Breakdown Characteristics and Conditioning of Carbon and Refractory Metal Electrodes*

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Abstract

High voltage carbon and refractory metal electrodes employed in devices used in space, such as ion thrusters and traveling wave tubes, can be easily damaged by electrical breakdown and arcing events. Modification of the electrode surfaces due to these events can impact the voltage hold off capability of the surfaces, which could lead to additional arcing, further damage, and the potential for device failure. On the cathode-potential surface, the arc energy is deposited by all of the processes at the surface ultimately responsible for net electron emission, such as melting, vapor and particulate formation, sputtering, ion bombardment, etc. On the anode-potential surface, the energy is deposited from the plasma or electron stream that crosses the gap, which causes surface damage by local heating. In spite of this energy dependence on the damage, many systems that use arc discharges characterize the amount of material removed from the surfaces and the lifetime of the device for voltage hold-off by the amount of current that passes through the arc, or the "Coulomb-rating". The results of a series of tests that were performed on the voltage hold off capability and damage to carbon-carbon composite surfaces and molybdenum surfaces due to induced arcing will be presented and discussed. Damage to the surfaces was characterized by the field emission performance after the arc initiation and SEM photographs for the different energy and coulomb-transfer arc conditions. Both conditioning and damage to the surfaces were observed, and will be related to the characteristics of the electrical breakdown.

I. INTRODUCTION

Electrode voltage hold off is of critical importance in many applications such as ion sources, ion thrusters, microwave sources and pulsed power devices. A considerable amount of work over the last century has been focused at understanding and characterizing voltage hold off of various materials and electrode geometries. Degradation of the voltage hold off capability due to damage of the surface incurred during breakdowns is also of importance as it affects the long term life and reliability of the devices.

A series of experiments have been undertaken to explore the voltage hold off capability and surface damage during arcing of advanced carbon materials now under development for ion sources and traveling wave tubes. Carbon-carbon composite materials and pyrolytic graphite have been subjected to various arc discharges up to 1 kA peak, and the voltage hold off capability of the surfaces at 1 to 5 kV before and after arcing was characterized by the threshold for field emission to occur. These results are compared to graphite and molybdenum surfaces, which are normally used for most high voltage accelerator grid and electrode applications. We find that both conditioning and damage to the surfaces can occur dependent on the arcing parameters, and limiting the total amount of current that flows during the arc breakdown minimizes the surface damage to all these materials and increases the voltage hold off and reliability. A suggested maximum electric field rating for these different materials is developed.

II. EXPERIMENTAL CONFIGURATION

High voltage breakdown has been studied for over a hundred years. Breakdown voltages reported in the literature depend on the electrode material, the surface properties, the electrode geometry and the electrical characteristics of the tests. It is often difficult to apply literature results to modern applications where the surface conditions and electrode configuration may be different, or entirely new materials may be used. A survey of voltage breakdown results was published by Kolh [1] in 1967. Figure 1 shows Kohl's breakdown voltage as a function of electrode gap spacing for refractory metals in vacuum for conservative situations, or what he called "practical spacings". Kolh's results are consistent with high power electron gun breakdown results reported by Staprans [2] in 1966, also shown in Figure 1, especially for gaps of less than about 4 cm. Staprans developed a scaling law for the breakdown voltage of $V=kd^n$, where k and n are constants of the material and geometry. This author's rule-of-thumb breakdown voltages for refractory

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metal electrodes, developed in various devices at HRL Laboratories in the early 1990's, are also shown and compare well to Kolh and Staprans for small gaps.

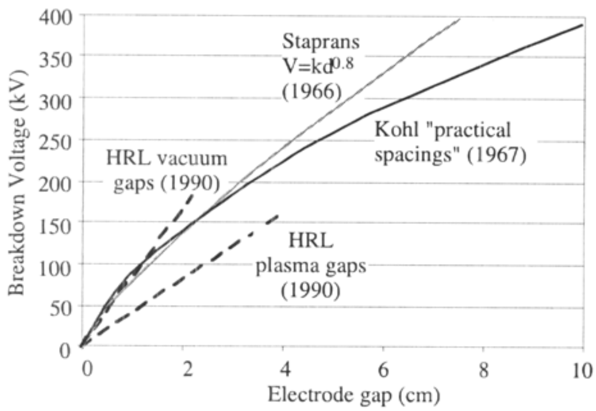

Figure 1. Voltage breakdown of refractory metals from the literature and the author's experience at HRL.

A series of voltage breakdown experiments were performed using a simple pulser circuit and a classic "plate-and-ball" electrode configuration shown in Figure 2. A capacitor was charged by a high voltage power supply through a 1 MΩ charging impedance and discharged into the gap between the two electrodes by a vacuum relay. The peak current was limited by a series resistance. In these experiments, voltages over the range of 1 to 5 kV were tested with capacitance values of 0.01 to 5 μF and current limiting resistor values of 5 to 100 ohms. These values correspond to stored energies in the range of 5×10^{-3} J to 50 J, peak currents in the range of 10 to 1000 A, and total charge transfer per pulse of 0.01 to 20 mC. The gap between the plate and ball was varied from 50 μm to 2 mm by a precision manipulator capable of reproducible positioning within 10 μm. The turbo-pumped UHV vacuum system used in these experiments had a 10^{-8} Torr base pressure, and is shown in Figure 3 with the high voltage feedthrough supporting the plate seen on the left and the grounded precision manipulator seen on the right.

Since our test geometry did not use parallel plates, the peak electric field between the plate and ball is reduced by the curvature of the equi-potential field lines around the spherical ball. This actual applied electric field is easily calculated analytically. For the parameters used in these experiments, the error in the electric field compared to that calculated by the voltage divided by the gap was less than 5%.

Physical damage to surfaces by arcing is attributed to very localized energy deposition on the electrode surface that causes melting or evaporation of the material. Power supplies used in high voltage systems are often characterized by their stored energy. In deposition systems that use arc discharges and in most of the arc erosion measurements in the literature, the amount of material removed from the surfaces and the lifetime of the device is usually characterized by the amount of current that passes through the arc. This "Coulomb-rating" is related to the energy deposition in the electrodes in a simple manner. The power running in the arc is $P = I V_a$, where I is the discharge current and V_a is the voltage drop in the arc. If this voltage drop occurs primarily in the cathode sheath, the energy deposited by the arc in the cathode surface is

$$E = \int P \, dt = \int I V_a \, dt . \qquad (1)$$

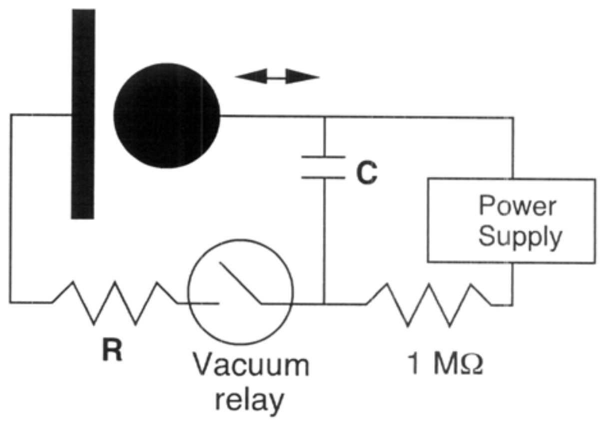

Figure 2. Simplified schematic of the test and pulser arrangement for these tests.

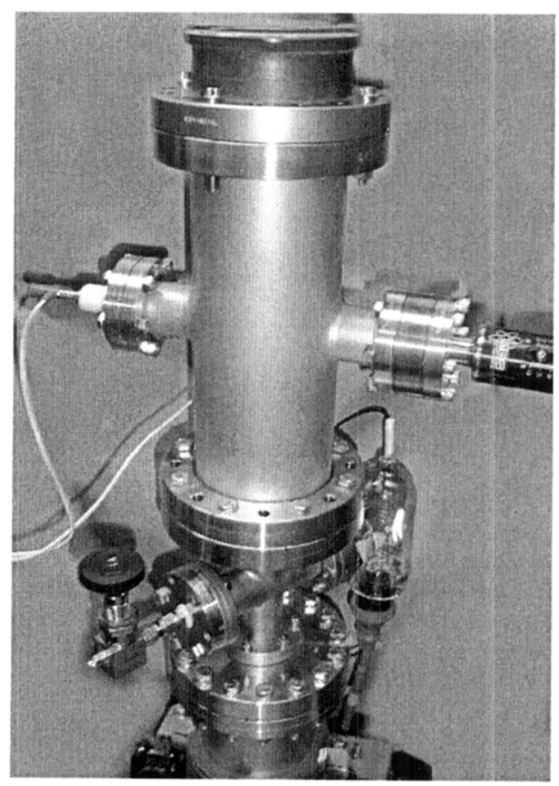

Figure 3. UHV turbo-pumped vacuum facility with high voltage feedthrough (left) and precision manipulator.

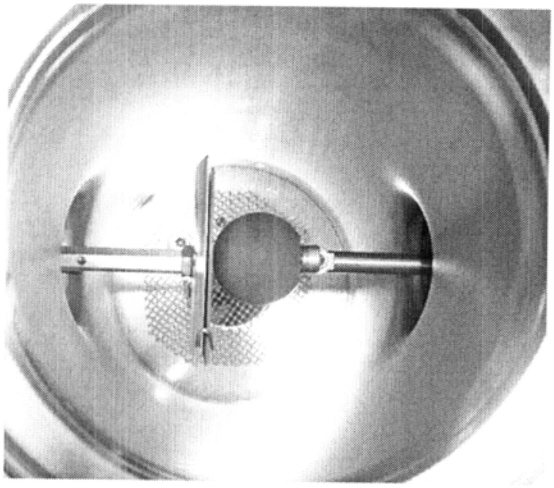

Figure 4. Photograph of the plate and ball test configuration inside the vacuum system.

The voltage drop in a graphite arc is essentially independent of the amount of current running in the arc up to several hundred amps [3], so the energy deposited in the arc is

$$E = V_a \int I \, dt = V_a Q \,, \quad (2)$$

where Q is the total charge transferred in the arc. Since V_a depends primarily on the cathode material and is essentially a constant for graphite [3], the energy deposited in the arc is characterized by the total charge transferred by the power supply or pulser circuit. Assuming that the arc remains lit during the entire time required to discharge the capacitor, the total charge transferred through the arc is Q = CV, where C is the capacitance and V is the capacitor charging voltage. If the arc current falls below the "chopping current" (the minimum stable arc current and is prematurely extinguished, then the total charge transferred must be evaluated by integrating the discharge current over the pulse duration.

To determine the Coulomb damage threshold of carbon grid materials, samples of the CC material that had been normally process with a final CVD coating, but without apertures machined, were inserted into the test fixture and evacuated to pressures of at least the 10^{-7} Torr range. The threshold for field emission, defined in these experiments by the voltage (or electric field) at which 1 μA of current was drawn between the electrodes, was measured as a function gap between the ball and plate. The sample was then connected to the negative leg of the pulser, and a series of 10 arcs were taken. The arc current was detected by a current transformer and the data stored by a digital oscilloscope that automatically integrated the current pulse to provide the total charge transfer for each pulse. Since the chopping current is very low for these materials, the error in using the capacitance times the charging voltage in the pulser is less than 5%.

III. EXPERIMENTAL RESULTS

The threshold voltage versus the gap spacing measured for molybdenum electrodes is shown Figure 5. The molybdenum surface was first cleaned and then grid blasted lightly to provide some slight surface texture. We see a similar voltage behavior with gas as described by Staprans, with the molybdenum surface capable of holding well electric fields of over 100 kV/cm. After 10 arcs of 1 mC in charge transfer, the surface is actually conditioned and the threshold voltage increases at every gap. Higher coulomb arcs then tend to damage the surface and reduce the voltage hold off, resulting in breakdown at electric fields of 50 to 60 kV/cm.

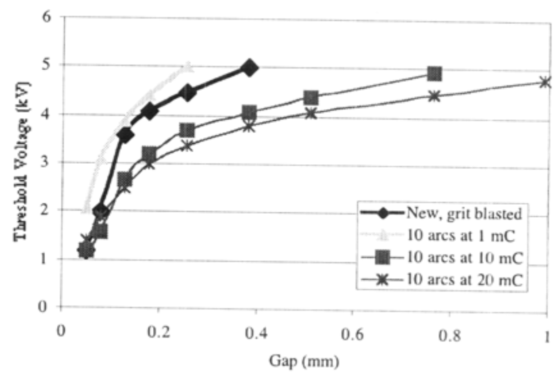

Figure 5. Threshold voltage versus gap for molybdenum for various coulomb-transfer arcs.

Graphite is often used in industrial ion source grids and TWT e-beam collector electrodes. Poco graphite breakdown behavior is shown in Figure 6. We see that small arcs condition the graphite surface to better hold-off than the as-new, and the surface degrades to near the "as-new" surface as the arc Coulomb amount increases. This is why graphite is often used in commercial ion sources and in the power utility market because the surface holds voltage well and degrades only slightly due to arcing.

Carbon-carbon composite material is fabricated from graphite fibers and various binder and filler material. After a graphitization step, the surface is CVD coated with carbon to fill any voids and smooth the surface. The voltage hold off of carbon-carbon composite is shown in Figure 7. We see that arcing of the surface degrades the voltage hold off to the level of the same material without the CVD layer for Coulomb transfers of 0.5 to 5 mC. At Coulomb transfer levels of 10 mC, it appears that the surface conditions. However, careful examination of the plate and ball surfaces show that carbon material "blow-back" from the anode at these high Coulomb transfers coated the cathode surface. This is similar to the CVD layer deposition used to originally smooth of the surface. Arcing at Coulomb-transfer levels greater than about 0.2 mC are therefore found to roughen the cathode surface and degrade the voltage hold off to non-CVD levels. Care must be taken to limit the Coulomb transfer to less than about 5 mC to avoid damage to the anode electrode.

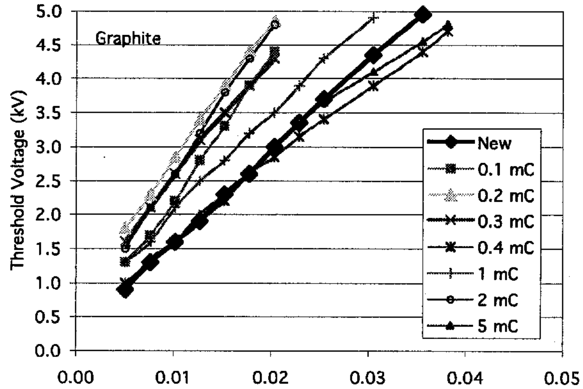

Figure 6. Threshold voltage versus gap for Poco graphite for various coulomb-transfer arcs.

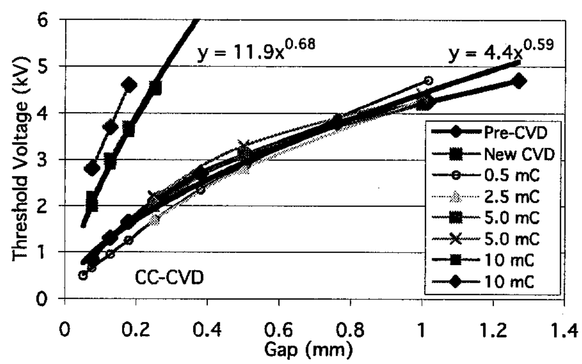

Figure 7. Voltage hold-off behavior of carbon-carbon composite showing arcs roughens surface and reduces the voltage hold off.

Pyrolytic graphite is also a candidate for accelerator grid electrodes in ion sources. The material is grown on a mandrel and then machined to the desired configuration. Pyrolytic graphite is configured with the carbon crystal planes normal to the surface. Test coupons were fabricated in this manner, but featured small surface structures residual from the growth process. These took the form of very slight bumps and depressions. Figure 8 shows the threshold voltage versus gap for the convex and concave surface structures of the pyrolytic surfaces, and the results of a mild sand blasting of the surface to smooth the edges. We see that the concave depressions showed higher field emission, probably from the edges of the depressions. Sand-blasting grades the edges and improved the voltage hold off. Arcing of the surfaces was found to expose the edges of the crystal planes and enhance the field emission again. This resulted in a lower voltage hold off than all the other materials tested, and a greater susceptibility to surface damage and reduced voltage hold-off due to arcing.

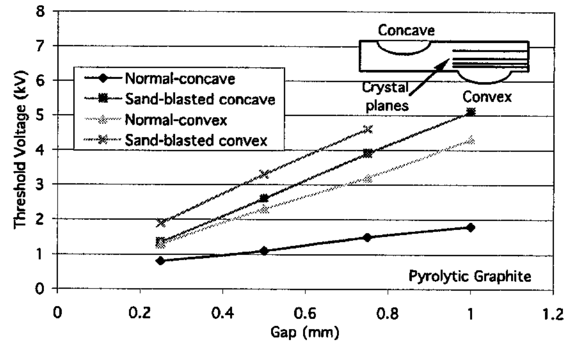

Figure. 8. Pyrolytic graphite material threshold voltage, which depends strongly on the surface conditions.

Finally, the threshold electric field of the materials tested is summarized in Figure 9. Polished copper, molybdenum and CVD coated CC-composite were found to hold the highest voltages, while arcing reduced the stand-off capabilities of all the materials tested.

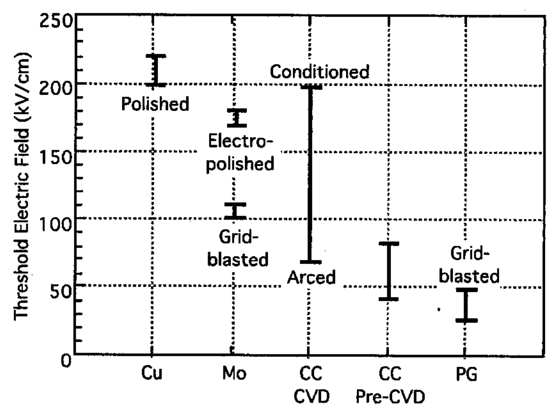

Figure 9. Summary of the threshold breakdown electric fields for the different materials tested.

IV. SUMMARY

The voltage breakdown behavior of molybdenum and various graphite materials has been investigated in the range of 1 to 5 kV. While molybdenum and graphite hold electric fields in excess of 100 kV/cm and are not significantly damaged at peak currents of less than 1 kA and 20 mC of charge transfer, carbon-carbon composites reliably hold about 25% of the molybdenum levels. The carbon-carbon materials roughen during arcing, but still reliably hold field strengths in excess of about 25 kV/cm.

V. REFERENCES

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