Electric Field Breakdown Characteristics of Carbon-based Ion Optics

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Ion thrusters are being designed for long-term operation at power, specific impulse, and thrust levels of up to 29 kW, 7000 seconds, and 0.64 N, respectively. The total propellant throughput goal of these thrusters is nearly 100 kg/kW, which corresponds to ~100 khr of operation. Carbon-based grids have been chosen as the baseline design to achieve this propellant throughput and life time goal. One concern is the long term ability of an ion optics system comprised of advanced carbon-based material to withstand applied voltages in excess of 5 kV and electric fields up to 2.3 kV/mm. In recent testing, anomalous accelerator current behavior has occurred in full-sized, carbon-based ion optics systems. To address these concerns, sub-scale ion optics assemblies (i.e., gridlets) are used herein to evaluate the electric field breakdown and field emission characteristics of carbon-carbon (CC) composite and graphite materials. Arc characterization data have been collected over electric field values from 1.5 kV/mm to 11.4 kV/mm and for grid gaps ranging from 0.5 mm to 2.7 mm. Test results are presented for the mean period between arcing events for various operating voltages and applied electric fields for both beginning of life (BOL) and heavily worn gridlets. Wear of the gridlets was performed in an accelerated fashion that simulates the wear expected when ion optics systems are operated in space. Investigations to date correspond to simulated in-space operation of 3 to 6 years on some surfaces and 24 to 48 years on other surfaces. In addition to statistical data on arcing rates, measurements are presented of field emission and electric field-breakdown strength made with and without ion beamlet extraction. In general, the arcing characteristics of the CC gridlets were found to be very sensitive to the charge transferred in an arc and the number of conditioning arcs that were applied. A specially designed power supply system is discussed that was used to control the total coulomb transfer in an arc event from 0.01 mC to 1 mC. Gridlet test results indicate that electrode wear has a minimal effect on the field emission and voltage standoff capability of the gridlets once the electrode surfaces were conditioned with a series of controlled arcs. Conditioning to ~700 mC (at sub-millicoulomb increments) was found to be adequate for 7.5-cm x 7.5-cm gridlets to completely eliminate anomalous accelerator currents and return the field emission and electric breakdown-field strength to levels measured at BOL. A method to predict the maximum applied breakdown field for arbitrary grid geometry is 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 10-15% of measured values. Properly conditioned NEXIS grids fabricated from carbon-carbon materials are predicted to operate at fields up to 4 kV/mm ±15% at nominal spacing.

Nomenclature

\[ \begin{align*}
\Lambda_e & = \text{Effective emitting area} \\
\ell_g & = \text{Grid spacing} \\
C & = \text{Capacitance} \\
E & = \text{Electric field}
\end{align*} \]

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$E_m$ = Microscopic electric field acting at protrusion tip
$J_B$ = Beam current
$J_{FE}$ = Field emission current
$Q$ = Total charge transferred in an arc
$t$ = Time between arc events
$V_T$ = Total applied voltage
$\beta_{FE}$ = Electric field enhancement factor
$\beta_w$ = Weibull slope parameter
$\Phi$ = Work function
$\eta$ = Characteristic life

I. Introduction

The successful demonstration of the NASA Solar Electric Propulsion Technology Applications Readiness (NSTAR) ion engine on NASA’s Deep Space 1 spacecraft and the Extended Life Test (ELT) of the NSTAR flight spare has spurred interest in ion propulsion for more demanding missions requiring $\Delta V$s ranging from 40 to over 100 km/s. The most demanding missions would require power levels of 10’s of kW, specific impulses of 6000-8000 seconds, and operational lifetimes as high as 10 years. The Nuclear Electric Xenon Ion System (NEXIS) ion thruster is being designed by the Jet Propulsion Laboratory for ambitious missions at a power level approaching 25 kW, a specific impulse of 7500 seconds, and a propellant throughput of 100 kg of xenon per 1 kW of thruster power. The NEXIS ion optics design utilizes carbon-carbon (CC) composite grids. Carbon-carbon ion optics are very attractive for high specific impulse, long duration missions because of their very low sputter erosion rates compared to molybdenum, which has been used on the majority of ion thrusters to date. In this regard, it is noted that the service life of the NSTAR ion thruster at full power was limited by erosion of the molybdenum accelerator grid. The successful development of carbon-carbon ion optics could potentially eliminate accelerator grid erosion as the primary life-limiting concern of ion thrusters. In addition, carbon-carbon grids have been tested on thrusters that normally use molybdenum grids and similar performance has been obtained.

One concern identified by the NEXIS program is the long term ability of an ion optics system comprised of advanced carbon-carbon matrix material to withstand applied voltages of ~5.5 kV and applied electric fields of ~2.3 kV/mm in an environment where the negatively biased accelerator grid is being bombarded and slowly eroded by a very low current density of moderately energetic ions. Damage from an arc can include both melting and vaporization on some surfaces in combination with severe erosion of material due to intense plasma formation and subsequent energetic ion bombardment. Both forms of damage can become problematic if they cause the accelerator grid surface to become progressively more susceptible to the initiation of follow-on arcs. Surface damage increases with the charge transferred in an arc, and values above 5 mC can cause damage to both screen and accelerator surfaces. As an example of the severity of the problem, a recent endurance test of an ion thruster with 14-cm carbon-carbon grids was terminated because of excessive arcing between the grids.

In order to determine what will happen to electric field breakdown behavior early in life and later on during a mission, accelerated wear tests were conducted and will be described in this paper. Briefly, selected areas of the accelerator gridlet were sputtered in a SPECTOR™ Ion Beam Deposition (IBD) tool. This was done to “age” the gridlet in a way that simulates how wear occurs on the accelerator grid of an actual ion thruster. The highest electric fields occur on the upstream face of the accelerator grid nearby the entrance to apertures, and so the “aging” process was performed using masks that limited wear to these regions where arcing is most likely to occur. Specifically, the accelerator gridlet was mounted beneath a mask on a fixture that tilts and rotates relative to an energetic ion beam. The erosion caused during sputter processing was performed at rates that are at least hundreds of times faster than erosion expected during thruster operation in space on some surfaces. Although not identical to the wear that occurs during actual use in space, the accelerated-erosion processing results in a sputtered surface texture that is representative of an actual worn accelerator grid. After fixed periods of aging, the gridlets were remounted in the gridlet test fixture, and the arcing characteristics were re-measured under ion beam extraction conditions. The aging and arcing characterization tests were repeated a number of times on different gridlets to determine if erosion processes would affect long-term ion thruster operation at high specific impulse conditions. In order to avoid unintentional arc damage, the electric-field breakdown tests were performed using advanced arc suppression power supplies that were provided by Colorado Power Electronics.
Our paper is organized by first describing the gridlet test and accelerated wear facilities in Section II. Field emission and log-normal statistical theory are reviewed in Sections III and IV, respectively. Section V contains a description of test procedures while Section VI presents a summary of our results. Conclusions and recommendations for future work are provided in Section VII.

II. Gridlet Evaluation Technique Summary

A. Gridlet Testing Facility

Photographs of the gridlet test facility, the ion source, and a drawing of gridlet geometry are shown in Fig. 1. The sketch in Fig. 1b shows the ion optics geometry and Table I contains a list of NEXIS ion optics geometrical parameters. In brief, tests were conducted by mounting an assembly comprised of two gridlet electrodes to a ring-cusp discharge chamber. The screen and accelerator gridlets were insulated from one another using standoff insulators and were aligned through the use of pins that were passed through precision-placed holes. 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 beamlet 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. Most of the gridlets used in this study had seven apertures.

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 Fowler-Nordheim (F-N) plots of the field emission current that flows from the negatively biased accelerator when the 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 electric field enhancement factors due to protrusions, 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 the accelerated wear test facility, one can determine how arcing rates and related phenomena vary over life and whether arcing characteristics are related to field emission processes. 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. 1b 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 ffx simulations, which predict a beam divergence angle of less than 20 degrees for the most severe operating conditions at close grid spacing. Quartz heaters were installed that allow for bake out of the chamber. The chamber is also well equipped for future diagnostic work with 53 feedthroughs that are available on the chamber floor, 7 around the sides, and 6 at the top.

Figure 2 shows photographs of the CC screen and accelerator gridlets prior to testing. The fabrication of the NEXIS-style CC gridlets used for this study is described by Beatty et al. The only difference being that the gridlets in our study did not receive the final surface coating by chemical vapor deposition after the laser machining process was performed to drill the holes and cut the outside dimensions of the gridlet plates. This final process typically fills the open voids exposed during machining and provides a surface finish of glassy carbon (hence the black markings seen near some of the holes in Figure 2). Although this final coating increases the voltage standoff of the grid assembly, it is expected that the coating will erode away on some surfaces after a few thousand hours into a mission.
TABLE 1. NEXIS geometry and nomenclature specific to the current study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Dimension*</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_s$</td>
<td>Screen hole diameter</td>
<td>3.600</td>
</tr>
<tr>
<td>$t_s$</td>
<td>Screen grid thickness</td>
<td>3.601</td>
</tr>
<tr>
<td>$d_a$</td>
<td>Accel hole diameter</td>
<td>3.543</td>
</tr>
<tr>
<td>$t_a$</td>
<td>Accel grid thickness</td>
<td>4.850</td>
</tr>
<tr>
<td>$l_g$</td>
<td>Grid-to-grid gap$^*$</td>
<td>3.575</td>
</tr>
<tr>
<td>$l_{cc}$</td>
<td>Center to Center spacing$^*$</td>
<td>3.620</td>
</tr>
</tbody>
</table>

* Dimensions are relative to NSTAR thruster optics
$^*$ Nominal relative to NSTAR cold gap measurement, but varied in this study
$^*$ Hexagonal hole pattern

Figure 1a. High voltage sub-scale ion optics testing facility.

Figure 1b. Gridlet geometry definitions. (See Table 1 for more information.)

Figure 2. NEXIS-style CC gridlets prior to testing.
B. Accelerated Gridlet Wear Testing Facility

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 et al\textsuperscript{12}. The accelerated-wear facility is shown in Fig. 3. The facility is fully automated and utilizes a 16-cm diameter ion source 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 test sample that was mounted to a water-cooled target plate, which can be rotated to different zenith angles during a test to change the angle of incidence of the ions on the gridlet being subjected to accelerated wear testing.

An analysis was performed using ffx to estimate how fast the upstream surface of a NEXIS accelerator grid will be worn under deep space conditions. Sputtering data from Williams et al.\textsuperscript{13} were used to estimate sputter erosion while estimates of NEXIS total impingement current in space conditions was obtained from Goebel\textsuperscript{14}. These calculations were then used to determine the amount of time the gridlets would need to be exposed for in the facility described above. Additional discussion concerning this work is presented in Section V of this paper. 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 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.\textsuperscript{15,16}

C. Arc Suppression Switch System

In order to avoid unintentional arc damage of sensitive CC composite surfaces, the electric-field breakdown tests for the NEXIS gridlets processed in the accelerated wear test facility must be performed using arc suppression circuitry that consists of high speed (opening) switches. Photographs of the switch and the enclosure used to mount it are shown in Fig. 5. The circuit diagram of the switch placement in our power supply system is shown in Fig. 6. Operation at total voltages up to 8 kV is possible. The switch system is capable of limiting the charge transfer in an arc to values as low as 4 $\mu$C (from the power supply system to the load line). The switch was designed to open quickly and minimize the amount of charge it passes for arc control applications. In order to provide additional charge to the arc between the accel and screen gridlets, we have added a capacitor that is placed across the grids and downstream of the switch. The value of the capacitor and the voltage applied between the grids (C in Fig. 6) will be 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 the arc). A digital output signal from the switch control card that indicates when an arc occurs is monitored with a data acquisition card to determine the arc frequency, total number of arcs during a test, and related statistical information. Both switches shown in Fig. 6 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.
III. Field Emission Theory

Electrical breakdown between electrodes has been investigated for over a century. Before voltage breakdown (arching onset), small electron currents are often seen. It is commonly believed that these currents play an important role in initiating electric field breakdown events between grids. In 1928 Fowler and Nordheim published a calculation of the tunneling probability through a triangular barrier and applied it to the emission of electrons from a metal under the influence of a strong electric field, now referred to as Fowler-Nordheim field emission. The work function of a conductive material describes the height of the roughly square potential well that keeps conduction electrons from leaving the surface of the material. Applying an electric field to the metal makes the top of the well slant downwards so that an electron can tunnel out of the well if the slant is steep enough. Alpert et al. showed, in a quantitative manner, the clear relationship between the observed values of pre-breakdown (field emission) currents with observed values of breakdown voltage. The principal outcome of Alpert’s study was a phenomenological picture, which was applicable to broad area electrodes as well as to point-to-plane geometries, and which provided a single explanation for several heretofore unrelated observations. The basic Fowler-Nordheim (F-N) model persists to this day, albeit with various modifications and enhancements (for instance Ref. 20). In Ref. 20, Latham presents the derivation of the most useful form of the F-N equation:
\[
\ln \left[ \frac{J_{FE}}{E^2} \right] = \ln \left[ \frac{1.54 \times 10^{-6} A_e}{\phi} x 10^{4.5} \right] - 2.84 \times 10^9 \phi^{1.5} \frac{1}{E} \tag{1}
\]

If we assume that the field emission current flowing between the grids comes from a single microprotrusion at which the electric field is enhanced by a factor \( \beta_{FE} \) over the macroscopic value \( E \) existing at a perfectly smooth grid surface, then the microscopic field \( E_m \) acting at its tip will be given by

\[ E_m = \beta_{FE} E = \beta_{FE} \frac{V_L}{\ell_g} \tag{2} \]

Substituting Eq. (2) into Eq. (3), yields a logarithmic form of the F-N equation expressed in terms of the externally measurable parameters \( J_{FE} \) and \( V_T \),

\[
\ln \left[ \frac{J_{FE}}{V_T^2} \right] = \ln \left[ \frac{1.54 \times 10^{-6} A_e \beta_{FE}^2 10^{4.5} \phi^{\beta \phi}}{\phi_g^2} \right] - 2.84 \times 10^9 \frac{\ell_g \phi^{1.5}}{V_T} \tag{3}
\]

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

\[
\frac{d(\ln(J_{FE}/V_T^2))}{d(1/V_T)} = -\frac{2.84 \times 10^9 \ell_g \phi^{1.5}}{\beta_{FE}} \tag{4}
\]

and an intercept

\[
\left[ \ln\left(\frac{J_{FE}}{V_T^2}\right) \right]_{\text{int}} = \ln \left[ \frac{1.54 \times 10^{-6} A_e \beta_{FE}^2 10^{4.5} \phi^{\beta \phi}}{\phi_g^2} \right] \tag{5}
\]

Thus, from the slope of an F-N plot, one can obtain an approximation of the maximum electric field caused by surface imperfections and protrusions extending from the ion optics surface. The field enhancement factor is a good indicator of the quality of a grid surface, and, as explained later, can be used to predict the breakdown voltage. As the enhancement factor increases (decreases), the surface quality is worsened (improves) and the breakdown voltage decreases (increases). Experimental evidence suggests\(^{19,21}\) that these micro-protrusions, sometimes invisible by ordinary optical methods, can serve to multiply the average electric field by a factor of hundreds or more. Figure 7 is a scanning micrograph of a projection on an aluminum surface capable of such high field magnification (from Ref. 22). Using Eq. 5 one can also determine an approximation of the emitting area. The emitter area is extremely sensitive to the intercept, however, and calculated areas can vary over unphysical ranges, so it is difficult to attribute much confidence to calculations of emitter area extracted from a Fowler-Nordheim fit. This is most likely caused by adsorbed surface layers and impurities, which alter the pre-exponential term in the F-N equation.

**IV. Weibull Statistical Analysis**

In 1939, Waloddi Weibull developed a method for statistically evaluating the fracture strength of materials based upon small population sizes.\(^{23,24}\) Weibull analysis can 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 modeled such diverse phenomena as the length of labor strikes, AIDS mortality, and earthquake probabilities. The Weibull distribution has the great advantage in reliability work that by adjusting 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. In the case of ion propulsion, Weibull analysis can be used to characterize the mean period between arcs that occur between ion optics

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**Figure 7. Protrusion on surface.**\(^{22}\)
electrodes 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. Using Weibull plots is useful for graphically demonstrating if one grid surface is better than another 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 all plots in this paper by noting the intersection of the plotted data with a horizontal dashed line drawn at 63.2%.

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

\[
f(t) = \left(\frac{\beta_w}{\eta}\right) \left(\frac{t}{\eta}\right)^{\beta_w-1} \exp\left(\frac{t}{\eta}\right)^{\beta_w} .
\]

In Eq. (5), the value of \( \beta_w \) indicates whether the failure rate is increasing, constant, or decreasing. A value of \( \beta_w < 1 \) indicates that failure rate (or arc rate in our case) is decreasing. 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. A value of \( \beta_w = 1 \) indicates a constant arc rate probability. Frequently, components (or grids in our case) that have survived burn-in will subsequently exhibit a constant failure (or arc) rate that shows up as \( \beta_w = 1 \) when plots are made of total failed components (or arc events) versus time from the start of a test. A common phenomenon that displays \( \beta_w = 1 \) is radioactive decay. A value of \( \beta_w > 1 \) indicates an increasing failure rate. This is typical of products that are wearing out. Finally, the Weibull characteristic life, \( \eta \), is a measure of the scale, or spread, in the distribution of data.

V. Approach to Characterization of Arcing Behavior

Arcing characterization tests are performed to determine the effects of surface conditioning, electric field, beam extraction time, grid spacing, active gridlet area, and beamlet current. Post test inspections have been performed to locate areas where arcs occurred, and numerical simulations have also been performed to determine regions where the highest electric fields exist and regions where the highest concentrations of charge exchange ions are being collected. Two overriding issues guided the evaluation of the arcing behavior of gridlet surfaces under conditions where ion beamlets are being extracted:

- Wear of test accelerator gridlet surfaces by ion bombardment is needed to simulate the surface condition of an accelerator grid during in-space operation,
- Conditioning of test accelerator gridlet surfaces with arcs of specified coulomb transfer and applied voltage is needed to prepare gridlet surfaces worn by ion bombardment prior to characterization of arcing behavior at various electric field values.

Other areas of investigation requiring additional work include determining how arcing behavior will scale from gridlet tests to full-size grids and how the active gridlet area-to-total gridlet area ratio might affect the arcing measurements. An additional issue was the magnitude of the total voltage that may be necessary at nominal spacing to induce arcs (when the accelerator gridlet surface is in a pristine BOL condition). A review of the arcing threshold data collected by Goebel under the Carbon-Based Ion Optics program on drilled and un-drilled CC composite material (without ion beam extraction) was conducted. The arcing threshold data were presented in terms of onset electric field versus spacing. These data showed that arcs above 0.1 mC appeared to degrade the electric field standoff capability measured on pristine pyrolytic coated CC surfaces. However, arcs above ~0.5 mC appeared to result in similar electric field standoff values (i.e., the arc onset electric field saturated). Arcs higher than 5 mC were identified as not desirable due to damage they cause to both the accelerator and screen electrode. Based on early data gather by Goebel, it was decided that a low charge transfer value per arc of 0.25 mC would be used for the first grid set tested (Grid Set #0). After completing the testing of the grids, high magnification photographs were
taken to visually document any damage caused by the 0.25-mC conditioning arcs. No obvious arcing damage was observed on the grids due to the low level of charge transferred during an arc, which is in agreement with previous arcing studies done on carbon-carbon composite material.\(^7\) The displacement of some of the fibers was noted, but this could have occurred during handling and processing of the gridlets as these features were seen in images taken of gridlets that have not been operated. Thus, following these tests, the charge transfer value was increased to 1.0 mC per arc for the next two grid sets (Grid Set #1 and #2). Conditioning arcs of this magnitude cause some surface damage to both the accelerator and screen electrodes, allowing for investigation of the effect this damage has on arcing behavior.

A final issue was the level of uncertainty that might occur in the onset electric field measurement (independent of what spacing was selected for the test). To address this concern, it was decided that Weibull statistics be used (as described in section IV). The Weibull tests were conducted separately from the electric field threshold tests by operating the grids for a specified number of hours at a fixed electric field condition and recording the time between successive arc events (performed at the minimum charge transfer level of our equipment ~0.01 mC). The goals of the statistical analysis included (1) determining if conditioning performed prior to the timed test has resulted in a stable surface, (2) measuring the mean arc period at a given electric field value, and (3) characterizing the level of uncertainty of each measurement set.

Based on the aforementioned issues, the following procedures were completed to investigate the electric field breakdown characteristics of high voltage carbon-carbon ion optics:

1) Expose upstream surface of test accelerator gridlet to ion bombardment (i.e., wearing) using two different methods:
   - Fast exposure in gridlet test facility at high perveance conditions thru direct impingement of one sample
   - Higher fidelity exposure under simulated conditions expected in space
2) Expose test accelerator gridlets to a specified number of arcs at a specified value of coulomb transfer (i.e. conditioning)
3) Evaluate test accelerator gridlets for their electric field onset characteristics at nominal and reduced grid spacing with and without ion extraction at the minimum charge transfer value. Perform timed tests of several hours in duration so that the time between successive arcs can be analyzed using Weibull statistical techniques followed by field emission measurements.

Table 1 summarizes the pre-test cleaning procedures used for each of the three different CC gridlet sets tested during this investigation. Each set underwent similar testing and the results of which are presented in the next section.

<table>
<thead>
<tr>
<th>Grid Set</th>
<th>Cleaning Procedure</th>
<th>Charge Transfer per Arc</th>
<th>Grid Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>#0</td>
<td>No cleaning procedure used to remove laser beam soot material from hole edges</td>
<td>0.25 mC +/- 10%</td>
<td>0.5 – 2.7 mm</td>
</tr>
<tr>
<td>#1</td>
<td>Used cleaning solution and acetone to remove soot followed by heating at 250°C at atmosphere for 20 minutes</td>
<td>1.0 mC +/- 10%</td>
<td>0.5 mm +/- 2%</td>
</tr>
<tr>
<td>#2</td>
<td>Used same procedure for grid set #1 except that the grids were heated to 900°C under vacuum for 1.5 hours</td>
<td>1.0 mC +/- 10%</td>
<td>0.5 mm +/- 2%</td>
</tr>
</tbody>
</table>

As mentioned above, the exposure time used in the accelerated wear test facility was determined by first calculating the expected amount of erosion that would be expected in space using CSU’s ffx numerical simulation program for a given amount of time (e.g., 3 years). Once the total mass loss per unit area was obtained from ffx at several locations on the accelerator electrode, the number of atoms removed per unit area was determined. Next, we determined the amount of time to expose the gridlet in our accelerated wear facility so that a similar amount of erosion would result. Only one mask was used, and this complicated our ability to wear the accelerator barrel...
regions to the same level that the upstream entrance to an aperture. For example, the two erosion sites on the accelerator gridlet expected to be important in arcing behavior (the barrel region of an aperture and the upstream surface immediately adjacent to an aperture entrance) cannot be eroded to the same amount of in-space operation with the mask that was used in the accelerated wear facility. We estimate that when the equivalent of ~3 years of in-space erosion has been performed on the barrel region, approximately 24 years of erosion has been performed on the upstream side of the accelerator grid. Therefore, this particular grid set case can be thought of as a worst-case scenario. Figure 17 shows a photograph of Grid Set #1 after being conditioned with the equivalent of 48-yr of in-space erosion on the aperture entrance regions. High magnification images showed a very rough texture around the aperture edges consistent with what is observed after long term ion thruster endurance tests. A fast exposure technique of directly impinging the accelerator surface by operating at very high beamlet currents was also performed. In this case however, only the upstream surface was eroded, and the operational time was selected to result in the equivalent of 3 yrs of in space thruster operation. Further related information on this technique can be found in Ref. 26. Typically only a few tens of minutes of operation under direct impingement resulted in adequate erosion. To avoid confusion between the accelerated wear test facility and the fast exposure (i.e., direct impingement) processes, the equivalent in-space exposure times are listed herein as the wear on the upstream face.

VI. Results

Experimental and analytical results are broken up into three sections. The first section presents the results of the Weibull statistical analysis of arc period probability distributions for gridlets operated at a given electric field and intra-grid spacing while extracting ion beamlets. The second section presents the analysis of the field emission characteristics of the gridlets with and without beam extraction. The final section contains results of tests conducted to characterize the electric field condition where continuous arcing occurs.

A. Weibull Analysis

As discussed above, Weibull statistical analysis was used to analyze the arc period probability distribution of the gridlets when operated at given electric field and intra-grid spacing while extracting ion beamlets. Our approach has been to characterize the electrical breakdown behavior 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 gridlet tests were performed with an advanced arc suppression switch (see section II, part C) along with a LabView program that records the time of an arc event. The data acquisition system records an arc event through a counter in the arc suppression supply. The data system monitors the status of the arc suppression switch electronics every 0.5 sec, and consequently, the minimum resolution of arc period measurements is ~1 sec. The arc events that occurred in a particular test are then ranked from earliest (shortest period between two arcs) to latest (longest period between two arcs), and then plotted on Weibull probability graph paper. Figure 8 contains comparisons of Weibull plots obtained at 4.09 and 5.93 kV/mm that demonstrate a significant decrease in average time between arcs with electric field. The shape parameter for the measurements was between 0.6 and 0.70.

![Weibull plots for 4.09 and 5.93 kV/mm showing effect of electric field on arc period. Note that each data set was obtained during 3-hr runs.](image)

Figure 8. Weibull plots for 4.09 and 5.93 kV/mm showing effect of electric field on arc period. Note that each data set was obtained during 3-hr runs.
Although the data points shown in Figure 8 are fit reasonably well with a straight line (which implies that the Weibull distribution can be used to describe the probability distribution of arc period), some arc period distributions that we’ve measured do not lie on straight lines. A possible reason for non-Weibull like behavior is multiple arc initiation modes caused by changing grid temperature, grid conditioning, or erosion. Also, it is pointed out that there may be the need to plot the data using another probability distribution.

Figure 9 shows the effect of increasing the number of 0.25 mC conditioning arcs on the arc period for a grid gap of 0.5 mm. Each data set corresponds to the ion source being operated for 3-hrs. The general trend is that the mean time between arcs increased as more conditioning arcs were initiated. The non-linear Weibull plot behavior at low arc periods did not occur as often during tests conducted later in the test matrix (presumably after conditioning).

Figure 10 shows the effect of increasing the conditioning charge transfer to 1.0 mC. 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. Figure 11 summarizes the data in Figures 9 and 10 where the differences between the results of using 1.0 versus 0.25 mC are more apparent. Figure 12 is a plot of mean time between arcs and Weibull shape parameter versus cumulative run time for an 8-hr run at a grid spacing of 1.04 m and an electric field of 5.48 kV/mm. Although the data are reasonably well behaved, it is noted that the mean time between arcs continued to improve throughout the test. This trend was also observed for testing done at a grid spacing of 0.5 mm during 3-hr run tests. Further testing at extended operating times is needed to better quantify this behavior, but our preliminary conclusion is that the 0.01 mC charge transferred in an arc during Weibull testing must help improve the grid surface.
Figure 11. 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.

As was 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 Figure 13. Grid Set #1 at BOL was noticeably different from the #2, which took much longer to condition. We believe that 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. Although grid set #1 was not baked, it was placed within the vacuum test facility for a longer period of time prior to conditioning.

Figure 12. Mean time between arcs and Weibull slope as a function of cumulative test run time. The dotted lines represents the trend for each Weibull parameter. The shape factor ($\beta_w$) remains relatively constant while the mean time between arcs is observed to increase with cumulative run time.

Figure 13. 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.
The effect of vacuum chamber pressure also affects the frequency of breakdown. Both Kaufman\(^27\) and Kerslake\(^28\) 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 \(1.2 \times 10^{-5}\) Torr. It is therefore likely that in space, the mean time between arc events in the Weibull plots shown above would be higher.

B. Field Emission Evaluation: With and Without Beam Extraction

Field emission is the limiting cause of electrical breakdown in high voltage systems at high vacuum. At high vacuum there are few ionizing collisions within the electrode spacing, therefore, the electrodes instead of the gas are the primary source of charged particles. Field emission describes the quantum mechanical tunneling of electrons out of a metal where the work function barrier is made lower by a strong electric field at the metal surface. Following each timed run to gather data for the Weibull analysis procedure, field emission characteristics of the gridlets with and without beam extraction were obtained. As discussed in Section III, the presence of an electric field between two electrodes can result in the 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 intense evaporation of the material or to the liberation of absorbed quantities of gas. The arc develops in the stream formed of the vapor of released material (or of the liberated gas). Knowledge of the emission characteristics of the accelerator grid is important in interpreting and comparing data concerning other breakdown parameters (e.g., the variation of breakdown voltage with grid spacing), since, otherwise, ambiguous conclusions can be drawn.

As mentioned above, Fowler-Nordheim (F-N) data analysis was used to investigate how accelerator grid surface features affect electric field breakdown of NEXIS-style CC gridlets. Most of the F-N data presented herein were collected without ion beam extraction (with a few exceptions). However, the field enhancement factors and emitting area are compared to measurements made while extracting ions (i.e., measurements of electric field breakdown strength and statistical behavior of arc frequency (or period). 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. An early set of experiments was conducted to determine how the electric field enhancement factor and the effective emitting area vary with grid gap and grid surface condition. 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 as abscissa and ordinate, and judging the quality of the straight line plot that was obtained. The correlation coefficient of the line of best fit then gives a direct measure of how well each model fits the experimental data. Although other models occasionally provided a good curve fit, only the F-N model resulted in consistently high correlation coefficients. Figure 14 is a typical F-N plot taken in this investigation. Using Equations 4 and 5 from Section III, the enhancement factor and emitter area are estimated to be approximately 280 and \(2 \times 10^{-13}\) m\(^2\). Typical emitter area values found in this study varied from \(10^{-13}\) to \(10^{-18}\) m\(^2\) depending on the condition of the grid surface.

![Figure 14 Typical F-N plot from experiments](image-url)
Figure 15. Typical F-N plots for various grid gaps. Selected data taken by hand to minimize clutter. Note: very minimal conditioning was conducted on the gridlet surface prior to recording the field emission measurements and enhancement factors shown.

Field emission plots are shown in Fig. 15 for various grid gaps of the first gridlet set. Although similar plots were taken for ten different grid gaps, only four (\(g = 1.04 \text{ mm}, 1.27 \text{ mm}, 1.78 \text{ mm}, \) and \(2.70 \text{ mm}\)) are shown as examples in Fig. 15. The data fall on straight lines over a range of several orders of magnitude, which suggests that F-N field emission is responsible for the monitored currents and that very little leakage is occurring across insulators. It is noted that a comparison between data taken by increasing and then decreasing the applied voltage to the grids was performed, and the resulting plots were nearly identical with no evidence of hysteresis. Care was taken to ensure that stable emission conditions were established before the F-N measurements were made and that no arcs occurred during a test. Arcs typically would occur at the maximum voltage tested and since these arcs can blunt or vaporize an existing protrusion changing the field emission, these data points were not used to characterize the field emission and enhancement factor. The variation of the slope of the F-N plots with grid spacing can be interpreted as a change in field enhancement, \(\beta_{FE}\), with grid spacing, since it may be supposed that the work function of the emitting point(s) is constant.

Figure 16 contains a comparison between the F-N curves taken with and without ion beam extraction for the 1.04 and 1.27 mm grid gap conditions. Although similar, the curves obtained with beam extraction were always
observed to fall just below the curves obtained without beam extraction. The slope of the curves, and hence the enhancement factors, are very similar indicating that the plasma only has a minor effect on the localized electric field nearby a protrusion.

There is a perception that arcing is more prevalent when ions are extracted from electrodes. The data in Figures 16 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 NEXIS operating conditions. The discrepancy between our observations and general intuition of many researchers is unexplained at this point. We point out, however, that it is generally believed that arcing rates are enhanced by out-gassing that may occur nearby small surface protrusions that are being heated by field emission current. And out-gassing may occur during ion extraction as the grids are heated. The effect of out-gassing on high arcing rates may be mitigated in our experiments due to baking and careful arc conditioning. Finally, we are fairly confident that grid spacing is well controlled in our experiments (within 2%), but this may not be the case in broad area sources where interfaces exist between structures with different coefficients of thermal expansion, temperature, and temperature gradients.

After investigating the erosion rate process using ffx, it was determined that the two erosion sites on the accelerator gridlet (the barrel region of an aperture and the upstream surface immediately adjacent to an aperture entrance) cannot be eroded to the same amount of in-space operation with the current mask that was used in the accelerated wear facility. We estimate that when the equivalent of ~3 years of in-space erosion has been performed on the barrel region, approximately 24 years of erosion has been performed on the upstream side of the accelerator grid. Therefore, this particular grid set case can be thought of as a worst-case scenario. Figure 17 shows a photograph of Grid Set #1 after being conditioned with the equivalent of 48-yrs of in-space erosion on the upstream side. High magnification images showed a very rough texture around the hole edges consistent with what is observed after long term ion thruster endurance tests. The processing of #1 was conducted in our accelerated wear test facility (see Section IIb) in 240 hours of exposure time. Measurements of field emission were made between arc conditioning sequences and F-N plots of these data at BOL and with 48-yrs of erosion are shown in Figure 18. Figure 18a shows how a few hundred 1-mC arcs effectively condition the surface while roughly 2000 are required to condition the #1 grids. With a slight increase in the charge transfer level the number of conditioning arcs can potentially be reduced significantly. However, Synder29 has shown that at the 2.5-mC charge transfer level, the field emission threshold begins to degrade and the surface starts to roughen.

Figure 17. NEXIS-style accel grid after testing with the equivalent of 48 years of erosion on the upstream side.

Figure 18. F-N plots for BOL and severely worn gridlets. The shift to the left and to higher slope magnitudes correspond to decreasing field enhancement factors presumably caused by the application of the 1-mC conditioning arcs.
Recall that grid set #1 was eroded using the higher fidelity 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. The fast exposure test involved operation at high beamlet currents that result in direct impingement of ions on the accelerator gridlet at the upstream entrance to each aperture. This test allows us to erode the upstream surface of the accelerator gridlet to the equivalent of 3 and 6 yrs of on-orbit operation in 22 and 44 minutes, respectively. Grid Set #2 was evaluated in the same manner as the gridlets eroded in the accelerated wear test facility (Grid Set #1). Figure 19 shows a photograph of Grid Set #2 after being conditioned with the equivalent of 6-yrs of in-space erosion on the upstream side (difference in grid color from Fig. 18 is due to a lighting issue). Measurements of field emission were made between arc conditioning sequences and F-N plots of these data at BOL and with 6-yrs of erosion are shown in Figure 20. Figure 20a shows how a few hundred 1-mC arcs effectively condition the BOL surface while roughly 2000 are required to fully condition the aged grids.

After each testing sequence was completed photographs of the screen and accelerator gridlets were taken to document erosion sites and grid condition. Figure 21 shows a photograph of the downstream side of the screen grid #1 and the upstream side of the accelerator grid #1 after completing testing with the accelerator grid having the equivalent of 24-yrs of on-orbit erosion. Recalling the pristine image of the grids shown in Figure 2, signs of arcing were present over the entire face of the gridlets, and not just in the active region where ions were being extracted. High magnification photographs were taken of both the downstream side of the screen gridlet and the upstream side of the accelerator gridlet after characterizing the eroded gridlets. Figure 22a contains a typical photo of the downstream side of the screen grid where craters are found that are likely due to vaporization caused by the high arc energy and the low thermal diffusivity of CC material. In contrast, Figure 22b shows the upstream side of the accelerator grid where much smaller diameter craters were observed. 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.

Numerical simulations were used to determine if the arc site locations corresponded to regions where the highest electric field exists. Figure 23 is an electric field plot at a beamlet current of 1 mA/hole for the NEXIS geometry using ffx. As expected, the highest electric field conditions on the negatively biased accel surface are at the upstream entrance of an aperture. The high electric fields near the downstream side of the screen grid correspond to where the largest craters (Fig. 22a) are observed.

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. The field enhancement factor $\beta_{FE}$ is calculated from the slope of the linear section of the F-N plot using Equation 4 with a value of $\Phi = 5$ eV for the work function. 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.$^{30,34}$ The work function can also temporarily be reduced as it is being wetted by out-gassing products from other components of the ion source, which can result in a large increase in the enhancement factor (i.e., the sensitivity of field enhancement to work function is 1.5\%/\%). The number of conditioning arcs is believed to result in a blunting of the protrusions and a reduction of the effective value of $\beta_{FE}$. Early on in the testing (with less than 200 conditioning arcs), the sharp drops seen in Figure 24 are likely due to relatively large protrusions on the surface being vaporized by the conditioning arcs. Enhancement factors in the thousands have been reported for carbon nanotubes$^{35}$ and graphite$^{36}$ with unconditioned surfaces.
The electric field enhancement factors (calculated from the slopes of F-N curves like the ones in Fig. 18) are plotted in Fig. 25 as a function of grid spacing. The trend of increasing enhancement factor with grid spacing follows the trend observed by others\textsuperscript{19,30-31}, 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 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. The alternate possibility of localized areas of extremely low work function 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, $\beta_{FE1}$, due to microscopic protrusions on the accel grid, and a local enhancement, $\beta_{FE2}$, associated with macroscopic changes in the electric field distribution at larger gap spacing due to fringing around hole 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 Alpert$^{19}$ 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 $\beta_{FE2}$ 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. The same analysis also showed that the $\beta_{FE1}$ reaches an asymptotic value when the opposing grid no longer affects the field at a microscopic point providing further evidence for the effect of field enhancement at the edges of the grid. 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 compress 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. Byers$^{33}$ experimentally showed that rounded edges when compared to square edges do provide larger breakdown fields between grids with holes.

Due to equipment constraints, plots such as the one shown in Figure 24 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 scatter in the data at the largest grid gaps is believed to be due to lack of further conditioning of the grids at these gaps.

The enhanced electrical-breakdown field (or microscopic field) at the accelerator grid surface is determined from Equation 2. Figure 26 shows the enhanced electric field against electrode separations. Although typically plotted on a log plot due to the error associated with the enhancement factor calculation, Figure 26 shows that the enhanced electric field is quite constant within the experimental error of measurement at a given gap spacing when plotted on a linear scale. This enhanced field will vary from one material to another but should be constant for each. Similar electric field breakdown work conducted on other types of electrode materials has shown a similar constant enhancement electric field trend over many orders of magnitude in gap spacing.$^{19,30,37}$ The variation in the values is probably attributed to the small uncertainty in the enhancement factor that arises from the analysis of a multiple-point emitting grid in terms of a single-point emitter.

An important consequence of these results is that the value of the breakdown voltage is thus directly related to, and predictable from, the observed characteristics of the pre-discharge field emission currents. Knowing the enhanced electric field where breakdown will occur, one can calculate the applied voltage where breakdown will occur. The average value from Figure 26 (shown by the black line across the plot) is 5389 kV/mm. This enhanced electric field value lies within values measured for a variety of electrode materials, which range from 5000 to 11000 kV/mm for fully conditioned electrodes.$^{38}$ Dividing this value by the known 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 5389 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 12.5 kV/mm for CC gridlet material. As will be shown below, 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 Figure 25 data at the highest grid gaps it is difficult to estimate what the breakdown field would be at the nominal NEXIS thruster grid gap. But a rough approximation of the breakdown field is estimated to be 4.0 kV/mm for fully conditioned grids at the nominal NEXIS grid gap. In addition, extrapolating the curve in Figure 25 to a grid gap of 0.25 mm, one obtains an enhancement factor of 260, which results in a threshold electric field of 20.6 kV/mm that is about 13% higher than the value predicted by Goebel7. This agreement was expected from other research work32, which has shown that enhanced electric field strength is nearly a constant value regardless of the electrode area.

Figure 27 shows how the enhancement factor varies depending on when and how the grids are heated and out-gassed. Once the discharge and neutralizer filaments have been on for 1 hr, the enhancement factor can increase by 60% from the initial measurement taken prior to heating the discharge chamber and grids. This may provide some evidence for the possible influence that out-gassing can play in the onset of arcing. After extracting a beam and running the ion source for 1 hr, the enhancement factor begins to level off to a value just below the initial value measured. After this point, the enhancement factor remains constant no matter what is done to the grids under afterwards (except for application of conditioning arcs). Currently, we are looking at the parameters that can change the slope of F-N curves. One possible explanation of why the enhancement factor increases as the grids are first warmed is a temporary reduction in the work function of the surface as it is being wetted by out-gassing products and, as mentioned above, the field enhancement, $\beta_{FE}$, is sensitive to the work function (1.5 %/%). Although a work function change is a possibility, the likelihood of it dropping 40% due to wetting by out-gassing products is not considered to be very high.

As mentioned above, after eroding the surface, a 3-hr run was initially conducted (at the lowest possible charge transfer value of 0.01mC) prior to beginning the re-conditioning process. Two instances of erratic accelerator current were observed during our tests: 1) during the first 3-hr run after the upstream side of the accelerator grid was eroded to 24-yrs of on-orbit operation (3-yrs in the barrel region) and 2) during the first 3-hr run after the accelerator grid was eroded to 48-yrs of on-orbit operation (6-yrs in barrel region). No accelerator current spikes were observed after performing the fast exposure tests. Figure 28 shows the erratic behavior during the first 3-hr run for Grid Set #1 after being eroded to the equivalent of 48-yrs and prior to being conditioned.
Initially the accelerator grid current was relatively high or noted to be gradually increasing at a fixed beamlet current. As shown in Figure 28, the increases in the accelerator grid current did not seem to have much correlation with arc events. It is noted that similar anomalous accelerator current behavior was seen in the NEXIS 2000-hr wear test just after a cryopump regeneration.\textsuperscript{40}

From Figures 18 and 20, 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 steady with very little noise 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 originally dissolved or entrapped within the CC matrix. 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.\textsuperscript{41} Although the gridlets had been under vacuum ($1\times10^{-6}$ Torr) for 11 hours, testing began after just one hour of applying filament heater power. In addition to insufficient bake out times, surface adsorbates and entrapped gasses that resulted from the exposure of the gridlets to atmosphere could still have remained on or nearby the surface. Our experimental results suggest that surface contamination is being removed by the 1-mC conditioning arcs. A related explanation for the anomalous accelerator gridlet current could be due to the discharge filament initially heating the screen gridlet, causing contaminants from the hotter screen gridlet surface to re-adsorb on the cooler accelerator grid. As was seen in Figure 27, heating the gridlets with the discharge filaments does increase the enhancement factor in the first hour. Rougher grid surfaces also have a greater capacity for adsorbed gas. In addition, Collazo \textit{et. al.}\textsuperscript{42} reported an increased emission current which has been attributed to the presence of adsorbates on carbon nanotubes and explained that the adsorbates would introduce a resonant state enhancing the tunneling probability of the electrons. Adsorbed gas on the grid surface can be liberated under bombardment by pre-breakdown current to provide a medium in which sufficient current amplification occurs to produce breakdown.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{accelerator_grid_current_0.01_mC_arc_history.png}
\caption{Accelerator grid current and 0.01 mC arc history during the first 3-hour test after eroding the accelerator grid upstream surface to an equivalent of 48 yrs. Note the presence of accel current noise. (E = 4.01 kV/mm). \textit{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 field values.}}
\end{figure}

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\textbf{C. Electric Field Breakdown}

Due to the potentially destructive nature of the electrical breakdown phenomenon, the electrical breakdown characteristics of each of the carbon-carbon grid pairs were measured after the Weibull statistical characteristics and
field emission data had been obtained. Achieving higher electric fields for a given set of accelerator system operating voltages permits operation at a closer grid separation, which, in turn, facilitates operation at a higher current density and higher thrust density. The accelerator grid voltage was increased in magnitude to a fixed value while the screen grid voltage was increased until continuous electrical breakdown occurred. The charge transfer was limited to 0.01 mC during these tests. As in other lower voltage electric field breakdown studies performed at CSU early studies indicated that either the screen or accelerator voltage could be increased to induce breakdown because the magnitude of the electric field is the critical variable in determining when breakdown occurred. Although other arcing studies have determined the electric field breakdown point by the onset of a certain field emission current level, and not the arc initiation voltage, it was decided herein to use the continuous electric field breakdown voltage as the definition of the maximum applied electric field. Electric field breakdown data were first taken 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 chamber reached a pressure of approximately 1x10^-6 Torr, the electrical breakdown point was re-measured without beam extraction.

Following each conditioning process for grid set #1, electric field breakdown tests were conducted to record the variation in the breakdown voltage as a function of (a) beamlet current, (b) number of conditioning arcs, and (c) grid spacing. The electric field breakdown measurement consists of slowly increasing the total voltage until the grids begin to continuously arc and then noting the total voltage. Although we started testing with grid gaps above 2 mm, we soon needed to move down to a 1.04 mm gap and then to a 0.5 mm gap to achieve electric field values high enough to get the grids to arc without exceeding the limits of the arc suppression switch. Figure 29 shows the electric field breakdown results for the 0.5 mm grid spacing as a function of beamlet current. As mentioned above, the electric field breakdown characteristics were also performed without beam extraction and typical results are plotted in Fig. 30. 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 2%. The presence of the ion beam does not appear to be affected by the onset of continuous arcing. This result validates tests performed without beam extraction. Numerical simulations using ffx were conducted to study the effect of increasing the electric field. 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 barrel region of the accelerator grid. Going from an electric field of 2.2 kV/mm to 10 kV/mm results in the an increase of upstream erosion rate by a factor 5 during the first 20,000 hours of operation. Figure 30 shows that this increase in CEX ion collection has a minimal effect on the electric breakdown point with properly conditioned grids. Although not proven during our short-term tests, we believe that prolonged operation will result in reductions in the electric field breakdown point due to the upstream accelerator grid surface being bombarded by CEX ions, which will result in texturing and possible growth of field emitting protrusions.
The plots in Figure 31 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. This saturation effect was not observed on gridlet set #0 when the charge transfer in the conditioning arcs was set to only 0.25 mC. Grid set #2 takes many more arcs to reach the 11 kV/mm mark (shown by the dotted line in each figure) than grid set #1. This is likely due to the fact that grid set #2 was kept in a plastic bag for approximately two weeks after undergoing the laser beam soot cleaning process discussed earlier. An interesting observation is that although the electric field breakdown point and the enhancement factor (Figure 24) level off at about the same point, the arc period does not seem to stop increasing until after many more arcs have occurred between the grids. Although, the higher charge transfer value of 1-mC affects the mean arc period, electric field breakdown, and electric field enhancement factor, it is possible that the soot cleaning procedure also influenced the saturation behavior. Further testing with different charge transfer values are planned to better quantify this effect. 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 when CEX ions are present. This result was observed (see Fig. 31) once the C-C gridlets have been conditioned properly. The maximum breakdown field recorded for CC gridlets used in this study is 11.4 kV/mm.

An interesting observation from the plots in Figure 31 is the fact that despite the significant erosion placed on the upstream side of the accelerator gridlet, with proper conditioning of the grid surface, the BOL maximum breakdown field can still be reached. It is noted that the 48-yr erosion data curve shows quite a bit more oscillation than the curves for the BOL and 24-yr erosion curves indicating that the significant amount of erosion around the upstream side of the accelerator grid is beginning to have an effect on the breakdown field for a given number of conditioning arcs. Although, the sputter erosion on the upstream surface of the accelerator 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 nearly identical to the BOL grid surface once the accelerator gridlet surface has been conditioned with several hundred 1-mC arcs.

A preliminary investigation was also conducted to analyze 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. Due to lack of time, this test was not completed, however early data are shown in Figure 32. The first test conducted with the 7-hole Poco graphite grids was stopped once the maximum breakdown field saturated. This value agrees with the one obtained by Goebel for graphite. As shown in

Figure 31. Breakdown field dependency on the number of conditioning arcs. Dotted line represents 11 kV/mm mark.
Figure 32, the maximum electric field was obtained after 800, 1-mC conditioning arcs. Following this test, the 19-hole set was tested. Although the 19-hole set initially had a similar breakdown field to the 7-hole set prior to initiating any arcs, the breakdown field began to saturate at a lower breakdown field. Due to time constraints, further conditioning could not be completed. The lower breakdown field for a given number of conditioning arcs could be attributed to the increase in the number of field emitting protrusions caused by the presence of more drilled holes. The added holes provide more protrusions due to the edge effects from the drilling. Byers\textsuperscript{33} conducted tests with stainless steel electrodes with different numbers of holes and also found that the voltage breakdown level decreased with the number of holes drilled in the grids. But this difference was always less than 20% for grids with 1 to 37 holes (this so happens to be the difference between the data points in Figure 32 after some conditioning). The 19-hole set likely has a significantly larger amount of protrusions on the surface than the 7-hole grid set resulting in a lower breakdown field per conditioning arc. It is likely that further conditioning will eventually allow the 19-hole grid set to reach the maximum breakdown field as the 7-hole grid, however, this has not been demonstrated at the current time. It should be noted that the enhancement factor for the 7-hole grid set leveled off at a value that was 75% of the average value for the CC grid sets. Lower enhancement factors reduce the local enhanced field at any applied electric field condition, and consequently result in higher breakdown fields. The enhancement factor measured for the 7-hole grid set prior to initiating any arcs was approximately 5-10% lower than the steady state factor achieved by the CC grid sets. Based on the 0.5 mm grid gap data taken with the Poco grids, the estimated enhancement factor should be in the range of 5500-7200 kV/mm using the data for both the 7-hole and 19-hole grid sets.

Figure 33 contains field emission current data collected at a grid spacing of 0.5 mm. 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 surface condition but also the case where the maximum voltage standoff is achieved. As indicated above, the maximum breakdown field for both grid set #1 and #2 is ~11 kV/mm. From Figure 33, 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. Figures 31 and 33 clearly indicate although the onset of field emission may begin at a certain electric field value, the ultimate breakdown field (defined as just prior to continuous arcing) can be significantly higher.
VII. Conclusions

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-carbon ion optics in the total voltage range of 1 to 8 kV. Our results show that with proper conditioning using small, controlled charge transfer arcs, operation at electric fields up to ~11 kV/mm for a grid gap of 0.5 mm can be achieved if one is willing to permit high recycle rates. The maximum electric field was taken to be the value that the grids could withstand just prior to the onset of continuous arcing. For charge transfer values of 0.25 and 1.0 mC, the intra-grid arcing conditioned the grids and allowed for larger voltage standoff capability presumably due to the removal of field emitting protrusion from the surface. 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 reduction in arcing rate was strongly influenced by the number of conditioning arcs at the 1-mC level and by the applied electric field. Surprisingly, the effect of ion extraction on electric field breakdown and field emission levels was shown to be minimal even at high current densities. There is a perception that arcing is more prevalent when ions are extracted from electrodes. Our data suggest that this perception is not based on arcing that results from field emission processes. In addition, the effect of high beamlet currents or excessive CEX ion bombardment of the accel grid does not appear to degrade the electric field breakdown strength. The discrepancy between our observations and general perceptions of many researchers is unexplained at this point. We point out, however, that arcing rates are enhanced by out-gassing occurring nearby small surface protrusions being heated by field emission current. More out-gassing may occur during high current density operation as the grids are heated. The effect of out-gassing on high arcing rates is mitigated in our experiments due to baking and careful arc conditioning. Finally, we are confident that grid spacing is well controlled in our experiments (within 2%), but this may not be the case in broad area sources where interfaces exist between structures with different coefficients of thermal expansion, temperature, and temperature gradients. A study of the surface evolution due to erosion rate 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

![Figure 33. 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, slow = slow exposure, fast = fast exposure. Onset of field emission = 0.01 mA.](image-url)
characterization tests were completed and after conditioning the grid surface with 1-mC conditioning arcs. The erosion of the upstream side of the accelerator grid was equivalent to erosion expected to occur during in-space operation over periods from 3 to 48 years. The breakdown field, field emission, and arc rate characteristics returned to their original pre-conditioned values, however, once several hundred conditioning arcs were applied, these values returned to their original values. The electric field enhancement factor was observed to reach a steady state value after the 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 an arbitrary grid geometry is 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 10-15% of measured values. Properly conditioned NEXIS gridlets fabricated from carbon-carbon materials are estimated to operate at fields up to 4 kV/mm ±15% at nominal spacing. Finally, although spikes and anomalous excursions in the accelerator current were observed after aging the upstream side of the grid, this behavior was eliminated upon initiating conditioning arcs.

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