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**PROJECTION-TUBE STUDIES
OF VOLTAGE-BREAKDOWN ARC DISCHARGES
FROM TUNGSTEN AND NIOBIUM WIRES IN VACUUM**

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Abstract

The formation of "voltage breakdown" electric discharge arcs in vacuum between a wire cathode and a surrounding cylindrical anode has been studied with emphasis on behavior at the wire surface. Tungsten and niobium wires 2 to 10 mils in diameter were studied, using voltages up to 150 kV.

Conditioning of the wire by heating was found to have a strong effect on the behavior leading to breakdown. With unconditioned wire, very high pre-breakdown currents were observed, and final breakdown occurred at low voltage. With partially conditioned wire (baked 1 hr at 800°C), low pre-breakdown currents characteristic of field emission were observed. With further conditioning of the wire (baking overnight), no significant pre-breakdown emission occurred before final breakdown. Based on these observations, a breakdown correlation is proposed for design purposes that

involves three distinct regimes — initial, field emission, and ultimate — depending on prior conditioning of the surface.

With a projection tube used as the cylindrical anode, phosphorescent patterns on the tube caused by the discharges were recorded with a high-speed camera, and the corresponding areas of the wire were studied with an electron microscope. Areas of the wire surface where pre-breakdown discharges occurred were found to be marked by micron-sized condensed droplets of aluminum and silicate, evidently transported there from the anode surface in plasma form during the discharge. Often these droplets were condensed on the ends of whiskers of wire material pulled up from the wire surface in a pre-breakdown discharge. The final discharge appears to be a number of simultaneous arcs, each originating in an area of dense whisker formation on the wire surface.

Introduction

The objective of this research was to study the formation and discharge of arcs during voltage breakdown in vacuum. The experimental geometry involved a small tungsten or niobium wire 2 to 10 mils in diameter, serving as the cathode, surrounded by a large cylindrical anode 2 to

4 in. in diameter. This geometry made it possible to achieve surface fields of the order of 1 MV/cm on the wire cathode with modest power supply voltages (<100 kV). The apparatus is shown in Fig. 1 with the vacuum-chamber bell jar raised.

These studies were motivated by two applications important to fusion reactor development: Breakdown from grid surfaces represents a limiting feature in direct conversion devices intended to collect and electrostatically convert fusion-ion energy to high-voltage dc electrical output. Also, a similar critical problem occurs at the high-voltage extraction grids in high-energy ion sources which are under development for injection into fusion plasmas.

Fig. 1. The voltage breakdown apparatus used in this study.

Voltage-Current Characteristics

While breakdown from wires has been studied for many years (e.g., Ahearn and Chambers in the 1930's), no general breakdown criterion has been published.¹ To investigate some of the basic characteristics of breakdown, our initial runs were carried out with stainless steel anodes. Provision was made for conditioning the wire being studied. It was possible to resistively heat the wire while voltage was applied, and baking of the wire in situ (i.e., at hard vacuum) was extensively used for conditioning.

1. An extensive review of earlier work, breakdown theory, and design correlations was presented in an earlier report by the author (UCRL-51482, Dec. 1973).

Some typical current-voltage plots are shown in Fig. 2 for a 7-mil tungsten wire. Three regimes of operation are illustrated in Fig. 2, all related to prior conditioning of the wire. In the initial regime, i.e., before conditioning of the wire, very high pre-breakdown currents were observed, and breakdown occurred at low voltage. After the wire was partially conditioned by baking it at ~800°C for an hour, low pre-breakdown currents were observed which are characteristic of field emission; hence this is termed the field emission regime. An ultimate regime could be obtained by baking the wire overnight where no field emission was observed prior to breakdown.

Fig. 2. Typical plot of emission current vs voltage for a 7-mil-diam tungsten wire after various conditioning processes.

In addition, it will be noted from Fig. 2 (runs 12, 6, and 8) that the final voltage breakdown point remained fixed independent of wire temperature during

the run, even when thermionic pre-breakdown emission currents from the hot wire were much larger than the pre-breakdown currents from the cold wire.

Fig. 3. Voltage breakdown correlation as a function of wire diameter.

These data are consistent with the following physical interpretation. Dirty surfaces prior to conditioning cause large pre-breakdown currents and er-

atic breakdown behavior. Arcs can be initiated by clumps of material or gases leaving the surface. After partial conditioning, only low pre-breakdown cur-

rents are observed until the voltage becomes large enough to raise surface protrusions or whiskers. Due to the large length/diameter ratio of such a whisker, the electric field at the tip of the whisker is enhanced by a factor of 10^3 or more, causing characteristic field emission. Breakdown becomes more predictable because these emission currents initiate arcs by, for example, melting whiskers. Some scatter still occurs, however, due to the random nature of the number, size, and shape of

the whiskers. In the ultimate regime, the surface is free of whiskers, at least up to the moment of arc initiation.

These concepts are illustrated again in the plot of breakdown voltage vs wire diameter in Fig. 3. While all three regimes tend toward a correlation of the form $V_b \propto d^{1/2}$, the actual breakdown mechanisms are different in each. This is not surprising since well-known theories such as the Cranberg clump-model, various whisker-emission theories, etc. all suggest similar correlations.

Projection Tube Studies

To study the arc formation more closely, a projection tube² was substituted for the outer cylinder (anode). As shown in Fig. 4, this is simply a glass tube coated on the inside with a phosphor. Electron currents produce a bright glow on the phosphor which is visible through the glass. A thin aluminum coating on the inside (wire side) of the phosphor provides electrical contact.

Projection tubes have been used by several workers prior to this study, but their tubes were not rugged enough to study high currents or actual arc breakdown. The present design was worked

2. I. Brodie and L. Weissman, Vacuum 14, 299 (1964).

Fig. 4. Glass anode with internal phosphor coating (the "projection tube").

out to allow these investigations, and good success was obtained although damage to the tubes did eventually occur after extensive arcing.

Both still and high-speed sequential photography were used to record the dynamics of spot growth and breakdown. A typical variation of the spots with increasing voltage is shown in Fig. 5. While the current-voltage characteristics remained fairly smooth as shown earlier, the size and location of the current-carrying spots underwent constant variations. The birth or death of spots, even at constant voltage, was frequently observed, and this was accentuated with changing voltage.

It was found, as illustrated in Fig. 6, that the emission current was closely correlated with the spot density for a wide range of conditions and wires. The spot density appears, however, to increase somewhat faster than predicted by

a linear relation with current. This is probably to be expected in light of the statistical variation in the shape and current-carrying capacity of individual whiskers.

These observations are in general agreement with the earlier picture of a dynamic "eruption" of whiskers from the surface under the influence of the applied field. The spot size and shape observed on the screen can be used to make an estimate of the whisker size. The high-speed sequential photographs allow a gross observation of the final breakdown, but the resolution is poor because of the relatively slow time response of the phosphor. Perhaps the most striking observation is that a number of arcs appear to erupt simultaneously along the wire rather than at a single spot. Thus it is thought that debris and shock effects proliferate the arcing along the surface.

Surface Studies

The projection tube made it possible to locate the precise emission sites causing the pre-breakdown currents. The section of the wire leading to bright spots was sectioned and studied under a scanning electron microscope. In some instances a surface configuration such as shown in Fig. 7 was found. The spherical object in this photo is roughly $6\text{ }\mu\text{m}$ in diameter, and it is on a whisker about $2\text{ by }10\text{ }\mu\text{m}$ that projects from the wire. Microprobe analysis shows that the spherical ball is mainly composed of aluminum and silicate from the phosphor and electrical coating on the projection

tube. The whisker supporting the ball is mainly material from the wire, with a thin outer coating of materials from the projection tube. This suggests that the pre-breakdown currents involved a low density plasma composed of electrode material. Such vapor formation has been observed in other studies.³ Due to its low melting point, aluminum dominated the plasma, and it was gradually condensed out on the whisker tip.

Studies were made of damaged areas on the surface after arc breakdown

3. D. Davies and M. A. Biordi, J. Appl. Phys. **41**, 88 (1970).

Fig. 5. Photographs of sequence of spots observed on the projection tube with increasing voltage.

Fig. 6. Density of spots observed on the projection tube vs pre-breakdown current.

occurred, and the results suggested that the final arc originated in an area of dense whisker formation. For example, Fig. 8 shows some ball/whisker formations around the edge of an arc-created

Fig. 7. Electron microscope photograph of a whisker on the surface of a niobium wire. Microprobe analysis indicates that the ball on the whisker is mainly aluminum (~5300X).

crater that were partly melted by the breakdown but remain clearly visible.

One consequence of these observations is that the deposition of materials on whisker surfaces as well as the damage to their crystalline structure during erection are now thought to affect the work function of this localized area. Thus large emission currents can be obtained with relatively small field enhancement, i.e., length, diameter ratios. Such a mechanism would be consistent with earlier observations by Brodie,⁴ who found that minute quantities of material evaporated from adjacent thermionic cathodes "activated" the tips of existing whiskers on nickel electrodes, causing enhanced field emission.

4. I. Brodie, J. Vac. Sci. Technol. **2**, 249 (1965).

Fig. 8. Electron microscope photograph of a damaged area with whisker/ball formations near the edge of the crater (~4400X).

Conclusions

This work has demonstrated that the projection tube technique provides a valuable method for studies of pre-breakdown and breakdown arcing in vacuum. In addition to providing information about arc dynamics, the spots observed made it possible to accurately locate wire sections for subsequent studies with a scanning electron microscope.

The observations add important evidence for a dynamic model of whisker formation by field erections, followed by pre-breakdown emission involving transport, via low-density plasma, of anode

material to the whisker. This emission eventually grows into a full arc while simultaneously propagating to other sites along the surface. For design purposes, a voltage breakdown correlation is proposed that involves three distinct regimes of breakdown — initial, field emission, and ultimate — depending on prior conditioning of the surface.

Work is now in progress to employ the projection tube technique to study voltage breakdown from wire surfaces blistered by helium bombardment. Results from these studies will be reported in the near future.

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