High Voltage Breakdown Limits of Molybdenum and Carbon-based Grids for Ion Thrusters

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An investigation of the high voltage breakdown thresholds for molybdenum and carbon-based electrodes used in ion thruster accelerator grids has been undertaken. The maximum electric field for the onset of field emission, and the threshold for arc initiation, has been measured for graphite, carbon-carbon composite, pyrolytic graphite and molybdenum with different surface treatments. Modification of the electrode surfaces due to arcing events, and the subsequent impact on the voltage hold off capability of the surfaces, has been determined for voltages of up to 15 kV and electric fields in excess of 100 kV/cm. The surface damage is well characterized by the amount of charge transfer in the arc, not the stored energy in the power supply. Both conditioning and damage to the surfaces have been observed, and are related to the characteristics of the materials and the electrical breakdowns. The voltage hold off capability of the surfaces was found to be well characterized by the field emission threshold after the arcing events, by the amount of Coulomb-transfer in the arc, and by surface modification apparent in SEM photographs of the subsequent surfaces. The results suggest values for the maximum reliable electric fields that should be used in the design of thruster ion optics using these materials. The results of `these experiments on the carbon and molybdenum surfaces for voltages of up to 15 kV and for electrode gaps up to 4 mm are presented.

Nomenclature

E	=	energy in an arc
I	=	current running in an arc
P	=	power running in a arc
Q	=	total charge transferred in an arc
t	=	time
V_a	=	voltage drop across the arc

I. Introduction

The major concern for the life and reliability of the accelerator grids in ion sources and electrodes in vacuum devices such as traveling wave tubes is the potential damage that can occur to the surfaces during breakdown and arcing events. A large amount of work over the last century has focused on understanding and characterizing the voltage hold-off of various materials and electrode geometries. This work has been summarized in recent years in books on high-voltage engineering [1][2] and vacuum arcs [3-6], and numerous articles in the literature. Degradation of the voltage hold-off due to surface damage incurred during breakdowns and arcing is also of importance as it affects the probability of subsequent breakdowns. Numerous articles have investigated the erosion and breakdown of molybdenum and carbon electrodes [7-14]. Unfortunately, the characteristics of breakdown and surface modification are strongly dependent on the specific material type, surface condition and power supply features, and often high voltage design rules or scaling for new applications cannot be found in the experiments surveyed in the literature.

A series of new experiments have been undertaken to understand the high voltage stand-off capability of carbon-carbon composite and pyrolytic graphite electrodes at voltages of up to 5 kV. These materials are of interest for ion sources and vacuum device electrodes due to their enhanced structural properties compared to graphite. To

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benchmark the results, molybdenum and graphite electrodes were also tested. The experimental set up consists of a classic "plate and ball" configuration, where flat samples of the material of interest is spaced a given distance in a vacuum system from a 2.5 cm-diameter ball of the same material at ground potential. The flat sample is biased negatively relative to the ball, and the threshold voltage at which significant field emission occurs is measured as a function of the separation distance between the two electrodes. Electrical breakdown between the electrodes is then triggered by over-voltaging the gap with a high voltage pulser, which discharges a capacitor through a current limiting resistor into the arc between the electrodes. The breakdown is characterized by the amount of charge transferred through the arc, and the subsequent threshold voltage for field emission is found to be well correlated with the arc initiation voltage. SEM photographs of the before and after surfaces clearly show the surface damage due to the arcs and likely field emission sites that can contribute to subsequent breakdowns.

In most applications, high voltage breakdown between grids or electrodes causes some fraction of the stored energy in the power supply to be deposited on the electrode or grid surface. This can cause a modification to the surface and is a likely mechanism for some of the problems encountered during earlier development and testing of carbon-carbon and pyrolytic grids for ion sources [15-19]. The formation of a carbon arc at the cathode electrode (the accel grid) and the deposition of a significant amount of electron power from discharge into the anode electrode (the screen grid) can cause both the screen and accel grids to be modified and/or damaged. The breakdown events usually impact the subsequent voltage hold-off capability of the surfaces. This paper attempts to determine the voltage stand-off capability for new electrode surfaces, and the impact of breakdown events on the subsequent hold-off and reliability of the high voltage surfaces.

A common challenge in discussing high voltage breakdown is coming to some agreement on the units that the data is presented in. Most engineers think in units consistent with various rule-of-thumb values used in their industry with common units of volts per mil or kilovolts per millimeter. For this work, the breakdown electric fields will be presented in kilovolts per centimeter.

The paper is organized as follows. A brief background discussion on the expected breakdown voltages for high voltage electrodes in vacuum is given in Section II. The experimental configuration for the present investigation is given in Section III, and the characterization of the arcs in terms of Coulomb-transfer is described in Section IV. The experimental results of all the voltage hold-off and breakdown experiments are given in Section V, and the results summarized and discussed for the different materials tested in Section VI.

II. Electrode Breakdown

High voltage breakdown of electrodes has been studied for over a hundred years. Breakdown voltages reported in the literature depend strongly on the electrode material, the surface properties and conditions, and the physical geometry and electrical characteristics of the tests. For this reason, it is often difficult to apply literature results to modern applications where the surface conditions and geometries may be radically different, or entirely new materials may be used. A reasonable survey of high voltage breakdown results was published by Kohl [2] in 1967. Fig. 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". Kohl's results are consistent with high power electron gun breakdown results reported by Staprans [20] 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 vacuum breakdown voltages for refractory metal electrodes, developed in various devices at HRL Laboratories in the early 1990's, are also shown and compare well to Kohl and Staprans for small gaps.

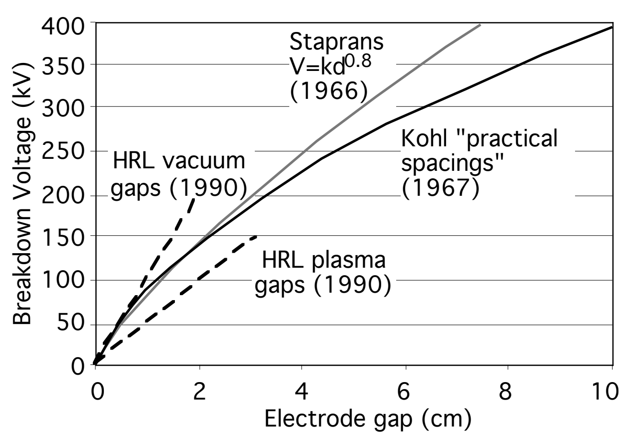


Figure 1. Breakdown voltage versus gap spacing for refractory metals, with data from Kohl [2], Staprans [20], and HRL Laboratories.

Breakdown is often described in terms of the electric field applied to the surface that causes an arc or discharge to start. Figure 2 shows the electric field calculated from Kohl's "practical spacings" for refractory metals. Electric fields of 40 to 100 kV/cm are found, which is consistent with the range of breakdown fields experienced by the author at HRL with refractory electrodes and shown by the dashed

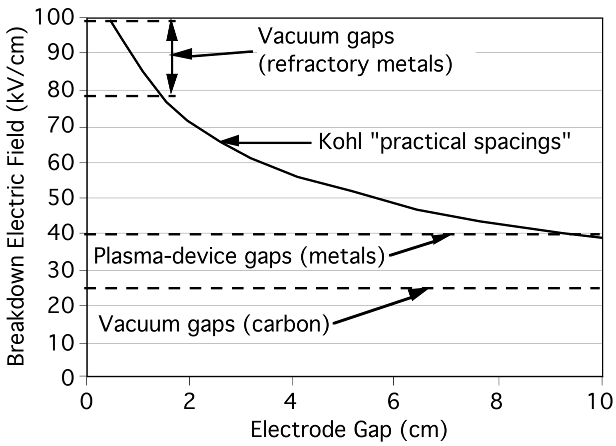


Figure 2. Maximum electric field that refractory metal and carbon electrodes could reliably hold, with the HRL experience shown in dashed lines.

lines. In addition, we found that the electric fields that various carbon materials could reliably withstand were significantly lower than the refractory metals, and a rule of thumb of about 25 kV/cm was often used for the maximum reliable electric field useable for all carbon materials.

The investigation of voltage standoff undertaken here is aimed at applications with somewhat complex geometries like accelerator grids ion sources or electron beam collector electrodes. For this reason, the threshold voltage as a function of gap spacing and the breakdown electric field was measured for flat plate samples and plates with holes or edges machined into them. This provides a reasonable configuration dependent range in the data for the design of other high voltage electrode geometries.

In the experiments to be presented here for molybdenum and carbon materials, we find that arc breakdown is well correlated to the onset of field emission [6, 21-23]. Other authors have attributed arc breakdown to the presence of particulates on the surface [3, 24]. While we carefully prepared the surfaces and test geometry to avoid insulating particles that could enhance the electric field and initiate arcing, the materials were tested in the as-fabricated state to account for any surface structure and particles that might normally be on the surface. Even in the presence of some marginally bound particles on the surface that might evolve to be ionized or bombard the surfaces, we still found that field emission onset always correlated with the voltage hold-off and breakdown probability. It appears that particulates in these experiments contributed to the breakdown primarily by enhancing the field emission.

III. Experimental Configuration

To understand the breakdown characteristics of modern carbon-carbon composite materials and pyrolytic graphite, a high voltage vacuum-breakdown test setup was assembled. A classic "plate and ball" geometry was used to avoid edge effects in the breakdown region that might cause spurious arcs. In this geometry, the item under test was manufactured as a thin, 5cmx5cm plate and clamped to a stainless steel holding fixture that was mounted on a high voltage standoff in a turbo-pumped, UHV vacuum facility with a base pressure in the 10^{-8} Torr range. A 2.5 cm diameter ball of the same material as the plate was mounted on a grounded linear manipulator coupled into the vacuum system. The gap between the plate and ball was controlled by the precision manipulator with a resolution of better than 10 µm. The plate electrode was connected to a high voltage pulser shown schematically in Figure 3, which consists of a capacitor charged through a high impedance by a power supply and connected to the test-plate fixture through a vacuum relay. A photograph of a carbon plate and ball set up in the vacuum chamber is shown in Figure 4.

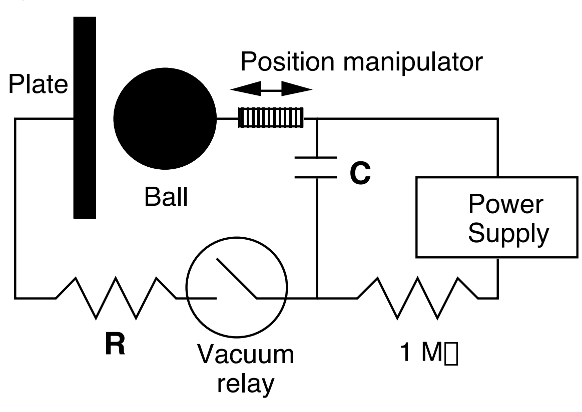


Figure 3. Simple electrical schematic of the plate-and-ball configuration and high voltage pulser.

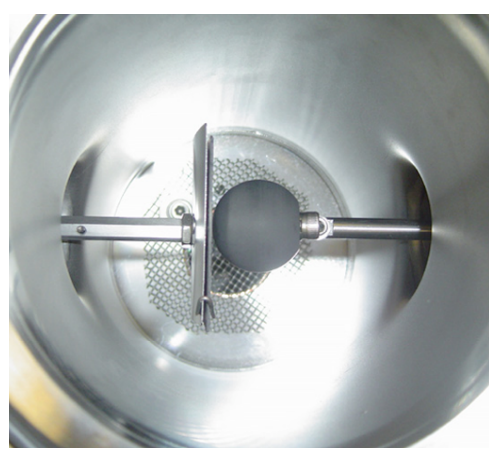


Figure 4. Photograph of plate-and-ball layout in the UHV vacuum system.

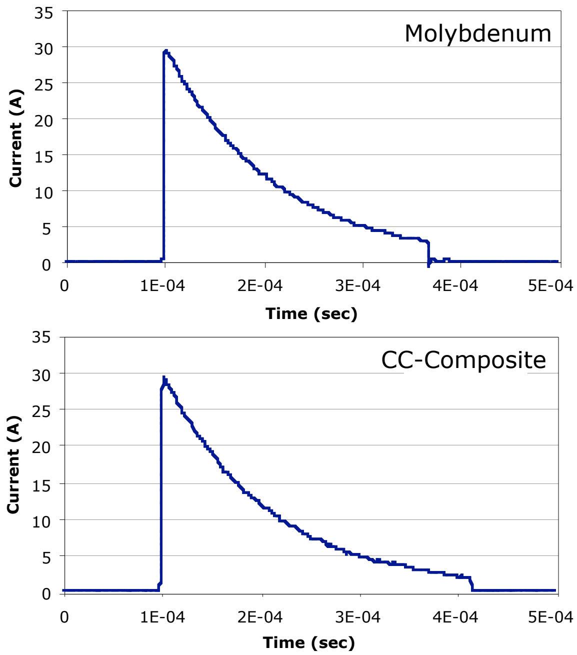


Figure 5. Current versus time waveforms for the plate and ball tests with 1 μF capacitor charged to 3 kV and current limited by 100 Ω.

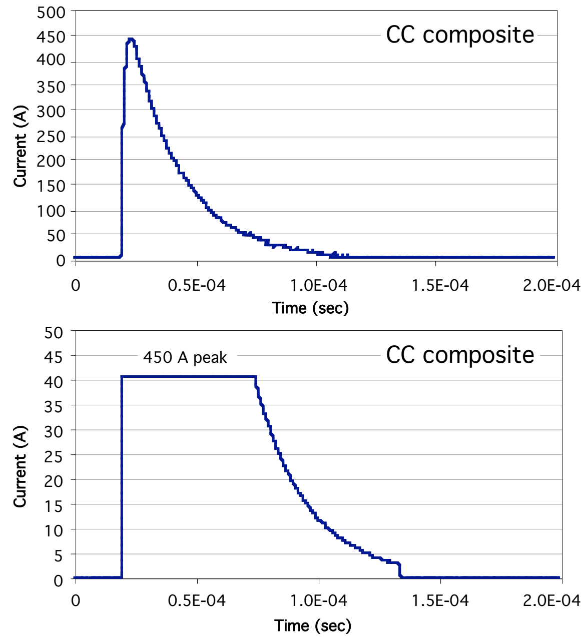


Figure 6. High current waveforms of the carbon plate-and-ball tests with a 2 μF capacitor charged to 5 kV and current limited by a 10 Ω resistor.

In the arcing tests, the vacuum relay is pulsed on until the capacitor is discharged, and the peak current is limited by a series resistor. This configuration is representative of modern high voltage switching power supplies in that the output filter capacitance discharges first into the load arc, and the modulator circuit interrupts the inverter before significantly more energy than the capacitor stored energy is delivered to the arc.

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 effect can be corrected for analytically [1], but the error in the electric field is completely negligible if the gap between the plate and ball is much less than the ball radius. In our experiments, the ball radius was 12.7 mm while the gap ranged from 0.05 mm to 40 mm. For this range, the maximum electric field at the point of closest approach can be taken with insignificant error to be the applied voltage divided by the gap distance.

In our experiments, voltages in the range of 1 to 5 kV were used 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 $5x10^{-3}$ 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.

An example of the current waveforms recorded for molybdenum plate-and-ball and carbon plate-and-ball tests with a 1-μF capacitor charged to 3 kV are shown in Fig. 5. In these tests, the gap was set to 0.25 mm and the current limited by a 100-Ω resistor. The breakdown occurs when the gap is "over-voltaged" by closing the vacuum relay, which initiates the surface arc. The current peaks to about 30-A for both materials and then decays with the characteristic "RC" time constant.

It is clearly seen in Fig. 5 that the arc current extinguishes before the capacitor is fully discharged. This self-interruption current, called the "sustaining current" or "chopping current" [3-5], is the minimum current at which the arc is self sustaining. The chopping current exists due to the requirement for the arc to deliver sufficient energy to the cathode surface to evolve enough ionizeable material to maintain the arc. Arcs initiate and run at the lowest chopping currents on surfaces with volatile impurities that are easily sputtered or vaporized to feed the arc. Higher temperature materials, such as refractory metals, typically have higher chopping current because more power is required to liberate the material from the surface. In these experiments, molybdenum was observed to have 3 to 4 A chopping currents, while the carbon materials typically had lower chopping currents of about 2 A. This behavior causes the total energy delivered to the arc discharge to be slightly less than the total stored energy in the capacitor.

The chopping current is found to be independent of the peak current running in the arc at the voltages and Coulomb-transfer values tested here. This is not the case for very high Coulomb-transfer systems such as AC arc welders and lamps [3] where the chopping current decreases with arc duration and duty. Fig. 6 shows the current waveform from the carbon plate-and-ball configuration with a 2-μF capacitor charged to 5 kV and discharged with

10 Ω in series. The current peaks at about 450 A, as seen in the top graph, and the current decays to near zero with the $2x10^{-5}$-sec RC time constant. However, expanding the vertical scale of the same breakdown event in the lower graph of Fig. 6 shows that the chopping current is essentially unchanged at about 2.5 A. Variations in chopping currents of about ±1 A were routinely observed depending on the surface conditions of both the plate and the ball. It is likely that the short duration arcs in these experiments resulted in modest surface damage or heating, causing the chopping current to be only dependent on the surface material.

In order to characterize the surface conditions before and after arcing, a threshold breakdown voltage measurement was taken after each individual arc events or after a series of arcs had been accumulated on a given surface. For this measurement, the high voltage pulser was disconnected from the system and the field emission current measured as a function of the applied voltage and the gap using a high impedance hipotter. The threshold breakdown voltage was somewhat arbitrarily defined as the voltage at which 1 μA of field emission current was obtained. As will be shown in Section VI, this value is directly related to the arc initiation voltage, and so is a reasonable figure-of-merit to characterize the voltage stand off of the surface. The threshold electric field is found by dividing the measured threshold voltage by the gap dimension.

The affect of arcing on the voltage standoff of the surfaces was investigated by first measuring the threshold voltage as a function of gap spacing, over-voltaging the gap to induce one or more arcs, and then re-measuring the threshold voltage again. The number of arcs used was determined by measuring the threshold electric field after each arc in a series triggered at a fixed location on the sample. Figure 7 shows the threshold electric fields for three different CVD-coated carbon-carbon composite samples as a function of the sequence number of each arc. In this case, the Coulomb-transfer was set to 5 mC by charging the same 0.1 μF capacitor to 5 kV for each data point. We see that reproducible results for each surface are obtained after about 5 arcs. For that reason, we established a standard test procedure to measure the threshold voltage as a function of the gap spacing, arc the surface 10 times, re-measure the threshold voltage as a function of the gap spacing, and then move to a new position on the sample for the next data point. It should be noted that the threshold electric field measured after 10 arcs is essentially independent of the value of the series resistance, and therefore the peak current of the arc. This effect was consistently observed for peak current up to 1 kA.

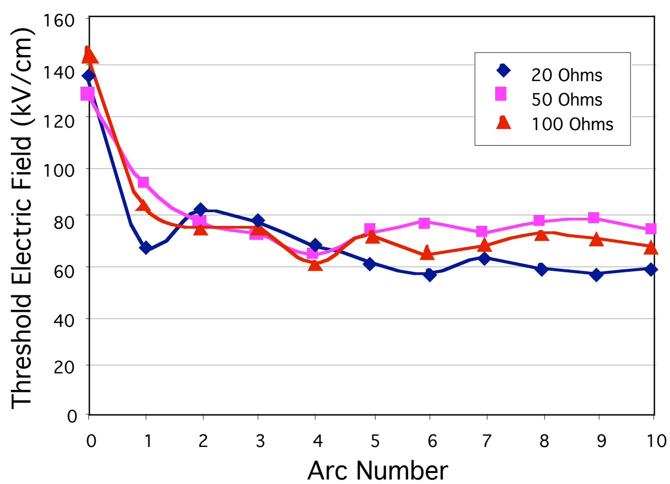


Figure 7. Threshold electric field measured after each arc of 2.5 mC showing reproducible results after several arcs were accumulated.

IV. Characterization of the Arcs

The breakdown events described here produce moderate current (10 to 1000 A peak) self-sustained arcs that modify the cathode surface. Physical damage to surface is attributed to localized energy deposition on the electrode surface during the arc that causes melting or evaporation of the material. On the cathode surface, the 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 surface, the energy is deposited from the plasma or electron stream that crosses the gap, which causes surface damage by heating without the processes necessary for electron emission. The energy stored in the capacitor is then distributed between the series current limiting resistor, the voltage drop at the cathode surface, and the voltage drop in the plasma discharge and anode sheath. These voltage drops can be modeled as series resistances in the energy balance of the system.

In these experiments, we are primarily concerned with the voltage hold off capability of the negatively biased (plate) electrode that acts as the cathode electrode in any breakdown. Engineers often rate the possibility of a power supply damaging the electrodes by the amount of stored energy in the power supply. However, in material-deposition systems that use arc discharges, in high voltage switches, 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-transfer 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. Assuming that most of the voltage drop is in the cathode sheath, energy deposited by the arc on the cathode surface is

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

The voltage drop of refractory metal and graphite arcs is nearly independent of the amount of current running in the arc up to several hundred amps [25],[26]. This is shown in Figure 8 (from ref. [25]), where the data for graphite shows the discharge voltage changing by 15% for a current change of over an order of magnitude. Therefore, V_a can be considered to be essentially a constant, and the energy deposited by the arc on the cathode is

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

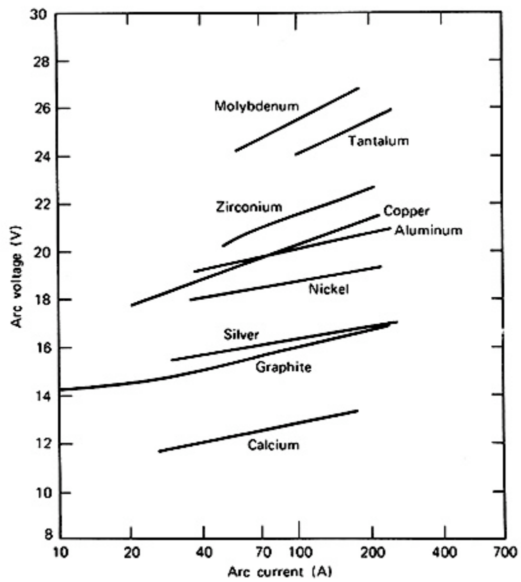


Figure 8. Arc voltage versus arc current for several materials. (reproduced from ref.[25]).

where Q is the total charge transferred in the arc. We see that the arc energy deposited on the cathode surface for a given electrode material is characterized by the total charge transferred by the power supply or pulser circuit, and not the stored energy in the power supply. 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" and is prematurely extinguished, then the total charge transferred must be evaluated by integrating the discharge current over the pulse duration. For these experiments, the effect of the arc extinguishing early reduced the charge transfer by less than 5% compared to the calculated CV total available.

It should be noted that the amount of energy delivered to the cathode surface by the arc, and the amount of damage to the surface incurred by material removal, is independent of any series resistance in the circuit as long as the current is stable during the duration of the event (i.e. the current is above the chopping current). This means that simply adding a series resistor to one leg of the high voltage power supply circuit will not reduce the surface damage due to an arc unless the arc current drops to less than the chopping current. The only mechanism that reduces surface damage if the current is large compared to the chopping current is to limit the total charge transfer. This requires either reducing the power supply capacitance at a given voltage, or actively shunting (crowbaring) or opening the circuit once the arc is detected to reduce the arc duration.

The experimental procedure in these tests is to measure the threshold breakdown voltage from the on-set of field emission (previously described), and then initiate a series of between one and 10 arcs at a given Coulomb transfer (Q=CV) by "over-voltaging the gap" at a selected peak current determined by the current limiting resistor R. After the series of arcs, the threshold voltage is again measured for different materials, Coulomb transfers, gap spacings and peak currents.

V. Experimental Results

A. Molybdenum Electrodes

To benchmark these experiments, the breakdown and voltage hold off behavior of molybdenum electrodes was tested. Molybdenum is a standard electrode material used in ion sources, electron guns and other pulsed power devices. To examine typical material used in ion sources, a molybdenum surface was first cleaned, polished and then lightly grid blasted to provide a slight surface texture. This produces a surface commonly used in ion thrusters to retain sputtered material to avoid flaking, and is characteristic of molybdenum electrodes in vacuum devices that have been single-point machined and used without polishing. The threshold voltage versus the gap spacing measured for molybdenum electrodes is shown Figure 9. We see a power-law dependence of the threshold voltage with gap spacing, as described by Staprans [20] and Mesyants [4], [6], which is sometimes called the "total voltage effect". While there are numerous possible mechanisms for the total-voltage effect [6], [27-29], the increased gap reduces the surface electric field and the field emission current but increases the probability of an atom or particulate

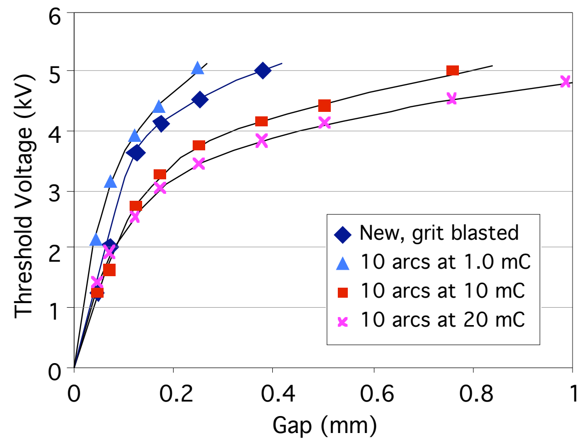


Figure 9. Threshold voltage versus gap for molybdenum after 10 arcs of varying charge transfer per arc.

being ionized while traversing the gap. The ionized atom or particle is then accelerated into the cathode potential electrode and produces secondary electrons. If sufficient ionizations and secondary electrons are produced, the process cascades and the gap breaks down. This is equivalent to the Paschen breakdown [2] mechanism in gas filled devices, and is caused by the release of gases or particulates from the surfaces in vacuum gaps. After 10 arcs of 1 mC in charge transfer, the threshold voltage was measured again and the threshold voltage is observed to increase for every gap tested, indicating that the surface is being conditioned. Improving voltage stand off of electrodes with a series of low Coulomb-transfer arcs is common practice in the high voltage industry, and often historically called “spot-knocking”. Higher Coulomb transfer arcs then degrade the voltage hold off as the surface is being damaged and roughened.

As the gap between the electrodes increases, the threshold voltage curves becomes more linear and the surface asymptotes to a constant threshold electric field. Figure 10 shows the threshold voltage and electric field for large gaps for three different molybdenum surfaces, polished, grit blasted and grid material with apertures. All the molybdenum surfaces are initially capable of holding electric fields of well over 200 kV/cm, but the surface roughening to retain flakes and aperture edges associated with real grids cause the voltage hold off to decrease. In all cases, the series of high Coulomb-transfer arcs degrade the voltage hold-off due to damage of the surfaces that increases the number of field emitters. For grid material, the resulting surface is susceptible to breakdown at electric fields of about 50 kV/cm.

Figure 11 shows an SEM photograph of the molybdenum surface after one breakdown with a Coulomb transfer of 1 mC. The arc tends to modify the surface over a small area, causing the characteristic “arc track” [30], [31]. Increasing the Coulomb transfer of the arc causes the area of surface modification to increase, as seen in Fig. 12 for a single 5 mC arc, but the surface modification inside the “arc-track” appears similar to the lower Coulomb arc seen in Fig. 11.

In general, arcs on refractory metal surfaces move about on the surface in an attempt to evolve volatile material necessary to sustain the arc. Higher Coulomb-transfer arcs tend to cover more surface area as the arc looks for loosely bound material to provide the neutral gas or particles to feed the arc. This is seen in Fig. 13, where a close-up of the edge of the arc-track is shown. The surface texture of the grit-blasted and arced surfaces is essentially the

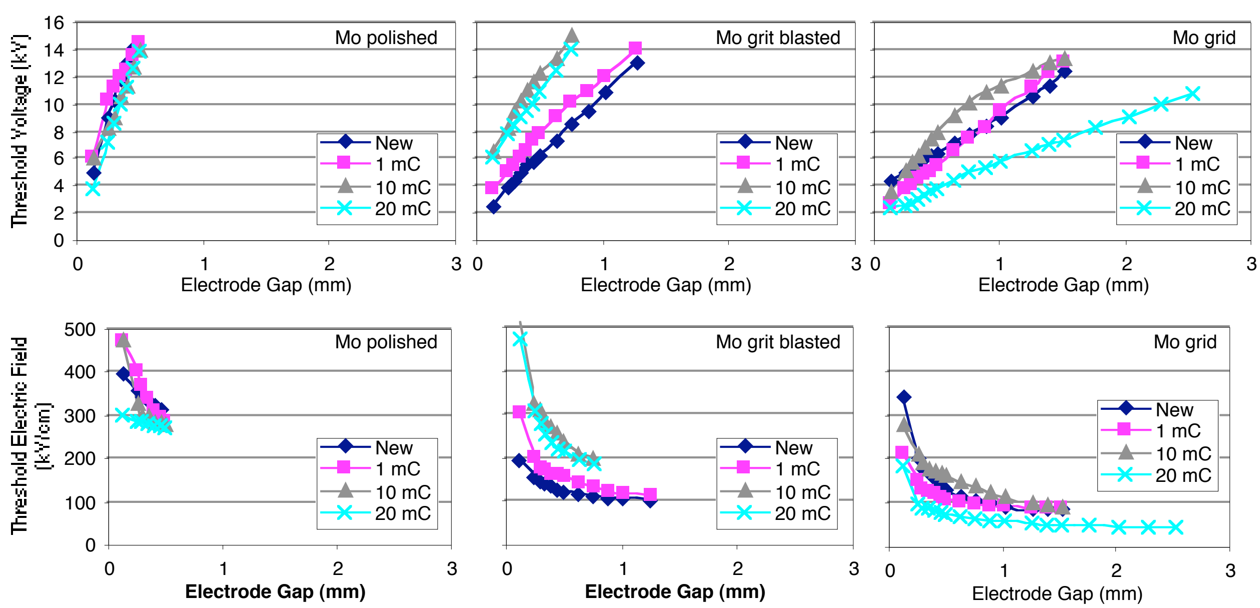


Figure 10. Threshold voltage and electric field versus gap for molybdenum material with three different surface structures. Grit blasting or machining in apertures significantly reduces the voltage hold off.

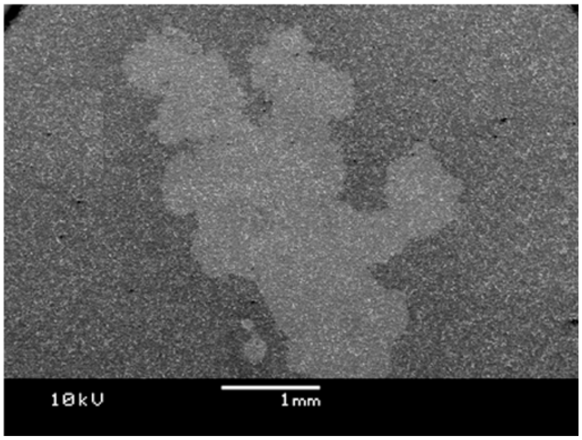


Figure 11. SEM photograph for a single arc on molybdenum at 1 mC of charge transfer.

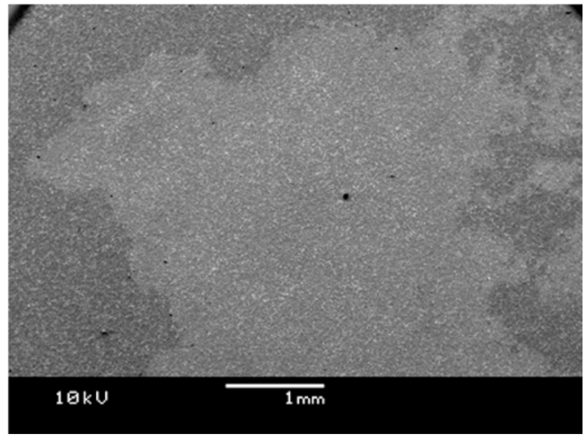


Figure 12. Molybdenum SEM for a single arc at 5 mC of charge transfer.

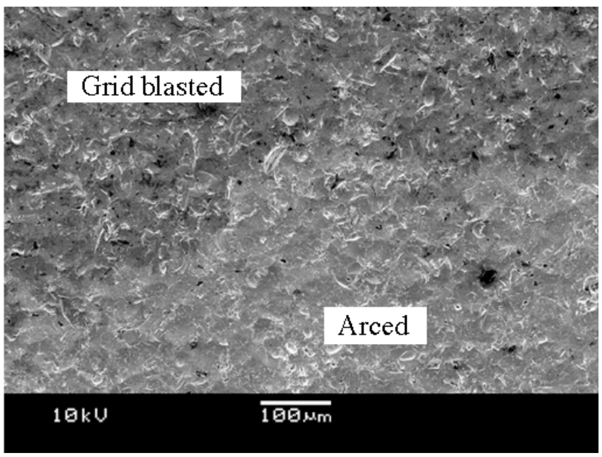


Figure 13. Molybdenum SEM photograph showing little texturing but significant cleaning of surface due to arcing.

same, but the darker color and greater number of black inclusions in the non-arced area is indicative of loosely bound impurity material that the arc removes. During these tests at peak currents under 1 kA and total Coulomb transfers of less than 20 to 50 mC, the arcs don't tend to anchor in one spot or evolve a significant amount of the molybdenum base material. While the arcs tend to clean the surface without changing the gross texture, high Coulomb-transfer arc clearly modify more surface area and can leave behind more field emitters that tend to lower the threshold breakdown voltage, as was seen in Figs. 9 and 10.

B. Carbon Materials

1. Graphite

Several different types of carbon materials were tested. Graphite electrodes are commonly used in industrial ion sources and space traveling wave tubes, and this material was tested as a baseline for the more complex carbon materials such as carbon-carbon composite and pyrolytic graphite. The breakdown behavior of Poco graphite, which is often used for vacuum applications because it is very dense, small grain and pure, is shown in Figure 14. We see that small arcs condition the graphite surface to

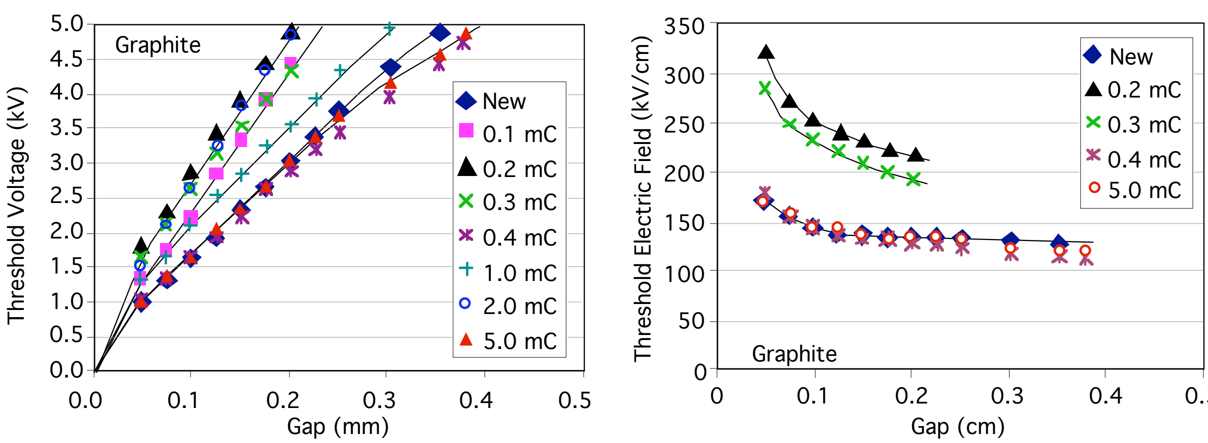


Figure 14. Threshold voltage (left) and electric field (right) versus gap for Poco graphite for various coulomb-transfer arcs.

better hold-off than the as-new state, and the surface degrades to near the "as-new" condition as the arc Coulomb-transfer amount increases. Fitting the curves to a power function following Staprans [2], we see that the exponent ranges from 0.8 to 0.9, which is much higher than the metals and other carbon-materials tested. This behavior 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.

The threshold electric field for Poco graphite shown above in Fig. 14 indicates that the graphite electrodes start out holding the order of 150 kV/cm, are conditioned by small arc currents to over 200 kV/cm, and degrade back to the better than 100 kV/cm as the Coulomb transfer increases. Further tests at Coulomb-transfers of up 20 mC showed similar behavior as the 5 mC case. Poco graphite with well-controlled surfaces and subject to reasonably small total-current-transfer arcs demonstrates excellent voltage hold-off.

2. Carbon-Carbon Composite Material

Carbon-carbon composite material used for electrodes is based on carbon fibers woven into a matrix with the fibers oriented in one or two dimensions. This material has enhanced strength and flexural modulus compared to pure graphite due to the carbon fiber properties. The carbon-fiber weave is impregnated with a resin and built up to the desired shape by progressive laminate layers on a mold. The resulting material is usually densified and graphitized at high temperature, and may be further impregnated or over-coated with a thin CVD carbon layer after this process to fill any voids or smooth the final surface. A 2-D carbon weave with the fibers oriented at 60˚ was used in these tests. The samples were tested for voltage hold-off after the graphitization step that produces the final dense material. Tests were conducted with and without the surface coating by CVD that is used to fill any voids residual after the graphitization step and to smooth the surface. The threshold voltage of the carbon-carbon composite samples with the CVD over-layer is shown in Figure 15. The newly coated material is observed to hold voltage extremely well. However, after a series of 10 arcs ranging from 0.1 to 0.5 mC, the voltage hold-off is seen to degrade with increasing Coulomb-transfer level.

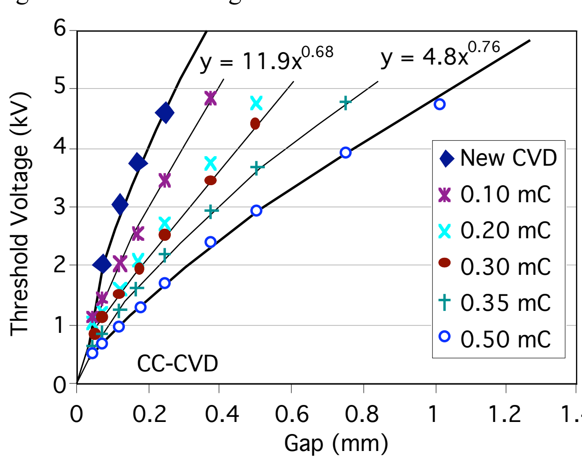


Figure 15. Threshold voltage versus gap for the carbon-carbon composite material with 10 arcs of increasing charge transfer at low levels.

The degradation of the carbon-carbon surface is related to the amount of surface damage produced by the arcing. Figure 16 shows three SEM photographs of the carbon samples after 10 arcs of 0.1, 0.5 and 5 mC per arc. The CVD coating is seen in the upper left un-arced region to nicely smooth the surface and round any particulates on the surface, resulting in low probability for sharp points and field emission. The Coulomb-transfer arcing of 0.1 mC in the top SEM does very little damage to this surface, and the arc location in the center of the photo shows only small punctures of the CVD coating. However, as the Coulomb-

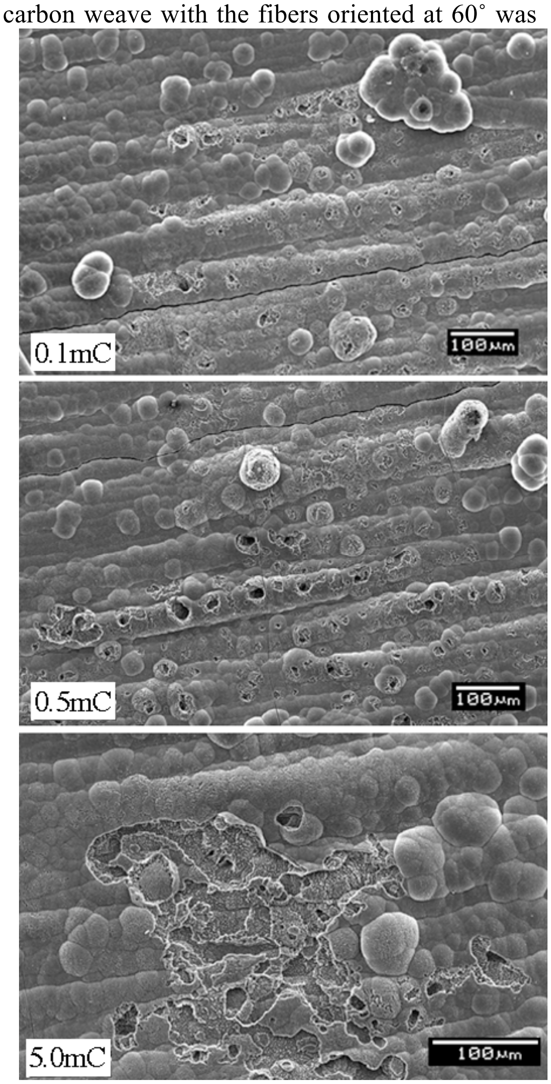


Figure 16. SEM photographs of three surfaces after 10 arcs at 0.1 mC (top), 0.5 mC (center) and 5 mC (bottom) showing increasing surface damage with total charge transfer of the arc.

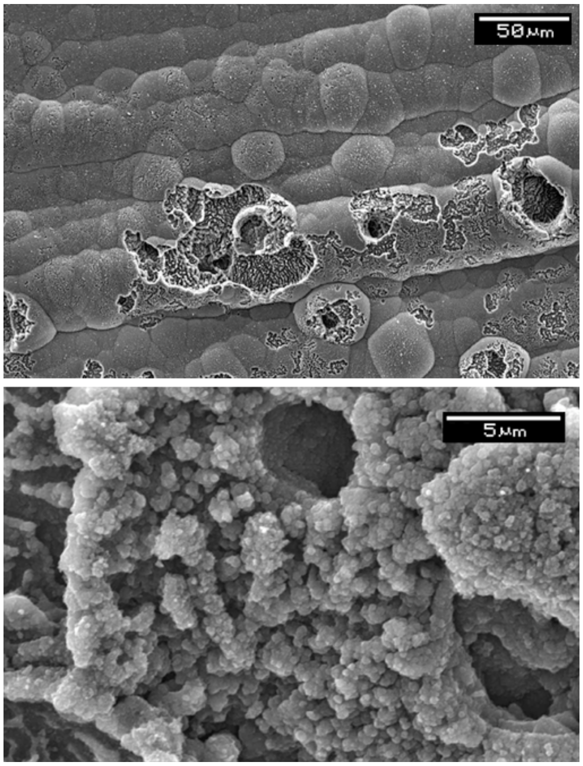


Figure 17. SEM photographs of the 5 mC arced carbon-carbon composite surface showing arc-spot anchoring and the production of sharp edges responsible for field emission.

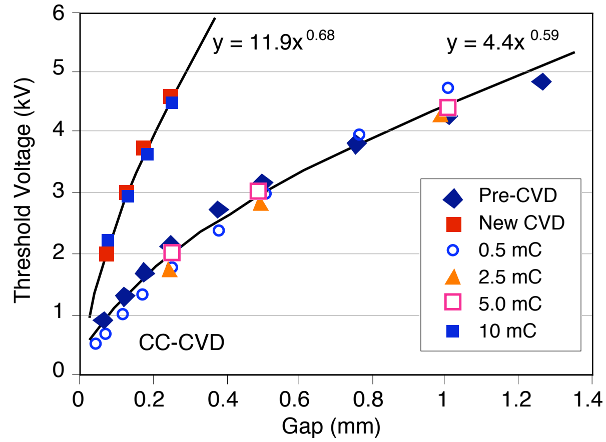


Figure 18. Threshold voltage for carbon-carbon composite material after 10 arcs at various Coulomb-transfers. Moderate charge transfer arcs roughen the surfaced to the non-CVD layer performance.

transfer level increases, the damage to the surface increases. At 0.5 mC, significant holes in the CVD coating are observed, and the particulate at the top-middle of the photo is significantly arced. For the 5 mC case shown in the bottom photograph, the entire CVD layer has been removed in the region of arcing, and many sharp edges that could potentially be field emission sites are exposed.

Figure 17 shows a close-up SEM photograph of one spot on Fig. 16 where the arc anchored for a short time directly on a fiber. In the top photograph, we see that the arc removed the CVD layer and then drilled directly into the fiber in two locations. The bottom photograph at higher magnification shows the exposure of the graphite grains and the edges of voids in the fiber, which provide the sharp field emission sites responsible for reducing the voltage hold-off.

Arcs with increasing total charge-transfer tend to progressively roughen the surface, but degrade the voltage hold-off to essentially the same threshold as that found for the carbon-carbon materials that were not CVD coated. Figure 18 shows the threshold voltage after 10 arcs of 0.5 to 10 mC each on the carbon-carbon-composite material. We see that arcing of the surface degrades the voltage hold off to the level of the same material without the CVD layer (called pre-CVD) for Coulomb transfers of 0.5 to 5 mC. Figure 19 shows an SEM photograph of the pre-CVD surface that features some particulates, unfilled delaminations and general roughness. The single 2.5 mC arc located in the center of the photo did not change the gross surface significantly, but tends to generate many small round nodules attributed to a liquid carbon phase during arcing [32] seen as specs on the surface. This general surface roughness has the same voltage hold-off characteristics as the carbon-carbon composite with the CVD layer after arcing with 0.5 mC or greater charge transfer, and therefore has a similar net number of active field emission sites.

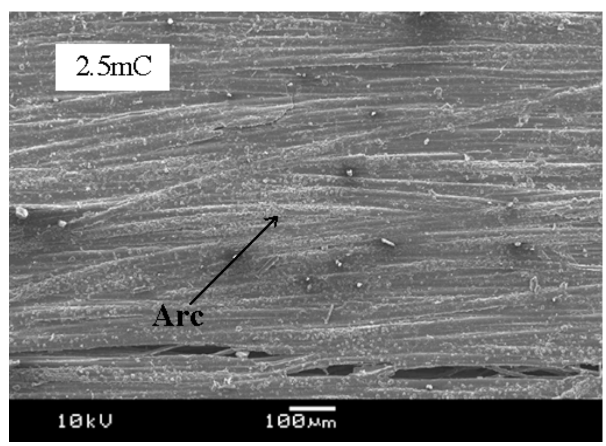


Figure 19. Carbon-carbon surface without final CVD coating showing surface roughness and voids. Arcing roughens surface slightly, but doesn't appear to change surface properties or voltage hold-off significantly.

A careful examination of Fig. 18 shows that the 10 mC arcing case appears to re-condition the surface and restore the as-new CVD-coated voltage hold-off characteristics. However, careful examination of the plate and ball surfaces after 10 arcs of 5 and 10 mC show that carbon material "blow-back" from the anode ball at these high Coulomb transfers coated the cathode surface. This is similar to the CVD layer deposition used to originally smooth of the surface. SEM photographs of the arced surfaces for > 5 mC arcs show some surface roughness associated with the arcing, but the surface is coated with carbon, which rounds the edges and suppresses the field emission. However, sometimes the redeposited coating does not cover the entire area that has been arced, and the voltage hold off is not improved. This is illustrated in Figure 20, where the threshold voltage measured as a function of the arc Coulomb-transfer is plotted for the case of a 0.25 mm gap between the electrodes. In this figure, each data point represents a new surface with 10 arcs at the indicated Coulomb-transfer per arc. We see that arcs with Coulomb-transfer levels greater than 0.1 to 0.2 mC tend to roughen the cathode surface to the pre-CVD condition, and arcs of over about 3 mC start to damage the anode electrode and transfer material back to the cathode surface. At 10 mC of charge transfer, in two cases the voltage hold off has repaired the surface and in another two cases it has left a roughened surface with reduced voltage standoff. It is clear that care must be taken in whatever application uses this material to limit the Coulomb transfer to well less than 5 mC to avoid damage to the anode electrode.

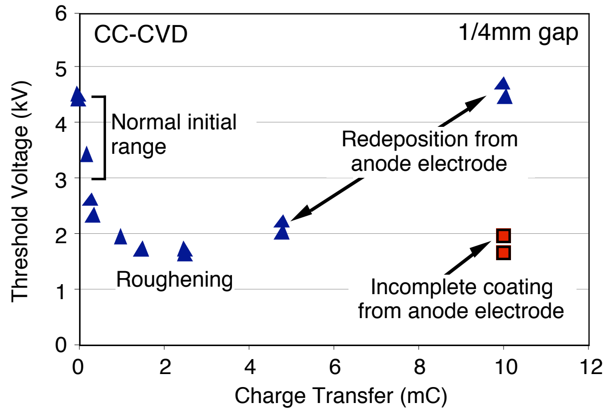
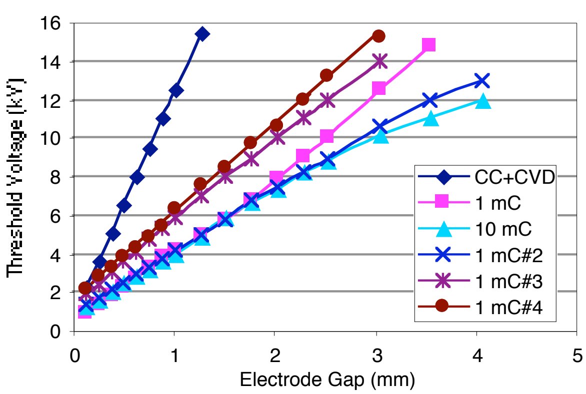


Figure 20. Threshold voltage as a function of charge transfer per arc for 10 arcs showing the degradation due to roughing at low Coulomb transfers and redeposition from anode ball sometimes improving the voltage hold off of the cathode electrode.

The surface damage and repair characteristics of CC composites from high Coulomb arcs is illustrated in Figure 21 for voltages of up to 15 kV and gaps of over 4 mm. New CC material with the final CVD layer has excellent voltage hold off behavior. Exposure to 10 arcs with 1 mC of charge transfer reduces the threshold electric field to the typical 40-to-50 kV/cm "roughened" level for this material. Subsequent exposure of one of the samples to 10 arcs of 10 mC actually resulted in a reduced voltage hold off of the surface, especially for large gaps, and threshold electric fields less than 30 kV/cm. Inspection of this sample showed that the redeposited material from the anode electrode had only coated the center of the arced region, and the edges of the arc region over a large area were significantly roughened and damaged. Exposure of this same sample to another 20 arcs of 1 mC (shown as 1mC#2) slightly improved the voltage hold off, and subsequent exposures of this same magnitude (shown as 1mC#3 and 1mC#4) further improved the threshold electric field to levels approaching 50 kV/cm, which was slightly better than the original 1 mC sequence but in the characteristic normal range. Clearly, the 10 mC arc significantly damaged a large area, and a large number of smaller arcs are required to re-condition the surface.

It should be noted that the carbon-carbon composite material starts with similar threshold electric fields as the graphite due to the smooth CVD layer, but roughens with arcing to about half the value characteristically found for



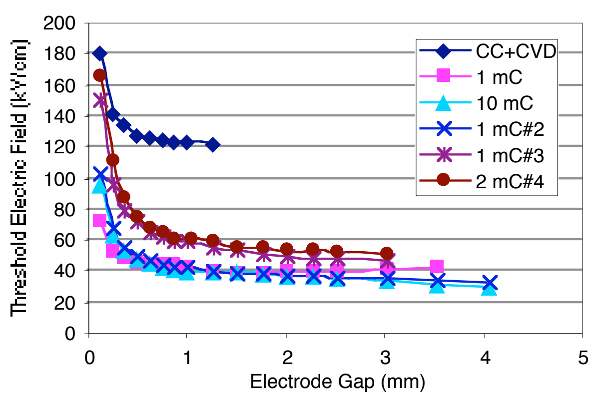


Figure 21. Threshold voltage (left) and electric field (right) versus electrode gap for flat CC material. Charge transfers of 1 mC degrade the threshold electric field to the typical 40-50 kV/cm, but 10 mC arcs can further degrade the surface. Subsequent exposure to 20 arc of 1 mC restores the surface to the nominal case.

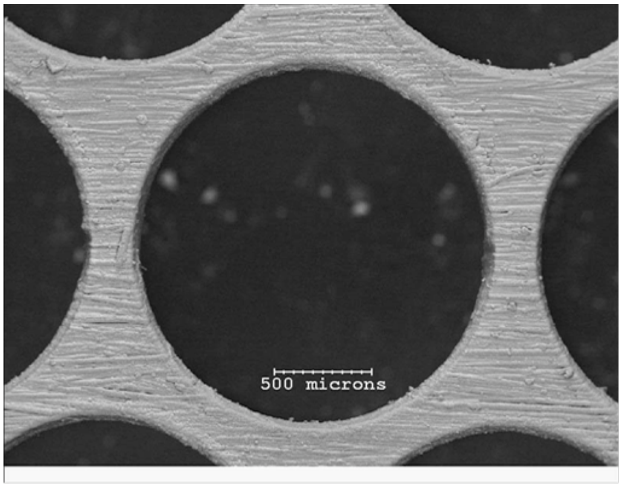


Figure 22. SEM photo of a carbon-carbon composite grid showing the smooth surface texture after the CVD coating.

graphite. This remains true for arcs up to 5 mC, above which the effects of the anode-electrode material blow-back obscure the standoff capability of the cathode surface. For arc of 10 mC or higher, significant damage to the composite surfaces are possible over large areas. However, subsequent arcing at lower charge transfer levels can repair the surface. Based on these results, the Coulomb transfer of ion thruster power supplies should be limited to the order of about 1 mC in order to minimize the damage associated with arcs.

The voltage standoff of grids fabricated from CC materials is similar to the CC flat plate just described. Figure 22 shows one of the CVD coated carbon-carbon composite grid-samples used for these tests. The edges of the laser-drilled holes of this sample tend to be chamfered slightly, and the CVD coating is seen to smooth the edges considerably. However, the CVD process leaves some small protrusions at the edges and particulates on the surface that can be clearly seen in the photo. The voltage hold-off of this grid was only slightly better than that found for the roughened CVD coated carbon-carbon composite surfaces after arcing, or the non-CVD flat surfaces.

Figure 23 shows the threshold voltage and electric field measured for the CC grid material as function of the electrode gap. The threshold electric field of the new material (with apertures) asymptotes to about the same 40 kV/cm field observed for low Coulomb-transfer arcs of flat material, suggesting that the aperture edges function similar to material roughness. Higher Coulomb transfer levels of 10 mC actually improved the voltage hold of slightly, but again due to material from the anode ball covering the grid apertures. These results suggest that carbon-carbon composite grids can be designed utilizing a field emission threshold of about 40 kV/cm, even for large gaps and voltages in excess of 10 kV, provided that the Coulomb transfer is limited by the power supply to less than about 1 mC. This 40-kV/cm field-limit is the highest voltage stress that should be allowed, and conservative design practices suggest somewhat lower fields should be considered.

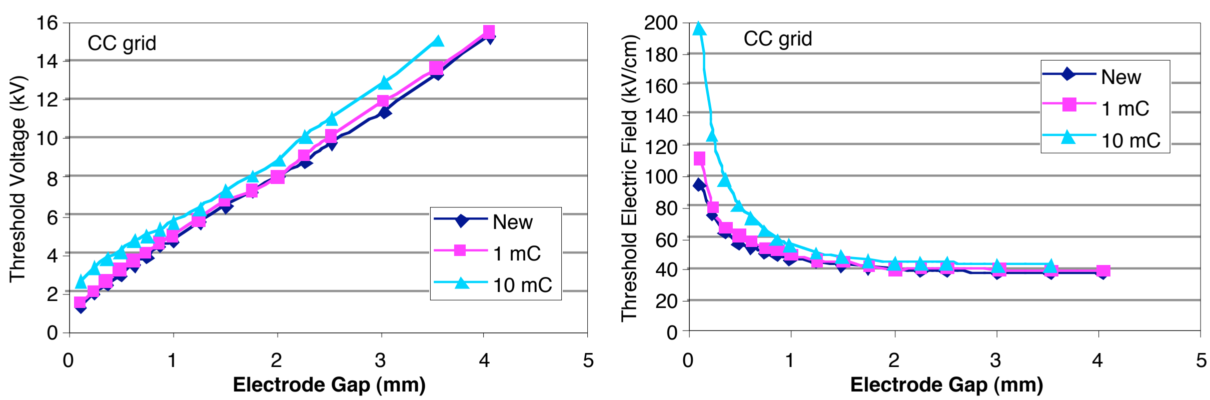


Figure 23. Threshold voltage (left) and electric field (right) versus electrode gap for CC grid material. Charge transfers of 1 mC degrade the threshold electric field to the typical 40-50 kV/cm, but 10 mC arcs can further degrade the surface. Subsequent exposure to 20 arc of 1 mC restores the surface to the nominal case.

3. Pyrolytic Graphite

Pyrolytic graphite (PG) is also a candidate for accelerator grid electrodes in ion sources. This material is configured with the carbon crystal planes normal to the surface. Pyrolytic graphite is grown a layer at a time to near the desired shape on a mandrel and then finished machined to the final configuration. Flat test coupons were fabricated in this manner, but featured small surface bumps and depressions that were residual from the growth process. Figure 24 shows the threshold voltage versus gap for the convex and concave surface structures of the

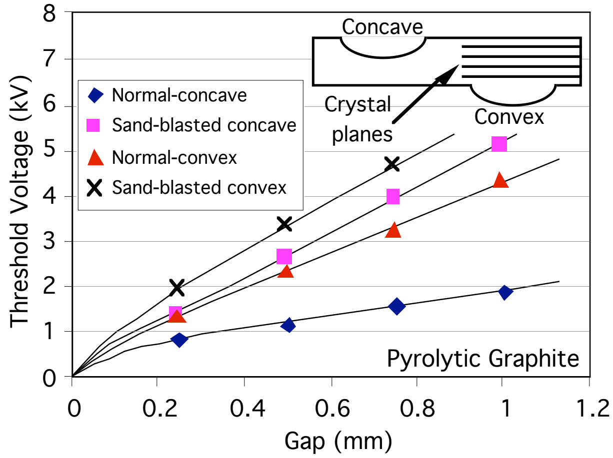


Figure 24. Pyrolytic graphite material threshold voltage versus gap for non-arced material.

pyrolytic surfaces, and the results of mild sand blasting to smooth any sharp edges on the surface. We see that the concave depressions showed higher field emission, probably from the edges of the depressions. Sand-blasting is very effective to grade the edges and improve the voltage hold off of the PG material.

Arcing of the pyrolytic surfaces was found for low-Coulomb-transfer to condition the surface by removing the sharp edges, or at higher Coulomb-transfers to re-expose the edges of crystal planes that are discontinuous on the surface and enhance the field emission. Figure 25 shows the effect of arcing on the threshold voltage and electric field of the flat pyrolytic surfaces for voltage of up to 15 kV and gap spacing of over 4 mm. The two cases of the dimples facing toward (concave) or away (convex) from the anode electrode are shown. Exposure to 10 arcs of 1 or 10 mC charge transfer degrades the threshold electric field to on the order of 40 kV/cm for large gaps in a similar manner as for CC material.

Figure 26 shows the behavior of PG grids that have apertures laser-machined into it and have been lightly sand blasted after laser machining to improve the voltage hold off. The new material demonstrated threshold electric fields of 20 to 30 kV/cm, which is lower than the CC grid material. However, a series of ten 1 mC arcs tend to smooth and condition the surfaces and raise the threshold electric field to over 30 kV/cm. High Coulomb arcs then improve the voltage stand off further to over 40 kV/cm due to the coating of the surface with carbon from the anode ball.

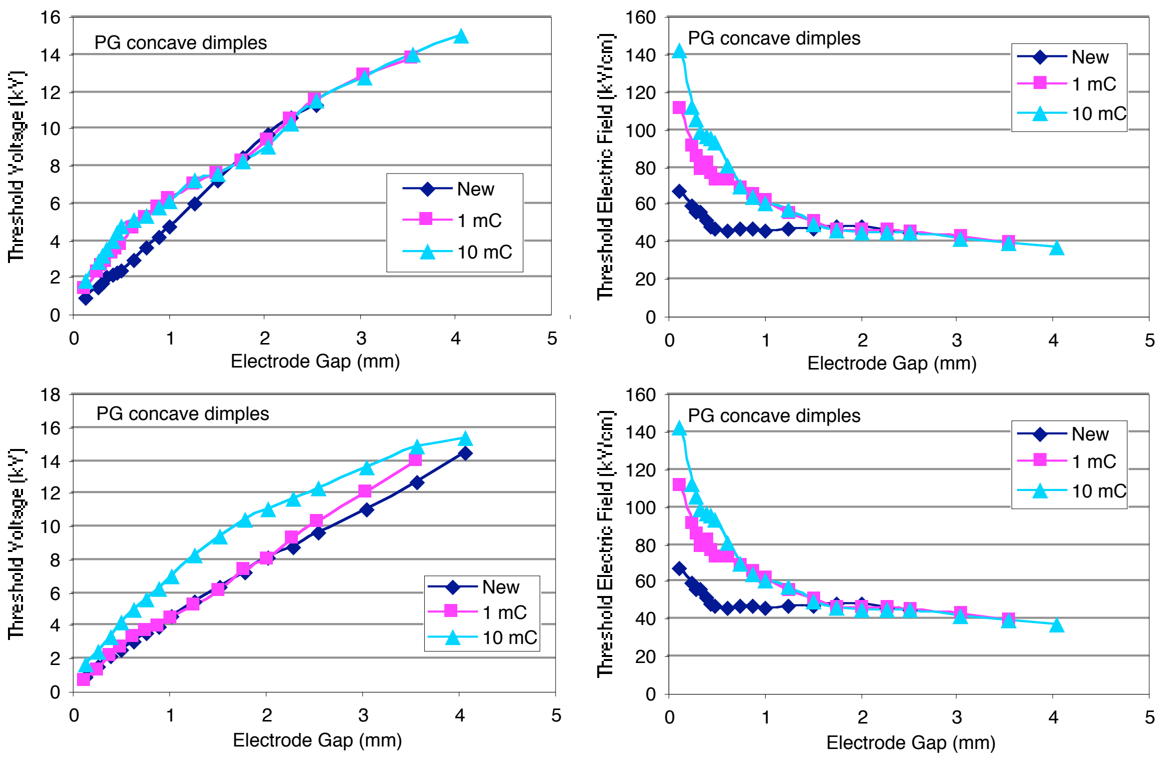


Figure 25. Threshold voltage and electric field for pyrolytic graphite (PG) material for the case of the dimples facing toward (concave) or away (convex) from the anode electrode. Exposure to 10 arcs of 1 or 10 mC charge transfer degrades the voltage hold off in a similar manner as for CC material.

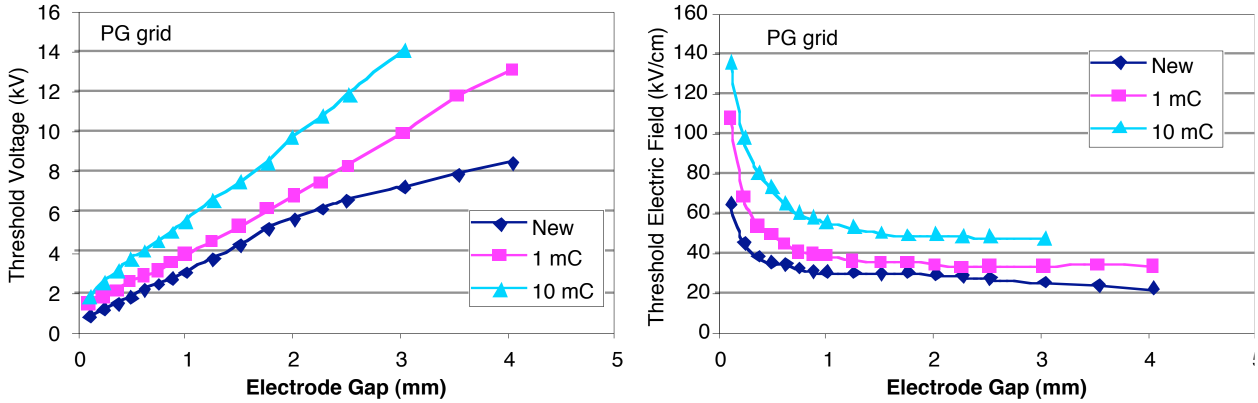


Figure 26. Threshold electric field for pyrolytic graphite with grid apertures and the final surface lightly sand blasted. Arcing at 1 mC tends to condition surface, and arcing at 10 mC coats the surface with carbon from the anode ball and raises the threshold voltage.

Figure 27 shows the SEM photographs of the pyrolytic graphite surface after arcing has occurred. The top photo shows no gross change in the surface after 10 arcs of 1 mC between the arc location in the center of the photo and the as-new surface near the edges. In fact, the surface is generally rough in spite of being machined and polished, and even arced. The pyrolytic surface is composed of planar layers that tend to form mesas because the surface cannot easily be machined and/or polished to a single crystal layer. These plane-edges can be sharp, and contribute to the field emission and lower voltage hold-off than graphite or carbon-carbon composites. The bottom photo in Fig. 27 shows a close up of the pyrolytic surface after a single 2.5 mC arc. Larger Coulomb-transfer arcs can create significant structure and many sharp edged field emission sites. The PG material is susceptible to significant surface damage and reduced voltage hold-off due to arcing, and limits to the amount of Coulomb transfer allowed by thte power supply are desirable. While pyrolytic graphite tended to hold slightly less voltage than the other carbon materials tested, it can be conditioned with low Coulomb-arcs to reasonable voltage hold-off.

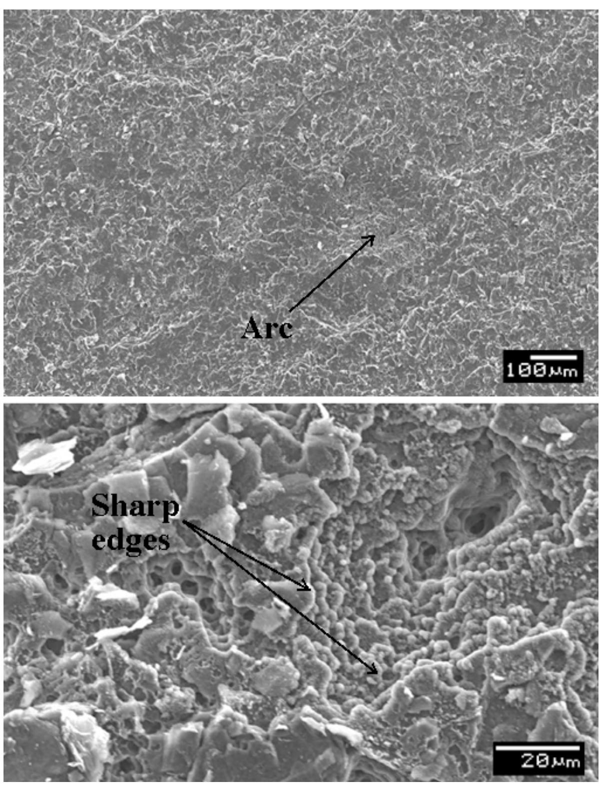


Figure 27. PG material SEM after arcing showing evolution of sharp edges at the ends of the crystal planes that reduce threshold voltage for field emission.

VI. Summary of Test Results

The voltage hold-off of the electrode materials tested depends strongly on the composition and surface structure. It is common to rate the voltage hold-off of materials by their threshold electric field. However, this rating is complicated for electrode materials by the fact that the threshold electric field depends on the gap spacing. However, an idea of the capabilities of the different materials can be found by plotting the measured field at a given gap. The threshold electric field for new material, conditioned surfaces with <0.5 mC arcs, and surfaces that have received 10 arcs of ≥5 mC at a nominal 1/4mm gap is summarized in Fig. 28. Polished copper was tested for reference due to its common use in rf accelerator cavities, and found have a high threshold electric field value in excess of 200 kV/cm like the polished molybdenum samples. The grit-blasted molybdenum and graphite surfaces demonstrated threshold fields of over 100 kV/cm for all the cases tested here. The carbon-carbon composite material with the CVD layer demonstrated excellent threshold fields of over 100 kV/cm, but degraded to near the rough non-CVD surface with about 50 kV/cm due to the arcing. Finally, pyrolytic graphite demonstrated 50 to 80 kV/cm threshold fields depending on the surface preparation and conditioning, but degraded to the order of

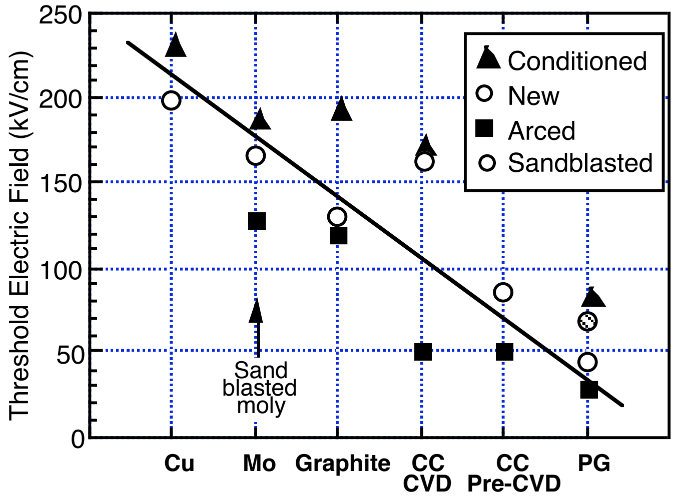


Figure 28. Summary of threshold electric field with a 1/4 mm gap for various materials and conditions of the surface.

30 kV/cm due to arcing at the moderate Coulomb-transfer ratings of 1 to 10 mC per arc.

All of the materials demonstrated the "total voltage effect" power-law dependence of the threshold voltage with gap spacing [20], [6]. The metals tended to have values of the exponent of 0.5 to 0.6, graphite demonstrated a value near 0.9, and the CVD coated composite and pyrolytic materials had a value of the exponent that ranged from 0.68 to 0.76. The non-CVD coated composite had an exponent value of about 0.6, suggesting that roughing the surface of the CVD or pyrolytic with arcing will degrade the voltage hold-off for larger gaps. The higher voltage hold-off of the metals is apparently due primarily to the much larger coefficient multiplying the power-law gap dependence. As the electrode gaps exceeded 1 to 2 mm, the voltage hold-off because more linear and the threshold electric field tended to asymptote to a constant value.

Since most of the new interest in the high voltage behavior of the carbon materials is related to their use for accelerator grids in ion thrusters, we tested the voltage hold-off carbon-carbon and pyrolytic surfaces with arrays of holes machined into the surface. All of the carbon-carbon grid sample breakdowns tended toward the same breakdown behavior before and after arcing as the non-CVD surfaces, in general because the end-state surface roughness leading to field emission was consistent. Only when large pieces of the material were removed or raw fiber edges exposed did the voltage hold-off degrade further. Pyrolytic graphite with grid holes also tended toward the worst case of the non-machined material. It is clear that grid sets fabricated from both of these materials should be designed assuming the "roughened" state, and care should taken with the power supply characteristics to limit the Coulomb transfer and avoid excessively damaging the surfaces.

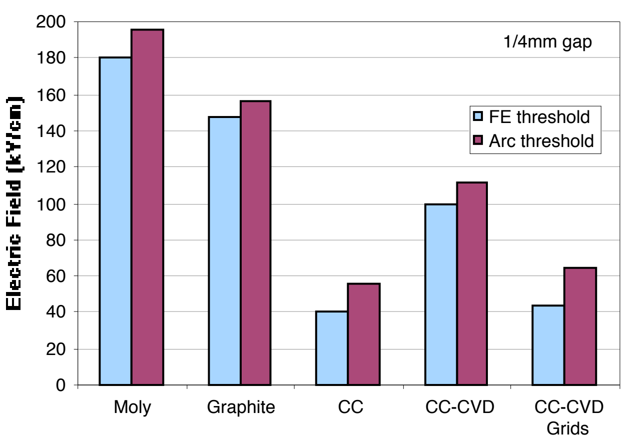


Figure 29. Threshold voltage comparison for field emission and for arc initiation.

Finally, the results presented in this paper are based on threshold voltage and electric field levels characterized by the onset of 1 μA of field emission, and not on the arc initiation voltage. A series of tests were conducted comparing the field emission threshold voltage with the minimum applied voltage required to initiate a full arc breakdown. Figure 29 shows the results of this comparison for the different materials tested. In all cases, the arc initiation voltage was less than 500 V higher than our somewhat arbitrarily defined threshold voltage for field emission. These results are consistent with most high voltage breakdown experiences in that some amount of field emission and even slight corona onset can occur before a high voltage gap will actually breakdown depending on the area of the electrodes. The correlation of the threshold voltage with the arc initiation voltage provides confidence that designing high voltage electrodes based on the results in this paper will produce a conservative design with reasonable margin to breakdown.

VII. Conclusion

A comprehensive investigation of the high voltage characteristics of molybdenum and carbon materials in the range of 1 to 15 kV has been undertaken for applications to ion thruster grids. The effect of arcing on the voltage hold-off of the surfaces was characterized in terms of the total charge transfer through the arc, and not the stored energy in the high voltage supply or the peak current of the arc in the range of 10 to 1000 A. The onset of arcing was observed to condition the surface (improve the voltage hold-off) for low Coulomb-transfer arcs, and roughen the surface (degrading the voltage hold-off) for higher Coulomb-transfer arcs for all the materials tested. This appears to be related to the removal or formation of field emission sites on the surface, which depends on the amount of Coulomb-transfer in the arc.

The performance of the baseline molybdenum material that has been used for thruster grids for the past 40 years actually depends strongly on the surface treatment and arcing history. Polished molybdenum material has excellent voltage standoff characteristics and is relatively resistant to arc damage. Textured molybdenum surfaces normally used in thrusters to retain sputter-deposited materials has poorer voltage hold off characteristics, but still demonstrates threshold electric fields for field emission onset of about 100 kV/cm. This value matches the common design guideline in the industry for electric fields permissible in high voltage devices for surfaces without sharp features. Molybdenum grids with apertures machined into the material showed threshold electric fields for field emission of 70 to 80 kV/cm, again matching the common design guideline value for ion sources, but only for the case of arc current transfers of 10 mC or less. Higher Coulomb transfers degraded this material performance significantly, likely due to damage at the aperture edges that enhances field emission sites.

Graphite electrodes demonstrated thresholds for field emission at electric fields on the order of 150 kV/cm, tend to hold more voltage than the other carbon materials tested, and only degraded in voltage standoff when the Coulomb transfer level exceeded about 5 mC. Carbon-carbon composite materials that have been smoothed by CVD coatings withstand electric fields of over 100 kV/cm, but are roughened and degraded in voltage standoff by arcs with Coulomb transfers of even less than 0.5 mC. Nevertheless, the arced carbon-carbon composites still demonstrate threshold electric fields for breakdown on the order of 40 kV/cm for large gaps in excess of 1 to 2 mm, provided that the Coulomb transfer in the arcs was less than about 1 mC. The flat pyrolytic graphite samples tend to have significant surface structure that leads to field emission sites, but reliably hold field strengths in excess of about 40 kV/cm even after significant arcing. Pyrolytic graphite grids with apertures machined into them hold significantly less voltage than the other carbon-based materials, and demonstrated field emission thresholds of about 30 kV/cm for gaps in excess of 1 to 2 mm.

Acknowledgments

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