. Gunther, "The Short-Circuit Current-Carrying Capacity of Vacuum Switches," Elektrie *31*, 493-494 (1977). In German.

*286. W. Frewe, W. Jakszt, and M. Schaumberg, "Vacuum Contactors — A New Approach to High Voltage Switching," Siemens Rev. *45*, 78-82 (1978).

*287. K. Funashashi, "Compact Substations," Meiden Rev. No. 3, 5-12 (1977).

*288. A. Gotsch, H.-J. Haupt, and E. Freund, "Influence of the Contact System on the Switching Behavior of Vacuum-Arc Quenching Chambers for Medium-Voltage Power Circuit-Breakers," Elektrie *31*, 492-498 (1977). In German.

*289. H. Hamada, "Present Status and Future Prospects of the Vacuum Circuit Breaker," Meiden Rev. No. 3, 1-4 (1977).

*290. R.M. Hruda, "Vacuum Switch for Electrolytic Cell Switching," pp 157-163 in *Proc. IEEE 24th Annual Petroleum and Chemical Industry Conference,* Dallas, TX, USA (1977).

*291. H. Himi, T. Takashima, Y. Shinmon, E. Umeya, and H. Yanagisawa, "145 kV Vacuum Circuit Breaker," pp 87-90 in *Proc Int. Conf. on Developments in Distrib. Switchgear,* London, UK (1978).

*292. M. Janker and R. Prohl, "Vacuum Interrupters for Medium Voltage Switchgear," Elektro-Anz. *31*, 38-39 (1978). In German.

*293. M. Janker, "Vacuum Interrupters in Primary Distribution Switchboards," Siemens Rev. *44*, 551-553 (1977).

*294. J.A. Kischefsky, "New Vacuum Loadbreak Switch for Automated and Supervisory System Operations," pp 99-102 in *Proc. Control of Power Syst. Conf. and Exposition,* Oklahoma City, OK, USA (1978).

*295. D.R. Kurtz, J. Panek, and C.H. Titus, "Transient Switching Voltage Test on Metalclad Switchgear," pp 53-56 in *Proc. Int. Conf. on Developments in Distrib. Switchgear,* London, UK (1978).

*296. B. McKean, V.J. Thompson, and R.H. Collins, "Further Developments in Vacuum Switchgear," pp 110-114 in *Proc. Int. Conf. on Developments in Distrib. Switchgear,* London, UK (1978).

*297. G.O. Mietz, W. Ros, and C.H. Titus, "3.3 kV-38 kV Metalclad Vacuum Switchgear," pp 28-31 in *Proc. Int. Conf. on Developments in Distrib. Switchgear,* London, UK (1978).

*298. Y. Murai, H. Toya, and T. Nitta, "Statistical Property of the Breakdown of Vacuum Circuit Breakers and Its Influence on Surge Generation in Capacitive and Reactive Current Interruption," paper F78 139-8, *IEEE Power. Eng. Soc. Winter Meeting,* New York, USA (1978), 7 pp.

*299. K. Nakomura and M. Watanabe, "Enclosed Switchgear HICLAD," Meiden Rev. No. 3, 13-19 (1977).

*300. S. Ochiai and T. Yokoyama, "Performance for Extinguishing Arc in Vacuum," Meiden Rev. No. 2, 29-33 (1977).

*301. J. Panek, "Synthetic Methods for Testing of Vacuum Breakers," IEEE Trans. Power Appar. Syst. *PAS-97,* 1328-1336 (1978).

*302. Z. Pasek, V. Stuchlik, and Robenek, "Vacuum Contactors, Their Applications and First Operational Experiences," Elektrotechnik *33,* 190-196 (1978). In Czech.

*303. R. Rutherford, T.V. Armstrong, and A. Hadley, "The Design of Vacuum Switchgear for 712/12 kV Distribution Systems," pp 20-23 in *Proc. Int. Conf. on Developments in Distrib. Switchgear,* London, UK (1978).

*304. E. Umeya, "Vacuum Interrupters," Meiden Rev. No. 2, 24-28 (1977).

*305. H.J. Yelland, "The Possibility of Using Vacuum Contactors for Mine Winder Stator Reversers and Surge Suppression of Electric Motors," Certif. Eng. 51, 198 (1978).

*306. R.J. Horvey, M.A. Lutz, and H.E. Gallagher, "Current Interruption at Powers Up to 1 GW with Crossed-Field Tubes," IEEE Trans. Plasma Sci. *PS-6,* 248-255 (1978).

*307. G.M. McCracken and D.H.J. Goodall, "The Role of Arcing in Producing Metal Impurities in Tokamaks," Nuclear Fusion *18,* 537-542 (1978).

*308. Y. Gomay, T. Tazima, and N. Fujisawa, "Discharge Cleaning Experiment in the JFT-2 Tokamak with Surface Observation by AES," J. Vac. Sci. Technol. *15*, 103-110 (1978).

*309. D.H.J. Goodall, T.W. Conlon, C. Sofield, and G.M. McCracken, "Investigations of Arcing in the DITE Tokomak," J. Nucl. Mat. *76 and 77,* 492-498 (1978).

*310. P.J. Harbour and M.F.A. Harrison, "The Influence of Electron Emission at the Diverter Target of a Tokamak Fusion Reactor," J. Nucl. Mat. *76 and 77*, 504-507 (1978).

*311. J.T. Hogon and A.T. Mense, "Numerical Modeling of Impurity Effects," J. Nucl. Mat. *76 and 77*, 504-507 (1978).

*312. A.V. Nedsopasov and V.G. Petrov, "Model of the Unipolar Arc on a Tokamak Wall," J. Nucl. Mat. *76 and 77*, 490-491 (1978).

*313. K. Ohasa, H. Maeda, S. Yamamoto, M. Nagami, H. Ohtsuka, S. Kasai, K. Odojima, H. Kimura, S. Sengaku, and Y. Shimomura, "Ion Sputtering, Evaporation and Arcing in DIVA," J. Nucl. Mat. *76 and 77*, 489 (1978).

*314. P. Staib and G. Staudenmaier, "Surface Effects and Impurity Production in Tokamak Machines," J. Nucl. Mat. *76 and 77*, 78-91 (1978).

*315. J.K. Tien, N.F. Panayotou, R.D. Stevenson, and R.A. Gross, "Unipolar Arc Damage of Materials in a Hot, Dense Deuterium Plasma," J. Nucl. Mat. *76 and 77*, 481-488 (1978).

*316. C. Wieckert, "Plasma Induced Arcs," J. Nucl. Mat. *76 and 77*, 499-503 (1978).

*317. I.I. Beilis, "Near-Cathode Region of Contracted Discharge at MHD-Generator," High Temp. *15*, 1088-1093 (1978).

*318. V.I. Kovbosyvk and N.N. Boronov, "Appearance of Interelectrode Arcs and Electric Fluctuations in an MHD Channel," High Temp. *15*, 1110-1118 (1978).

*319. L.P. Poberezhskii, "Mathematical Model of Interelectrode Breakdown in MHD Channels," High Temp. *16*, 367-369 (1978).

*320. L.P. Poberezhskii, "Mathematical Model of Interelectrode Breakdown in MHD Channels," High Temp. *16*, 367-369 (1978).