Electric Field Breakdown Properties of Materials Used in Ion Optics Systems

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Measurements are presented of the electric field at breakdown for perforated flat plates fabricated from carbon-carbon (CC) composite, Poco graphite, pyrolytic graphite (PG), and molybdenum. The perforated flat plates represent electrodes used in ion sources and ion thrusters and measurements are made with and without ion beamlet extraction through the perforations. A ranking of the materials is presented of their suitability in ion source applications in terms of their electrical breakdown characteristics. For effective use in space missions, materials for ion optics systems must be capable of withstanding moderate electric field stress for long periods of time. In this regard, a simple analysis is presented where thrust density is shown to vary with the square of the electric field. This result suggests that a 50% increase in electric field will result in 125% higher thrust density and a thruster area reduction factor of 0.44. The reduction in thruster area would enable a commiserate decrease in thruster and gimbal specific mass. Experimental data are presented on the field emission onset, electric field enhancement factor, and electrical breakdown properties of the materials listed above as a function of conditioning state, grid spacing, and charge transfer level per arc. Tests results are presented for both beginning of life electrodes and for electrodes that have been heavily worn.

Nomenclature

A_e	=	Effective emitting area
β_{FE}	=	Electric field enhancement factor
β_w	=	Weibull slope parameter
C	=	Capacitance
E	=	Applied Electric Field
E_m	=	Microscopic electric field acting at protrusion tip
f	=	Thrust Density
F	=	Thrust
g	=	Acceleration due to gravity
I_{sp}	=	Specific impulse
J	=	Ion current density
J_{FE}	=	Field emission current
ℓ_g	=	Grid gap spacing
$\dot{m}$	=	Propellant flow rate
m_+	=	Mass of a propellant ion
η	=	Characteristic life
η_u	=	Propellant utilization efficiency

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q	= Elementary charge
Q	= Total charge transferred in an arc
R	= Net-to-total accelerating voltage
t	= Time between arc events
U_e	= Ion thruster beam ion velocity
V_N	= Net accelerating voltage
V_T	= Total accelerating voltage
Φ	= Work function

I. Introduction

A major limitation to increasing the performance of an ion thruster is the maximum permissible electric field in the intra-grid region. Current high specific impulse ion thruster designs utilize relatively low electric fields (~2 kV/mm), which limit the maximum obtainable thrust density and require larger-than-desired thrusters to be built to handle a given amount of power and propellant.

The following simplified analysis shows how thrust density is related to intra-grid electric field strength. First the velocity of a thrust producing ion is related to the specific impulse and the propellant utilization factor by the following expression:

$$U_e = \frac{I_{sp}g}{\eta_u} \quad . \quad (1)$$

The net accelerating voltage is

$$V_N = \frac{m_+ U_e^2}{2q} = \frac{m_+}{2q} \left[\frac{I_{sp}g}{\eta_u} \right]^2 \quad . \quad (2)$$

Next, the total accelerating voltage (V_T) can be defined as:

$$V_T = \frac{V_N}{R} \quad . \quad (3)$$

By specifying the electric field, one can calculate the grid spacing to be

$$\ell_g = \frac{V_T}{E} = \frac{V_N}{ER} \quad . \quad (4)$$

The beam current per unit area can be related to the grid spacing and the total voltage using the following form of the Child-Langmuir equation for space-charge limited current flow:

$$j = \frac{4\epsilon_0}{9} \left(\frac{2q}{m_+} \right)^2 \frac{V_T^{3/2}}{\ell_g^2} = \frac{4\epsilon_0}{9} \left(\frac{2q}{m_+} \right)^{1/2} \frac{E^{3/2}}{\ell_g^{1/2}} \quad . \quad (5)$$

Although we recognize the three-dimensional effects of the geometry on the assumed 1-D behavior modeled in Eq. (5), this assumption allows us to proceed in a relatively straightforward way toward an approximate expression for thrust density.

$$f = \frac{\dot{m} \eta_u U_e}{A} = \frac{j m_+}{q} I_{sp}g \quad . \quad (6)$$

Combining Eqs. (2) and (4) gives

$$\ell_g = \frac{m_+}{2qER} \left[\frac{I_{sp}g}{\eta_u} \right]^2 \quad . \quad (7)$$

Equation (7) shows a direct dependence on m_+/q and I_{sp}^2 and an inverse dependence on E . When Eqs. (5) and (7) are inserted into Eq. (6), one obtains an expression showing how the thrust density is related to the applied electric field between the grids (neglecting 3-D effects):

$$f \approx \frac{\frac{4\epsilon_0}{9} \left(\frac{2q}{m_+}\right)^2 E^{3/2} \frac{m_+}{q} I_{sp} g}{\left[\frac{m_+}{2qER}\right]^{1/2} \left[\frac{I_{sp} g}{\eta_u}\right]} = \frac{8\epsilon_0}{9} E^2 \eta_u \sqrt{R} \quad (8)$$

From Eq. (8), one can see that thrust density is directly dependent on the square of the applied electric field (E), and one can conclude that as the applied electric field between the grids of an ion thruster is doubled the thrust density will quadruple.

Recent experiments have shown that small ion optics assemblies can be made to operate at higher electric fields through proper conditioning of the accelerator electrode using small controlled arcs between the grids that are initiated by over voltaging.^{1,2} One concern is the long term ability of these conditioned ion optics systems to withstand applied voltages in excess of 2 kV and electric fields above 3 kV/mm in an environment where the negatively biased accelerator grid is being bombarded and slowly eroded by a low current density of moderately energetic ions; a condition present during operation of an ion source. To address these concerns, carbon-based materials have been characterized for the applied electric field where breakdown occurs, and these results are compared to data collected with molybdenum electrodes. In addition to breakdown field measurements, Fowler-Nordheim (F-N) analysis of field emission current and applied voltage data was used to determine the electric field enhancement factor due to microscopic surface features, and the product of this factor and measurements of the applied breakdown field (i.e., the enhanced electric field at breakdown) are presented for each material type.

II. Experimental Apparatus

A. Gridlet Testing Facility

Photographs of the sub-scale ion optics (i.e., gridlet) test facility and ion source are shown in Fig. 1. In brief, tests were conducted by mounting an assembly comprised of two gridlet electrodes with seven apertures to a ring-cusp discharge chamber. The screen (positively biased) and accelerator (negatively biased) gridlets were insulated from one another using remote standoff insulators and the apertures in the gridlets were aligned through the use of pins that were passed through precision-placed holes located in each gridlet. The inner diameter of the discharge chamber was much larger than the active diameter of the gridlets to ensure that the discharge chamber plasma properties would be uniform over the entire gridlet ion extraction area, and thereby impose common behavior in all beamlets. The uniform discharge plasma condition allowed division of the measured beam current by the number of apertures to obtain the current per hole or beamlet current. A ground screen was placed between most of the inactive area of the accelerator grid and the beam plasma to limit the collection of beam plasma ions on the inactive regions of the accelerator gridlet surface. The impingement current collected by the accelerator grid was converted to a per hole value by dividing the ammeter reading by the number of active accelerator grid apertures. Both beginning of life (BOL) and highly worn gridlet surfaces were characterized to determine how electric field breakdown characteristics and other arcing-related phenomena change with lifetime.

Fig. 1 High voltage sub-scale ion optics testing facility. Inset shows xenon ion beam being extracted from a 7-hole gridlet.

As an example of the utility of gridlets, consider the following experiment where the beamlet current (ion current per hole) is controlled while the net voltage is increased and the accelerator current is monitored. At high electric fields, the accelerator current would be comprised of both field emitted electrons and charge-exchange ions. The total voltage and accelerator current data allow one to construct F-N plots of the field emission current that flows from the negatively biased accelerator when the assumed constant CEX ion current flowing to the accelerator gridlet is subtracted from the measured current. The F-N plots can then be used to extract the electric field enhancement factor due to protrusions and grid geometry, and to obtain estimates of the protrusion area while ion beamlets are being extracted. When these experiments are performed for different gridlets that have been artificially aged in our accelerated wear test facility, one can obtain insight into how arcing rates and related phenomena vary over life. This type of testing is very difficult to perform on full-scale ion optics assemblies due to the variation of beamlet current across the face of the thruster and the effect that the total voltage has on the ion extraction process.

The arc characterization test facility (shown in Fig. 1 with the ion source installed) has a volume of 0.65 m³ and a base pressure in the mid 10⁻⁷ Torr range. When the ion source is running at typical xenon flow rates, the pressure is 1.2x10⁻⁵ Torr. The facility is equipped with a cryopump to eliminate the concern that an oil-based system would interfere with arcing experiments. The gridlets are ~70 cm away from a graphite target attached to the top of the chamber. The size of the target was chosen based upon numerical simulations, which predict a beam divergence angle of less than 20 degrees for the most severe operating conditions at close grid spacing.

Figure 2 shows photographs of the carbon-carbon screen and accelerator gridlets prior to testing. The dimensions and geometry of the grids were identical for all the materials tested. These gridlets have the same dimensions and geometry as the Nuclear Electric Xenon Ion System (NEXIS) ion thruster full-scale grids (57 cm active beam diameter) developed by the Jet Propulsion Laboratory for ambitious, long duration (~10 years) robotic missions to the outer planets.³

As mentioned above, four types of materials were tested for this study including molybdenum, carbon-carbon composite, pyrolytic graphite, and Poco graphite. The molybdenum material had apertures drilled into the surface using a CNC machine, followed by careful burr removal, rounding of the edges and corners, and grit blasting to provide a surface texture similar to the material used for actual flight thrusters. Poco graphite, often used in vacuum applications, also had apertures drilled into the surface followed by light sanding with fine sand paper. Due to its growth process, the pyrolytic graphite material had slight bumps on one side and depressions on the other. To avoid excessive field emission from the edges of the depressions, the side with the bumps was chosen to face the screen grid. After drilling the holes into the surface, the edges and corners were rounded. No other cleaning or surface preparation (other than blowing air over the surface) was conducted. The carbon-carbon composite material was CVD infiltrated and coated by AllComp to fill any voids and smooth the surface. Unlike the other materials, the apertures in the CC plates were laser drilled. Following this, the soot and debris generated from the laser drilling process was cleaned away using acetone and lint-free wipes.

B. Accelerated Erosion Techniques

An ion beam facility has been developed by CSU to erode sub-scale accelerator grid surfaces in an accelerated fashion where 20-hrs of exposure in some regions produces wear that is equivalent to many 1000s of hours of in-space operation of a thruster. Details of the facility can be found in Martinez.⁴ Photographs of a gridlet subjected to accelerated erosion testing are shown in Fig. 3. The test facility is equipped with a 16-cm diameter ion source that

Fig. 2 NEXIS-style CC gridlets prior to testing.

Fig. 3 Photographs of (a) masked accelerator gridlet and (b) ion beam eroding upstream side of gridlet surface

was used to ion bombard (and sputter erode) accelerator gridlet surfaces either through masks or directly to produce erosion patterns and surface texture similar to what is expected at the upstream entrance of apertures, on the webbing of the downstream face, and within the aperture barrels. Figure 3b contains a photograph of an ion beam striking a gridlet surface that was mounted to a water-cooled target plate. The target plate was rotated to different zenith angles to vary the angle of incidence of the ions on the gridlet and better simulate the erosion that occurs in an actual application. Note that the azimuthal angle of the gridlet surface relative to the target mount was also varied.

An analysis was performed using CSU's ffx numerical simulation program to estimate how fast the upstream surface of a NEXIS accelerator grid will be worn during use in space. Sputtering data from Williams et al.⁵ were used to calculate sputter erosion while estimates of NEXIS total impingement current in space conditions were obtained from Goebel.⁶ These calculations were then used to determine the amount of time the gridlets would need to be exposed in the facility described above. This erosion process was only conducted with the carbon-carbon material and the resulting etch rate in this facility is at least 50 times higher than the erosion rate expected under deep space conditions. It is noted that the accelerated wear testing technique can be used as an alternative to extended ground testing of ion thrusters to investigate certain lifetime issues. This is because accelerated wear processes performed herein are not affected by backsputtering of beam dump materials, which can decrease the sputter erosion of ion optics in ground-based test facilities and therefore mask actual wear rates and surface feature evolution that would occur in space.

A fast exposure technique of directly impinging the upstream surface of the accelerator gridlet surface by operating at very high beamlet currents was also performed (as suggested to the authors by D. Byers, private communication, April 2005). In this case, the operational time was selected to result in the equivalent of 3 years of in-space thruster operation. Typically only a few tens of minutes of operation under direct impingement resulted in adequate erosion. The accelerated wear testing technique was used on a CC grid set designated as #1 while the direct impingement method was used on CC grid set #2. Figure 4 shows a simulation using the ffx numerical modeling code to illustrate the operating condition using the direct impingement method.

Fig. 4 Simulation of direct impingement accelerated erosion method.

C. Arc Suppression Switch System

To avoid unintentional arc damage of sensitive carbon-based gridlet electrodes, the electric-field breakdown tests were performed using arc suppression circuitry that consists of high speed (opening) switches. The circuit diagram of the switch placement in our power supply system is shown in Fig. 5. Operation at total voltages up to 8 kV is possible with significant (>100x) reductions in charge transfer levels over laboratory power supplies equipped with fast arc suppression circuits.

The switch system is capable of limiting the charge transfer in an arc to values as low as 10 μC . The switch was designed to open quickly and minimize the amount of charge it passes for arc control applications. To provide additional charge to an arc between the accel and screen gridlets, we have added a capacitor bank that is placed across the grids and downstream of the switches. The value of the capacitor and the voltage applied between the grids (C in Fig. 5) was used to set the desired charge transfer value (i.e., $Q=CV$ with the assumption that the total charge stored in the capacitor will transfer through an arc). For this

Fig. 5 Circuit used for setting the charge transfer in an arc between the screen and accel gridlets. $C1 \sim 2 \mu\text{F}$. $C2 (\sim 1 \text{ nF})$ is the capacitance of discharge and heater supplies (not shown) relative to ground. C is varied to set the charge transfer at a given total voltage condition (i.e., $Q = CV_T$). No impedance other than the electrical leads themselves was used to limit the peak arc current flowing between the gridlets under test, however, reverse bias diodes (not shown) were placed across C to eliminate ringing.

study the arc transfer level was varied from 0.01 mC to 10 mC. A digital output signal from the switch control card that indicates when an arc occurs was monitored with a data acquisition system to determine the arc frequency, total number of arcs during a test, and related statistical information. Both switches shown in Fig. 5 open simultaneously when an arc event is detected between (a) the screen electrode and ground, (b) the screen and accelerator electrodes, or (c) the accelerator electrode and ground. Care was taken to insure that the trip point of the current sensors was well below the peak current per arc level.

III. Experimental Results

A. Field Emission Evaluation

Field emission is likely the limiting cause of electrical breakdown in high voltage systems at high vacuum for common ion source grid gaps. At high vacuum there are few ionizing collisions within the electrode spacing, therefore, the electrodes instead of the background gas are the primary source of material that can be ionized. The presence of an electric field between two electrodes will result in field emission of electrons from the negative electrode (the accelerator grid) that can impact and heat small areas of the screen grid upon colliding with it, and give rise to evaporation of the screen material or to the liberation of absorbed quantities of gas. An arc can develop in the stream formed of the vapor of liberated or evaporated gas.

Fowler-Nordheim (F-N) data analysis was used to investigate how accelerator grid surface geometry and microscopic features can enhance the applied electric field and lead to arcs. The F-N data presented herein were collected with and without ion beam extraction. In general, surface conditions that result in high electric field enhancement factors are more likely to arc under a given operating condition or begin to arc continuously at a lower electric field. Experiments have been conducted to determine how the field emission characteristics vary with beam extraction, grid spacing, and grid surface conditioning. As a check, the data were also analyzed with regression analysis using Schottky emission and insulation leakage models by plotting the measurements using the appropriate mathematical form of these relations and judging the quality of the straight line plot that was obtained. Although other models occasionally provided a good curve fit, only the F-N model resulted in consistently high correlation coefficients.

Although various modifications to the Fowler-Nordheim model exist, for this study we have used the derivation as presented by Latham in terms of the externally measurable parameters of field emission current (J_{FE}) and total accelerating voltage (V_T):

$$\ln \frac{J_{FE}}{V_T^2} = \ln \left[\frac{1.54 \times 10^{-6} A_e \beta_{FE}^2 10^{4.52} \phi^{-0.5}}{\phi \ell_g^2} \right] - \frac{2.84 \times 10^9 \ell_g \phi^{1.5}}{\beta_{FE}} \frac{1}{V_T} \quad (9)$$

If the current-voltage data is presented in the form of an F-N plot, i.e., $\ln(J_{FE}/V_T^2)$ versus $1/V_T$, a straight line will result (assuming field emission is significant) with a slope of

$$\frac{d(\ln(J_{FE}/V_T^2))}{d(1/V_T)} = - \frac{2.84 \times 10^9 \ell_g \phi^{1.5}}{\beta_{FE}} \quad (10)$$

Thus, from the slope of a F-N plot, one can obtain an approximation of the local electric field caused by surface imperfections and protrusions extending from the ion optics surface by multiplying the field enhancement factor, β_{FE} , by the applied electric field, V_T/ℓ_g . Figure 6 contains a typical F-N plot. The usable field emission region between the arrows is used to obtain the field enhancement factors. No F-N data is used before or after this usable field emission region. The final breakdown field is to the left of the arc initiation point. Manually recorded data is often used to more quickly conduct F-N analysis.

Fig. 6 Typical Fowler-Nordheim (F-N) plot.

Fig. 7 F-N plots with and without beam extraction.

Figure 7 contains a comparison between the F-N curves taken with and without ion beam extraction for a 1.04 mm grid gap condition. Although similar, the curves obtained with beam extraction were always observed to fall just below the curves obtained without beam extraction (when the data without beam extraction was acquired immediately after the data with beam extraction). Some variability in the F-N data was observed, however, and the curve without beam extraction would slowly drop over time for some materials (especially CC and PG). The slope of the curves, and hence the enhancement factors, are similar in Fig. 7 indicating that ion extraction and the presence of CEX ions only has a minor effect on the localized electric field nearby a protrusion. The variability of the F-N data with time suggests that the work function of the accelerator electrode is affected by the presence of xenon on the electrode surface.

There is a perception that arcing is more prevalent when ions are extracted from electrodes. The data in Fig. 7 suggest that this perception is not based on arcing that results from field emission processes. In addition, the effect of CEX ion bombardment of the accel grid does not appear to enhance the amount of field emission current that flows from the accelerator grid to the screen grid for these high electric field operating conditions. As suggested above, the presence of xenon gas and CEX ion bombardment during ion beam extraction may serve to suppress the field emission through adsorption of xenon on the accelerator surface and near surface regions and subsequent modification of the surface properties. Experiments conducted with molybdenum have indicated that upon injection of xenon gas into the ion source, the measured field emission initially increases by 10%, but then drops and levels off at a value that is 10% to 30% below the original field emission value measured prior to gas injection. Similar observations were seen by other researchers when using argon.⁸ When the xenon gas flow is stopped the field emission eventually returns to its original value after several tens of minutes.

It is likely that arcing rates are enhanced by out-gassing that may occur nearby small surface protrusions that are being heated by field emission current. And more out-gassing may occur during ion extraction as a grid set is first operated and heated. The effect of out-gassing (caused during ion extraction) on high arcing rates may be mitigated in our experiments due to baking and arc conditioning. Finally, for the tests described herein, the grid spacing is well controlled (within $\pm 2\%$), but this may not be the case in broad area sources where interfaces exist between structures with different (1) coefficients of thermal expansion, (2) temperatures, and (3) temperature gradients.

Measurements of field emission were made between arc conditioning sequences and typical Fowler-Nordheim plots of these data are

Fig. 8 Typical F-N plots of conditioning process.

shown in Fig. 8. As can be seen, a few hundred 1-mC arcs effectively condition the surface while roughly 1500 arcs are required before little to no change is noted from one conditioning sequence to the next.

Figure 9 gives the variation of the localized electric field enhancement factor (using Eq. 10 with $\phi = 5$ eV) with the number of conditioning arcs at the 0.5 mm grid spacing. It is assumed that the work function remains constant once the conditioning process begins, although surface adsorbates could slightly alter the local surface work function at the beginning of testing prior to initiating any conditioning arcs and just after exposure to the atmosphere. The work function can also be temporarily reduced as it is being wetted by out-gassing products from other components of the ion source, which can result in an apparent change in the enhancement factor (i.e., the sensitivity of the field enhancement factor to the surface work function is 1.5%/%). The number of conditioning arcs is believed to result in a blunting of sharp microscopic surface features (i.e., protrusions) and a reduction of the value of β_{FE} . Early on in the testing (with less than 200 conditioning arcs), the sharp drops seen in Figure 8 are likely due to relatively large protrusions on the surface being vaporized by the conditioning arcs. It is noted that enhancement factors in the thousands have been reported for carbon-based electrodes with unconditioned surfaces.⁹ While factors of 200-300 are common for fully conditioned molybdenum electrodes.¹⁰ An alternative explanation for the large initial enhancement factors is provided by Collazo¹¹ who reported an increased emission current which has been attributed to the presence of adsorbates on carbon nano-scale structures where he proposed that adsorbates could introduce a resonant state enhancing the tunneling probability of electron emission.

High magnification photographs are shown in Fig. 10 of both the downstream side of the screen gridlet and the upstream side of the accelerator gridlet after arc conditioning the gridlets. Craters on the downstream side of the screen grid are likely due to vaporization caused by the high arc energy and the low thermal diffusivity of CC material. In contrast, the upstream side of the accelerator grid was observed to have much smaller diameter craters. One possible mechanism leading to electrical breakdown involves field emission from a protrusion on the accelerator grid that proceeds as a beam to the screen gridlet where it locally heats and possibly vaporizes screen gridlet material or releases adsorbed gases. Some of the evolving vapor becomes ionized by the electron beam. Any ions formed from the gases evolving from the gridlets that strike the accelerator can produce secondary electrons. In this way, the presence of the ions intensifies the electron emission still more, eventually causing breakdown of the gap. To investigate this theory further, upon fully conditioning each grid material, the ground screen was removed to allow viewing of a portion of the grid gap region. Interestingly, not only did all the arcs occur between the grids but about a quarter of the arcs seen were preceded by a slight glowing of a small area of the screen grid – presumably due to electrons emitting from a localized region of the negatively-biased accelerator grid. Only a portion of the grid gap was visible through the port, so it is conceivable that other regions of the screen grid had glowing dots on these surfaces as well, prior to electrical breakdown. It should be noted that the glowing area of the screen grid did not usually correspond to the location of a visible arc. The glowing regions on the screen electrode occurred across the entire surface and often tens of seconds passed before an arc occurred.

Numerical simulations were used to determine if the arc site locations correspond to regions where the highest electric field exists. Figure 11 is an electric field plot at a beamlet current of 1 mA/hole for the BOL NEXIS

Fig. 9 Electric field enhancement factor variation with number of conditioning arcs.

Fig. 10 Microscopic photographs of (a) edge of center hole on downstream side of screen grid and (b) just beyond the active area on the upstream side of the accelerator grid. Each fiber is $\sim 9\mu\text{m}$ in diameter.

geometry at a specific impulse of 7500 seconds using ffx. As expected, the highest electric field conditions on the negatively biased accelerator surface are at the upstream entrance of an aperture, and, although arc initiation sites were observed at the edges of the accelerator apertures, many more arc sites were observed on the accelerator grid webbing and in the regions of the electrode where no apertures existed. The high electric fields near the downstream side of the screen grid holes, as determined by the numerical simulations, correspond to where the largest craters are observed in Fig. 10, but it is noted that arcs from the accelerator grid could be directed through the screen grid hole and into the discharge chamber plasma. In addition, many arc craters were detected on the inactive regions of the screen electrodes.

As mentioned above, after eroding a surface to simulate operation in space, a 3-hr run was initially conducted (at the lowest possible charge transfer value of 0.01mC) prior to beginning the arc conditioning process. Two instances of erratic accelerator current were recorded during our tests:

1) during the first 3-hr run after the upstream side of the accelerator grid was eroded to 24-yr of on-orbit operation (3-yr in the barrel region) and 2) during the first 3-hr run after the accelerator grid was eroded to 48-yr of on-orbit operation (6-yr in barrel region). No accelerator current spikes were observed after performing the fast exposure tests. Figure 12 shows the erratic behavior during the first 3-hr run for Grid Set #1 after being eroded to the equivalent of 48-yr and prior to being conditioned.

Initially the accelerator grid current was relatively high or noted to be gradually increasing at a fixed beamlet current. The spikes in the accelerator grid current did not correlate with arc events or result in an arc in about half of the spike events. It is noted that similar anomalous accelerator current behavior was seen in the NEXIS 2000-hr

Fig. 11 Electric field with ion extraction from ffx simulation results for NEXIS geometry at BOL

Fig. 12 Accelerator grid current during the first 3-hour test after eroding the accelerator grid upstream surface to an equivalent of 48 years. Note the presence of accelerator current noise. Upon initiation of the first set of 100 conditioning arcs at 1-mC, the accelerator current spikes were eliminated and did not return even at higher electric fields values.

wear test just after a cryopump regeneration.³

From Figure 9, one can see that the field emission enhancement factor was very high prior to initiating any 1-mC conditioning arcs implying that very high local electric fields are present on the grid surface at this time. Upon initiating the first 100, 1-mC conditioning arcs, the field emission enhancement factor dropped substantially. In addition, the accelerator grid current was observed to be steady with very little noise ($< \pm 2\%$) after 100 conditioning arcs had been applied.

As mentioned above, the accelerator current variations could be due to the presence of surface adsorbates or evolving gasses that were dissolved or entrapped within the CC matrix during expose to atmospheric gases. The presence of surface contaminants can affect field emission largely through modification of the local surface work function, however, surface impurities can also create nucleation sites for protrusion growth.²⁵ Although the gridlets had been under vacuum ($< 1 \times 10^{-6}$ Torr) for 11 hours prior to the data collection documented in Fig. 12, testing began after just one hour after applying filament heater power. Our experimental results are insufficient to determine if surface contamination is being removed by the 1-mC conditioning arcs or if protrusion blunting is occurring as well. A related explanation for the anomalous accelerator gridlet current could be due to the discharge filament and discharge plasma initially heating the screen gridlet, causing contaminants from the hotter screen gridlet surface to re-adsorb on the initially cooler accelerator grid. Martinez *et. al.*¹ have observed that heating CC gridlets increases the enhancement factor in a transient manner by up to 60% in the first hour of operation.

One interesting finding (see Fig. 13) was observed with pyrolytic graphite when it was tested below the electric field value where continuous breakdown would occur. As shown in Fig. 13, the field emission current for PG would rise over time (~ 30 sec) to a value where an arc would occur. Note that the charge transfer level per arc was set at the 0.01 mC value. The field emission current would be lower immediately following an arc, but would begin to rise again over time.

Fig. 13 Variable field emission behavior commonly observed with PG material at electric fields below the value that causes continuous arcing (i.e., 9.4 kV/mm). Data shown were collected after 600, 1-mC conditioning arcs had been applied.

B. Applied Electric Field Evaluation

Experiments have been conducted to determine how the breakdown electric field and the enhancement factor vary with grid gap and grid surface condition. The electric field breakdown measurements were made by increasing the voltage difference between the accelerator and screen gridlets until continuous arcing occurred. The charge transfer per arc during these tests was limited to 0.01 mC. Although other arcing studies of ion optics materials have defined the electric field breakdown point more conservatively by the onset of a certain field emission current level or after a single arc was observed,¹² it was decided herein to utilize the less conservative continuous arcing field value to avoid outlier bias of the results. Electric field breakdown data were first measured with beam extraction at a moderate beamlet current. Then the xenon flow was turned off along with both the discharge and neutralizer filaments, and once the vacuum pressure dropped to $\sim 1 \times 10^{-6}$ Torr, the electrical breakdown point was re-measured without beam extraction.

Following each conditioning process, electric field

Fig. 14 Breakdown field comparison with and without beam extraction after 3400 and 5400, 0.25 mC conditioning arcs. Note: at 1-mC the values were achieved with an order of magnitude fewer arcs.

breakdown tests were conducted to record the variation in the breakdown voltage as a function of beamlet current, number of conditioning arcs, and grid spacing. Figure 14 contains a plot that compares field breakdown characteristics with and without beam extraction. It should be noted that very similar results were obtained for 1-mC arcs, but approximately an order of magnitude fewer conditioning arcs were required to achieve the same results. Differences in the two methods of obtaining the breakdown value are within 5% for the carbon-based materials and within 10% for molybdenum. It is noted that the insensitivity of the electric field breakdown point to whether ions are extracted or not lends validity to tests performed without beam extraction.

Numerical simulations using the ffx code were conducted to study the effect of increasing the electric field on the relative erosion rate of the upstream surface of the accelerator electrode. As the net voltage is increased, the energy of intra-electrode CEX ions increases causing an increase in the erosion rate of the upstream side and aperture barrel region of the accelerator grid. Increasing the electric field from 2.2 kV/mm to 10 kV/mm resulted in a proportional increase of the accelerator upstream erosion rate by a factor of 5 during the first 20,000 hours of operation. It is noted that the erosion rate of the upstream surface of the accelerator grid is not the limiting factor in accelerator grid lifetime for the NEXIS class thruster, and a 5x increase in this rate does not affect the throughput capability of the ion optics system.

Figures 15 and 16 summarize the effect that the number of 1-mC conditioning arcs has on the applied electric field breakdown strength for grid set #1 and #2. Recall that grid set #1 was eroded using the exposure technique conducted in the accelerated wear test facility, while grid set #2 was eroded using the fast exposure method conducted in our gridlet test facility at high perveance conditions through direct impingement. One can see that the curve for grid set #1 begins to level off after 400 conditioning arcs have been initiated between the grids. Grid set #2 (regardless of whether it was sputtered eroded or not) takes many more arcs to reach the 11 kV/mm mark than grid set #1. General guidelines from ion implanter and neutral beam injector technology indicate that arcing will occur if the electric field is increased above ~10 kV/mm. This result was observed once the CC gridlets have been conditioned properly.

An interesting observation from the plots in Figures 15 and 16 is the fact that despite the significant erosion performed on the upstream side of the accelerator gridlet, with proper conditioning of the grid surface, the BOL maximum breakdown field can still be achieved. It is noted that the 48-yr erosion data shows quite a bit more oscillation than the data for the BOL and 24-yr erosion curves indicating that the significant amount of

Fig. 15 Breakdown field dependency on the number of conditioning arcs using the accelerated wear exposure.

Fig. 16 Breakdown field dependency on the number of conditioning arcs using the direct impingement exposure.

Fig. 17 Maximum electric field for partially to fully conditioned CC gridlets at various grid gaps.

erosion around the upstream side of the accelerator grid is beginning to have a greater effect on the breakdown field for a given number of conditioning arcs. Although, the sputter erosion on the upstream surface of the accelerator

Fig. 18 Threshold electric field for field emission. Note: Unconditioned = prior to initiation of any 1-mC arcs, Conditioned = once the maximum voltage standoff is reached with fully conditioned grid surface, GS = Grid Set, accelerated = exposure in the accelerated wear test facility, direct impingement = exposure using the direct impingement method. Once of field emission = 0.01 mA.

gridlet is much more severe than what is expected to occur in space, we have found that the resulting standoff voltages (and other arcing related behavior are identical to the BOL grid surface once the accelerator gridlet surface has been conditioned with several hundred 1-mC arcs.

The maximum applied electric fields are plotted in Fig. 17 as a function of grid spacing for the CC material. Using the curve fit equation, one obtains a maximum electric field of 11.85 kV/mm for a grid gap of 0.5 mm (4% higher than measured) and ~5 kV/mm (through extrapolation to 2.36 mm spacing) for the NEXIS nominal grid gap. It should be noted that using the enhanced electric field of 5400 kV/mm for CC one obtains a predicted maximum electric field of 4.5 kV/mm (+/- 10%) for the NEXIS nominal grid gap as will be shown in the enhanced electric field section below.

Figure 18 contains field emission current data collected at a grid spacing of 0.5 mm for the carbon-carbon material. The unconditioned cases correspond to the gridlet surface prior to initiating any conditioning arcs at BOL or after the grids were eroded in the accelerated wear testing facility. Fully conditioned corresponds to not only the minimum field emission state of the surface but also to the case where the maximum voltage standoff is

Fig. 19 Plot of field enhancement factor against grid spacing of NEXIS-style CC gridlets.

achieved. As indicated above, the maximum breakdown field for both grid set #1 and #2 is ~ 11 kV/mm. From Figure 18, an applied electric field of 11 kV/mm would be at a relatively high level of field emission. If no (or very little) field emission was desired, then the maximum breakdown field for a 0.5 mm grid gap would be approximately 6.5 kV/mm. As Figs. 15, 16, and 18 clearly indicate, the onset of field emission may begin at a certain electric field value, but the ultimate breakdown field (defined as just prior to continuous arcing) can be significantly higher.

It should be noted that most ion thrusters typically operate at electric fields of 2-3 kV/mm due to field emission and electrical breakdown concerns. Figure 18 shows that through proper conditioning of the ion thruster grids using small controlled arcs at a level of ~ 1 mC/arc, future ion thrusters could potentially be operated at much higher electric fields and correspondingly higher thrust densities.

C. Enhanced Electric Field Evaluation

The electric field enhancement factors are plotted in Fig. 19 as a function of grid spacing for the CC material. The trend of increasing enhancement factor with grid spacing follows the trend observed by others^{8, 13-15}, however, one important difference is that most published work shows the enhancement factor leveling off between 1 and 2 mm grid spacing. This difference could be due to the fact that published work has focused on solid flat and solid spherical electrodes whereas we are using flat electrodes with holes. It should be noted that due to the voltage limitation of the arc suppression switch, the grids could not be re-conditioned at the largest grid gap conditions. The variation of the enhancement factor with grid spacing is likely due to enhancement of the electric field at small protrusions on the surface of the accelerator grid that is further enhanced by the presence of geometrical features. The alternate possibility of localized areas with different work functions is unlikely, since this is not expected to be gap dependent. The variation of the enhancement factor with grid gap can be interpreted in terms of the combined effects of an enhancement, β_{FE1} , due to microscopic protrusions on the accel grid, and a local enhancement, β_{FE2} , associated with macroscopic changes in the electric field distribution at larger gap spacing due to fringing around hole and edge features, where the overall enhancement is the product of these factors. Thus at larger grid gaps, fringing effects may become more significant at influencing the overall enhancement factor while the microstructure at the accelerator grid surface most likely remains unchanged. Analysis reported by Alpert¹³ using a model of a pair of semi-infinite slab electrodes with rounded corners, indicate that when the gap spacing becomes large compared to the radius of curvature at the edges of the electrodes, the enhancement factor β_{FE2} may become appreciable. The fact that the gridlets used in this study did not have rounded corners could also partially explain the lack of a saturation point in the enhancement factor at the largest grid gaps. It should be noted, that arc marks were also seen just beyond the edges of the 7.5-cm x 7.5-cm gridlet area on the grid assembly mount. When the local curvature differs from the main surface area (such as at the edges) this can cause local variations in the electric field and compression of the equipotentials nearby. The distortion also leads to a divergence of the lines of force, and is equivalent to a lens effect, resulting in higher local magnification. Byers¹⁶ experimentally showed that rounded edges when compared to square edges do provide larger breakdown fields between electrodes containing holes.

Due to equipment constraints, plots such as the one shown in Fig. 19 could not be made for every grid spacing tested. The maximum voltage of the arc suppression switch power supply is 8 kV, which is less than the voltage required to cause breakdown for grid spacing beyond 1.04 mm after just a few hundred conditioning arcs are applied. Once the grids were fully conditioned at the 0.5 mm grid spacing, the grid assembly was removed from the chamber and the grid gap was manually changed using shims of known thickness. Once the gap was reset, the assembly was reattached to the ion source inside the vacuum chamber and left at vacuum for 6 hours. The discharge and neutralizer filaments were also on for several hours to heat the grids and assist with out-gassing.

The enhanced electrical-breakdown field (or microscopic field) at the accelerator grid surface is determined by multiplying the enhancement factor by the applied electric field (i.e., $E_m = \beta_{FE} V_T / \ell_g$), and Fig. 20 contains a plot of the enhanced electric field versus electrode separation. Although there is considerable scatter in the data, Fig. 20 suggests that the enhanced electric field is relatively independent of the grid gap as expected. The enhanced electric field value at breakdown will vary from one material to another, and can be dependent upon surface treatment. Similar electric field breakdown work conducted on other types of electrode materials has shown a similar constant enhanced electric field breakdown trend over many orders of magnitude in gap spacing.^{13-14, 17}

An important consequence of Fig. 20 is that the value of the breakdown voltage is directly related to, and predictable from, the observed characteristics of the pre-discharge field emission currents and knowledge of the material dependent enhanced electric field breakdown value. The average value of the enhanced electric field at breakdown from Figure 20 (shown by the black line across the plot) is 5400 kV/mm. This enhanced electric field value lies within values measured for a variety of electrode materials, which range from 4,000 to 11,000 kV/mm for fully conditioned electrodes.¹⁸ Dividing this value by the measured enhancement factor at a given grid gap will result in an approximation of the maximum applied electric field possible with fully conditioned ion optics. For example, using the average enhanced electric field of 5400 kV/mm and dividing by the average enhancement factor of 420 for the 0.5 mm grid gap, one gets a maximum applied electric field of 12.8 kV/mm for CC gridlet material. As was shown above, this prediction of the electric field is within 10% of the maximum electric field at breakdown measured for fully conditioned grids at this grid gap. Due to the scatter in the Fig. 19 data at the highest grid gaps it is difficult to estimate what the breakdown field would be at the nominal NEXIS thruster grid gap of 2.36 mm. But a rough approximation of the breakdown field is estimated to be 4.5 kV/mm for fully conditioned grids. Our total voltage limitation of 8 kV resulted in a maximum applied electric field of 3.3 kV/mm at this grid gap and no indication of arcing was observed. Interestingly, other research has shown that the enhanced electric field strength is nearly constant regardless of the electrode area.²⁰

Fig. 20 Enhanced breakdown field versus gap spacing. For each point, the breakdown field is the product of the breakdown voltage and the enhancement factor, determined from Fig. 19.

D. Weibull Statistical Analysis

In 1939, Waloddi Weibull developed a method for statistically evaluating the fracture strength of materials based upon small population sizes.²¹⁻²² This method, now called Weibull analysis, can be used to make predictions about the life of a product, compare the reliability of competing product designs, statistically establish warranty policies or proactively manage spare parts inventories. In academia, Weibull (also referred to as log-normal) analysis has been used to model such diverse phenomena as the length of labor strikes, AIDS mortality, and earthquake probabilities. The Weibull distribution has the great advantage in reliability work in that through adjustment of the distribution parameters, it can be made to fit many life distributions. The major use for the Weibull distribution is as a time-to-failure model since by proper choice of its parameters it can represent the lifetime characteristics of a wide diversity of equipment. Many researchers attribute the success of Weibull analysis to its ability to identify the weakest link in complicated systems. In the case of ion propulsion, Weibull analysis can be used to characterize the mean period between arcs that occur within ion optics assemblies as a function of operating condition and geometrical configuration. The primary advantage of this analysis technique is its ability to provide arc period characteristics with extremely small sample size (i.e., the attainment of accurate arc rate data at low arc rate conditions in a few hours is possible). In addition to providing statistically correct estimations of the mean arc period, Weibull analysis provides a simple graphical form for presentation of data that allows one to easily distinguish between different populations. In other words, Weibull plots are useful for graphically demonstrating if one grid surface is better than another in terms of arcing rate or if a grid surface is degrading due to sputter erosion processes for example. In our Weibull plots, the horizontal scale is the time between two successive arc events and the vertical scale is the cumulative distribution function (CDF), describing the chance that an arc will occur after a given amount of time. The characteristic arc period is defined as the amount of time where 63.2% of the arcs in a given population will have occurred. The characteristic life (a.k.a., the B63.2 life) can be determined on the plots by noting the intersection of the data trend line with the horizontal dashed line drawn at $y=63.2\%$. The characteristic life is equivalent to the arc period in our implementation of the analysis method.

The 2-parameter Weibull distribution function was used to fit the arc period measurements, i.e.,

$$f(t) = \left(\frac{\beta_w}{\eta} \right) \left(\frac{t}{\eta} \right)^{(\beta_w-1)} \exp \left(- \left(\frac{t}{\eta} \right)^{\beta_w} \right) \quad (11)$$

In traditional Weibull analysis, the value of β_w is used to determine whether the failure rate is increasing ($\beta_w > 1$), constant ($\beta_w = 1$), or decreasing ($\beta_w < 1$). A value of $\beta_w < 1$ was observed in all our data sets examined to date. This scenario is typical of “infant mortality” in product failure studies, but in our study $\beta_w < 1$ indicates that either (a) the grids are arcing more in a “burn-in” period at the beginning of a test or (b) the grid arcs are occurring in clusters where one arc affects the probability of a follow-on arc. Both types of behavior have been observed, and sometimes they exist within the same data set.

Our approach was to characterize the electrical breakdown behavior (i.e., record the time of each arc event over a preset period of time) using the lowest arc charge transfer setting of our power supply system (~ 0.01 mC) after conditioning the accelerator gridlet with a number of arcs at a higher arc charge transfer setting that was set using a capacitor connected between the screen and accelerator gridlets. The time of an arc event was monitored using a time stamp resolution of 0.5 sec, and consequently, the minimum resolution of an arc period measurement was ~ 1 sec. For analysis purposes, the arc events that occurred in a particular test were ranked from the shortest period between two arcs to the longest period between two arcs, and then plotted on

Fig. 21 Typical Weibull plot obtained with beam extraction. As the electric is increased the data curve moves to the left indicating more frequent arcing. Note that each data set was obtained during 3-hr runs.

Fig. 22 Variation in number of conditioning arcs to reach a certain characteristic life for charge transfer values of 0.25 and 1.0 mC. Note: each data point was taken over a 3-hr run at $E = 7.41$ kV/mm.

Fig. 23 Arc period variation with number of conditioning arcs for two similar gridlets that were at BOL condition. Note that each data point was taken over a 3-hr run.

Weibull probability graph paper. Figure 21 contains a typical Weibull plot obtained at 5.48 kV/mm for the CC gridlets. Significant decreases in average time between arcs are observed when increasing the electric field. For example, at 4 kV/mm the mean arc period was approximately 400 s while Fig. 21 indicates 62 s for 5.5 kV/mm. The shape parameter (β_w) for all the carbon-based materials varied from 0.6 to 0.7 while molybdenum displayed a β_w value of 0.8.

Dozens of Weibull plots were recorded for various values of arc charge transfer levels and number of conditioning arcs. Figure 22 summarizes the differences between 0.25 mC and 1.0 mC conditioning arcs for C-C gridlets. As can be seen, for the same order of magnitude increase in the mean time between arcs, an order of magnitude fewer conditioning arcs are needed at 1 mC compared to the number needed at 0.25 mC. We did not investigate charge transfer values above 1 mC because significant arc damage occurs at levels higher than 1 mC as identified by Goebel¹².

As discussed earlier, one set of CC gridlets (Grid Set #1) was exposed in the accelerated wear test facility, and a second set of CC gridlets (Grid Set #2) was subjected to a fast exposure erosion technique. Both sets were conditioned using small controlled arcs at a level of 1-mC per arc. At various intervals in the conditioning process, 3-hr runs were conducted at an electric field of 7.81 kV/mm with a grid gap of 0.5 mm. These timed runs were used to generate Weibull plots identical to the ones shown above to determine the characteristic life (or mean time between arc events). This procedure was performed for the BOL grid surface and after each exposure was conducted. The variation in the characteristic life gives an indication of how well the surface is being conditioned along with providing a comparison of the surface quality of one grid set to the other. A summary of the measured characteristic life for each surface condition is summarized in Fig. 23. Grid Set #1 at BOL was noticeably different from grid set #2, which took much longer to condition to a high breakdown field (see Fig. 23). We believe that

Fig. 24 Electric field enhancement factor variation with number of 1-mC conditioning arcs.

Fig. 25 Breakdown field dependency on the number of 1-mC conditioning arcs. Grid spacing = 0.5 mm.

some of the differences are due to processing. Although grid set #2 was baked in vacuum to 900 C, it was left exposed to air for ~2 weeks prior to testing. Grid set #1 was not baked, however, it was placed within the vacuum test facility for a longer period of time prior to conditioning.

The effect of vacuum chamber pressure also affects the frequency of breakdown. Both Kaufman²³ and Kerslake²⁴ have reported that pressures below $\sim 10^{-6}$ Torr give a mean interval between breakdowns in ground tests of mercury thrusters that matches the rates found in space tested thrusters. Pressures above this range increase the arc frequency (or equivalently decrease the arc period). As noted earlier, the chamber pressure in this study was 1.2×10^{-5} Torr. It is therefore likely that in space, the mean time between arc events in the Weibull plots shown above would be higher.

IV. Summary of Experimental Results

Figure 24 gives the variation of the localized electric field enhancement factor with the number of conditioning arcs at the 0.5 mm grid spacing for all of the materials tested. The data are for the BOL grid surface for each

material. As can be seen from Fig. 23, CVD coated carbon-carbon composite material had an enhancement factor for its conditioned state very similar to pyrolytic graphite after initiating 1200, 1-mC arcs between the grids. The large initial enhancement factors for the carbon composite material could be due to loose fibers from the laser beam aperture drilling processes. Work functions of 5 eV were assumed for the carbon-based materials and 4.6 eV for the molybdenum material. The grit blasted molybdenum consistently had the lowest enhancement factors, reaching a low of 153 which agrees very well with other experiments on well conditioned molybdenum materials.^{9, 20, 27}

Electric field breakdown data as a function of the number of conditioning arcs were first taken with beam extraction at a moderate beamlet current followed by testing when no beam extraction was used. It was observed that the breakdown point did not vary much with presence or absence of beam current. Interestingly enough, the breakdown data for the carbon-based material only varied by at most 5% when comparing the results taken with and without beam extraction while the molybdenum material usually had a breakdown value without beam extraction that was usually 10% below the value with beam extraction (when measurements without beam extraction were taken shortly after ion beam termination). A summary of the breakdown field as a function of applied conditioning arcs (at 1-mC/arc) for all the materials is shown in Fig. 25. Poco graphite and molybdenum were found to sustain the highest electric fields while carbon-carbon composite and pyrolytic graphite displayed lower electric field values at breakdown. It should be noted that an additional 200 arcs at the 10 mC level were applied to the pyrolytic graphite and molybdenum beyond the 2000 1-mC arcs and no further increase in the breakdown field was observed.

An investigation was also conducted to determine the effect that active grid area has on the breakdown field. This test was conducted using two sets of Poco graphite 7.5 cm by 7.5 cm gridlets that were spaced at 0.5 mm. One set had 7 holes and the other had 19 holes. The results are also shown in Fig. 25. As expected, the additional holes act as additional field emission sites resulting in a lower breakdown field compared to the material with fewer holes. But upon application of additional conditioning arcs, the 19-hole grid set was able to achieve the same breakdown field as the 7-hole grid set. Figure 26 shows a summary of the threshold and breakdown fields for the 7-hole and 19-hole Poco grids. The threshold field was defined as the point where the field emission current rose above 1.0 μA . As can be seen, the 19-hole grids have lower threshold electric fields for both the conditioned and unconditioned states but the final breakdown fields are approximately equal. Future tests should involve larger grid areas with many more holes to determine if this trend continues.

As indicated earlier, the enhanced (or microscopic) breakdown field for carbon-carbon composite, after displaying some initial fluctuations for the unconditioned state, was found to be 5,400 kV/mm independent of grid gap. Unfortunately, only one grid gap was tested for the pyrolytic graphite, Poco graphite, and molybdenum (in contrast to the gaps of 0.5 mm to 2.7 mm tested for CC). Therefore, a high level of uncertainty exists in the enhanced breakdown field data for these materials (i.e.,

Fig. 26 Threshold field comparison for field emission and continuous arcing for 7 and 19 hole Poco grids. Onset field emission = 0.001 mA.

Fig. 27 Comparison of enhanced electric field breakdown data for carbon-carbon (CC), pyrolytic graphite (PG), Molybdenum, and Poco graphite.

± 1000 kV/mm). A summary of the measured enhanced electric field breakdown values for the conditioned materials is presented in Fig. 27. Poco graphite and CC were found to be similar at ~ 5000 kV/mm, while pyrolytic graphite and molybdenum were found to be lower at ~ 3000 kV/mm. It is noted, however, that the enhanced breakdown field for PG was observed to increase to ~ 4200 kV/mm in the presence of xenon and when ions are extracted.

Published data on the enhanced breakdown field for molybdenum is typically 5000 kV/mm (± 1000 kV/mm).^{10,18,26-27} The molybdenum material used in our study, however, was grit blasted to match the surface texture of the molybdenum material used in typical ion thrusters, and this could have lowered the enhanced breakdown field compared to published experimental data. In addition, studies have found that high voltage breakdown experiments are affected when molybdenum electrodes are exposed to the evaporation products of heated dispenser cathodes and thoria-coated tungsten filaments. These evaporated films tend to reduce the enhanced breakdown field down to 1000 kV/mm in the case of the 4:1:1 barium oxide dispenser cathode and down to 3700 kV/mm in the case of a tungsten filament.²⁶ In addition, field emission continuously increased with longer exposure to the evaporated products of the 4:1:1 cathode. This is interesting as 4:1:1 dispenser cathodes are typically used in ion thrusters. It is noted in this regard that 2% thoriated-tungsten filaments were used for both the discharge and neutralizer filaments in our ion source.

Figure 28 summarizes the overall findings of this study. As expected, unconditioned electrodes were found to display lower field emission onset and breakdown electric fields. Both onset and breakdown improvements of $\sim 2\times$ were observed after small controlled arcs were applied. Carbon-carbon was observed to be similar to or slightly better than PG after the conditioning process was completed. Both molybdenum and Poco graphite were found to be 1.5x to 2x higher in onset and breakdown electric fields both before and after conditioning compared to CC and PG. In addition, data taken by Goebel¹⁹ at JPL are shown in Fig. 28 with the same criteria for the threshold for field emission (1 μ A). It should be noted that the materials used in Goebel's study had slightly different surface conditions. Specifically, the carbon-carbon composite material used in our study did not receive the final CVD coating after the laser beam drilling process. This missing process step is the likely cause of the lower CSU threshold values shown in Fig. 28. The pyrolytic graphite used by Goebel was lightly sand blasted to smooth any edges in addition to having the holes laser drilled.

Fig. 28 Bar graph comparing threshold electric field for field emission and electric field breakdown data for carbon-carbon (CC), pyrolytic graphite (PG), Molybdenum, and Poco graphite. Onset field emission = 0.001 mA.

Fig. 29 F-N plots for all the materials tested in this study at their fully conditioned state.

Neither procedure was conducted for the pyrolytic graphite gridlets used in this study, but the threshold values are still relatively similar. The largest differences occurred for the molybdenum and Poco materials. Likely reasons for differences include (1) the use of a ball and plate setup in Goebel's work that eliminate edge effects, (2) the use of laser-drilled apertures in Goebel's molybdenum work that result in surface features that are dissimilar to apertures drilled using a CNC machine in the current work and (3) Goebel did not drill apertures into the Poco graphite material he tested. It is noted, however, that the final breakdown fields for molybdenum and Poco were similar to Goebel's conditioned threshold results, which were ~ 1000 V/mm lower than his field breakdown values.

Figure 29 contains F-N plots for all the materials tested in this study at their fully conditioned state. Both pyrolytic graphite and carbon-carbon had significantly higher levels of field emission compared to molybdenum. The large range in field emission for pyrolytic graphite (PG) is typical at all states of its surface condition. It is not known at this time why Pyrolytic graphite has such a large range in field emission output. The cause for the large variation between carbon-carbon (CC) grid sets #1 and #2 is also identified as an unknown. In this regard, it is noted that grid set #2 took many more conditioning arcs before it was able to achieve the same breakdown field as grid set #1, and this level of arc conditioning may have improved the surface of grid set #2.

V. Conclusion

A fundamental limit to increased perveance in ion thrusters is the maximum intra-grid electric field. This paper has presented an investigation of the electric field breakdown characteristics of carbon-based and molybdenum ion optics in the total voltage range of 1 to 8 kV. Our results show that with proper conditioning using small, controlled arcs, operation at electric fields up to ~ 11.5 kV/mm for carbon-carbon, ~ 10 kV/mm for pyrolytic graphite, 14 kV/mm for Poco graphite, and 15.5 kV/mm for molybdenum (all at a grid gap of 0.5 mm) can be achieved if one is willing to permit relatively high arcing rates. Intra-grid arc conditioning at charge transfer values per arc of 0.25 and 1.0 mC allowed for larger voltage standoff capability presumably due to the removal of microscopic, field-emitting protrusions from the surface of the accelerator grid.

The act of extracting ions through apertures in the electrodes was not found to significantly affect the electric field breakdown behavior. Furthermore, when ions were extracted, the field enhancement factor measured from F-N plots decreased $\sim 15\%$ from a value measured without beam extraction. An interesting observation seen with all the carbon-based materials is that although field emission data would initially be very similar with and without beam extraction (within 5% if taken within 10 minutes of ion beam termination), the field emission would steadily drop as the xenon gas was pumped from the chamber (sometimes to values that are only 5% of the beam extraction field emission levels). A corresponding increase in the breakdown field of $\sim 15\%$ and a decrease in the field enhancement factor of $\sim 30\%$ were regularly recorded for pyrolytic graphite after the ion beam and xenon neutral flow had been off for several hours. This result indicated that the neutral xenon gas has an effect on field emission that is not eliminated until the gas has completely been pumped out of the system and desorbed from the accelerator electrode surface. In contrast to the carbon-based materials, molybdenum showed the opposite effect (i.e., field emission decreased with the presence of xenon gas). In this case, we believe that xenon may suppress field emission by modifying the effective work function of the molybdenum electrode surface to higher values.

Electrical breakdown is a random process and Weibull statistical analysis was used to show that with an increasing amount of conditioning arcs, the time between arc events greatly increased at a given electric field condition. The Weibull shape parameter was found to be 0.7 to 0.8 for all of the carbon based materials and 0.9 for molybdenum, which suggested that burn-in and follow-on arcing processes are important.

A study of the effects of sputter erosion was also conducted to determine how the field emission and electric breakdown characteristics would change throughout life. Two grid sets were tested and eroded using two different, accelerated wear techniques. Each erosion process was conducted after full characterization tests were completed and after conditioning the grid surface with 1-mC conditioning arcs. The eroded surfaces returned to pre-conditioned performance levels (i.e., the breakdown field, field emission, and arc rate characteristics returned to their original pre-conditioned values), but the surfaces could be re-conditioned relatively easily. The electric field enhancement factor was observed to reach a steady state value after conditioning arcs were applied, and it is concluded that the saturation of the enhancement factor caused the electric field breakdown point to saturate. Although not confirmed during our short term tests, prolonged operation will probably result in degradation of the electric field breakdown strength due to the upstream accelerator grid surface being sputtered and texturized by energetic ion bombardment.

A method to predict the maximum applied breakdown field for a conditioned grid geometry and material was described and validated that uses measurements of the localized electric field at breakdown and the field enhancement factor. Calculations of the maximum applied electric field using this method were found to be within

10-15% of measured values. Properly conditioned NEXIS gridlets fabricated from carbon-carbon materials are estimated to operate at fields up to 4.5 kV/mm at the NEXIS nominal spacing of 2.36 mm. By simply extrapolating breakdown field data (taken for grid gaps of 0.5 mm to 1.78 mm), a maximum electric field of 5 kV/mm is expected at the a spacing of 2.36 mm, which compares well with the calculated value. Finally, although spikes and anomalous excursions in the accelerator current were observed after aging the upstream side of the carbon-carbon grid, this behavior was eliminated upon initiating a few conditioning arcs.

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