Evaluation of Sub-Scale NEXIS Ion Optics and Strategies for Performing Accelerated Wear Testing

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Sub-scale ion optics assemblies (gridlets) are used to investigate the operational limits of the NEXIS thruster on beamlet (or per hole) ion current. Gridlet data are presented over wide ranges of net and total voltage, grid-to-grid spacing, and accelerator hole diameter. A discussion of a technique that can be used for performing accelerated wear tests (at rates that are 50x higher than standard tests) is also presented that may be useful for quickly and inexpensively evaluating the life time of the NEXIS accelerator grid for missions requiring long (~100 khr) thruster firing times. The technique is based on exposing the accelerator grid surface (through a mask) to an ion beam that is capable of trenching pit and groove patterns on the downstream face and etching side-wall and etching upstream surfaces of apertures. The status of this work is summarized, and beam current profiles and related facility details are presented. Data on a specially designed power supply with ultra-low stored energy features are also presented. Low stored energy power supplies are critical for high specific impulse ion thrusters that utilize carbon-based ion optics systems in order to avoid arc damage of the accelerator grid surface when the thruster is operated at high total accelerating voltages.

I. Introduction

The Nuclear Electric Xenon Ion System (NEXIS) ion thruster1 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 baseline ion optics design utilizes carbon-carbon composite grids. 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.2 The historical approach that has been taken in ion thrusters to minimize the concern of electrical breakdown-induced damage is to prep the accelerator grid surface to minimize sharp points and protrusions and reduce the applied electric fields to values where very infrequent arcs will occur. Traditionally, once an arc occurs in an ion thruster and is detected, the high voltages applied to the grids are recycled (i.e., the screen and accelerator voltages are turned off and then back on) to ensure that the arc is stopped. In the past no conscious attempt has been made to limit the output capacitance of the screen and accelerator power supply system to minimize arc damage or to quickly shut down (or open) the screen/accelerator supply circuit due to the forgiving nature of molybdenum-based grids.

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Most conventional ion thrusters that use molybdenum grids display relatively high electrical breakdown rates when they are operated for the first time, but this rate typically decreases rapidly to values on the order of one arc per hour after a few tens of hours of operation. This recycle rate has been shown to be low enough to not limit the life time of a molybdenum grid set. It is expected that the same high recycle rate behavior at BOL will occur using grids fabricated from advanced carbon-carbon composite materials. If care is taken not to damage the grids during this break-in period, one would expect the recycle rate to drop similar to metal-based optics. However, as the carbon-based grids age over life due to sputter erosion by charge exchange ions, the surface may develop features that are susceptible to more frequent arc initiation. This concern is supported by electrical breakdown testing of carbon-carbon surfaces that have displayed very high arc frequency and low arc initiation voltages when their surfaces are not properly cleaned of debris and broken fibers or when violent arcs are allowed to develop due to operation with high output capacitance power supplies.

In this paper, the results of NEXIS sub-scale (gridlet) tests are described. Specifically, the effects of applied voltage, grid-to-grid spacing, and accelerator hole diameter on impingement current and electron backstreaming limits are presented. It is noted that all of the NEXIS data presented in this paper were acquired using gridlets fabricated from relatively inexpensive Poco graphite plates (polycrystalline graphite). Poco graphite is being used to develop the test and handling procedures that will be necessary to evaluate more expensive and until recently unavailable carbon-carbon (CC) composite material that will be used to construct NEXIS grids. The CC composite material selected for NEXIS grids is densified with carbon from a high temperature physical vapor deposition process, and then coated with pyrolytic graphite (after the apertures have been laser drilled). One goal of a multi-year program at Colorado State University (CSU) is to address the concern of withstanding high applied voltages and electric fields at the early onset or infant mortality stage (i.e., within the first ~1,000 hrs of operation). In order to determine what will happen later on during a mission, accelerated wear tests are being planned and will be described in this paper. Briefly, the accelerator gridlet will be subjected to intense physical sputtering in a SPECTOR™ Ion Beam Deposition (IBD) tool. The accelerator gridlet will be mounted on a target fixture that will be automatically and continuously tilted and rotated relative to an energetic ion beam to “age” the gridlet in a way that simulates how wear occurs on the accelerator grid of an actual ion thruster.

Accelerated aging will be predominately performed on the downstream face of the accelerator gridlet using masks that will only allow erosion to occur in pit and groove locations and to a lesser extent on the barrel regions of the accelerator gridlet apertures. Some “aging” will also be performed on the upstream face of the gridlet to simulate the anticipated amount of wear that occurs around the perimeter of accelerator holes on the upstream side of the grid. It is believed that the erosion caused during sputter processing will occur at rates that are at least 50 times faster than erosion expected during actual thruster operation. Although not identical to the wear that will actually occur, the accelerated erosion will likely result in a sputtered surface texture that will be representative of an actual worn accel grid. After fixed periods of aging, the gridlets will be remounted in the gridlet test fixture, and the maximum electric field will be re-determined under ion beam extraction conditions. The aging and electric field testing will be repeated a number of times in an effort to characterize electric-field-induced breakdown processes that may occur during long-term ion thruster operation at high specific impulse conditions. In order to avoid unintentional arc damage, the electric-field breakdown tests must be performed using advanced arc suppression power supplies. Results of gridlet breakdown testing are presented with a power supply based on three-phase-switching converter technology that was developed by Colorado Power Electronics where significant (100x) reductions in charge transfer were achieved over state of the art laboratory power supplies equipped with arc suppression circuits.

II. Gridlet Evaluation Technique Summary

A photograph and sketch of the gridlet test facility and a drawing of gridlet geometry are shown in Fig. 1. The sketch in Fig. 1b shows the ion optics geometry and Table 1 contains a list of the NEXIS ion optics geometry tested in this study. In general, the NEXIS geometry is scaled to be ~3.5 times larger than the NSTAR thruster except for the accelerator grid thickness, which is 5.4 times larger. Additional details concerning gridlet test procedures and evaluation of gridlet test results are presented in Laufer et al. 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 precision-placed alignment holes. The inner diameter of the discharge chamber was much larger than the active

2 American Institute of Aeronautics and Astronautics
diameter of the gridlets to ensure that the discharge chamber plasma properties would be uniform over the entire gridlet area, and thereby impose common behavior in all beamlets. The uniform discharge plasma condition allowed division of the measured beam current \((J_B)\) by the number of apertures to obtain the per hole or beamlet current \((J_b)\). 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 \((J_A)\) was converted to a per beamlet value \((J_{imp})\) by dividing the ammeter reading by the number of active accelerator grid apertures. Typical impingement data are displayed by plotting the ratio of \(J_{imp}/J_b\) versus \(J_b\). Limits on the beamlet current occur at both low and high values where processes occur that drive energetic beam ions directly into the accelerator grid. One goal of gridlet testing is to determine the range of beamlet currents where an ion optics system can be safely operated.

The ability of an ion optics system to impart a negative potential throughout the beamlet volume near the axial location of the accelerator grid determines its capacity to stop beam plasma electrons from backstreaming into the discharge chamber. The geometry of a typical ion optics aperture set applies boundary conditions that result in an electrostatic potential saddle point being formed near the axial location of the accelerator grid on the beamlet centerline. The saddle point presents the lowest resistance path to electrons on trajectories that could carry them from the beam plasma toward the discharge plasma. The magnitude of the negative voltage that must be applied to the accelerator grid to prevent electron backstreaming, the backstreaming limit, was measured at each beamlet current and grid geometry condition investigated. This was accomplished by (1) setting the accelerator voltage magnitude to a value where no backstreaming occurs, (2) slowly decreasing the accelerator voltage magnitude and simultaneously monitoring the beam current, and (3) reducing the beam current/accelerator voltage data to determine the voltage where the beam current increases to a value 2% due to backstreaming electron flow.

**TABLE 1.** NEXIS-like 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>3.585</td>
</tr>
<tr>
<td>(t_s)</td>
<td>Screen grid thickness</td>
<td>4.000</td>
</tr>
<tr>
<td>(d_a)</td>
<td>Accel hole diameter</td>
<td>3.578</td>
</tr>
<tr>
<td>(t_a)</td>
<td>Accel grid thickness</td>
<td>5.394</td>
</tr>
<tr>
<td>(\ell_g)</td>
<td>Grid-to-grid gap</td>
<td>3.574</td>
</tr>
<tr>
<td>(\ell_{cc})</td>
<td>Hole-to-hole spacing</td>
<td>3.577</td>
</tr>
</tbody>
</table>

* Dimensions are relative to NSTAR thruster optics
III. Results

Experimental and analytical results are broken up into three sections. The first section presents gridlet data where the impingement and electron backstreaming limits are determined for the NEXIS geometry as a function of applied voltage and grid-to-grid spacing. The second section contains results of tests characterizing the accelerated wear test facility and an analysis of the time required to “age” a grid surface to a given number of hours of actual in-space operation. The final section summarizes the electrical breakdown testing that has been performed to date with laboratory and specially designed arc-suppression power supplies.

A. NEXIS Gridlet Testing

Typical accel grid impingement current data display a “U” shape when plotted as a ratio of impingement-to-beamlet current versus beamlet current as shown in Fig. 2a. Note that the beamlet current was varied in this experiment by varying the discharge current while holding the discharge, beam, and accel voltages constant. At low beamlet currents, the relative impingement current rose due to crossover ion impingement on the downstream edge of the accel hole barrels. At moderate beamlet currents, the relative impingement current is flat and at a value dependent upon the background neutral density and the propellant utilization efficiency of the ion source. In our small vacuum facility operating at low propellant utilization, the baseline impingement current typically lies between 1% and 5% of the beam current. In comparison, the average accelerator-to-beam current of the laboratory model (LM) NEXIS engine was 1.6% during testing performed in the JPL “patio chamber.” As the beamlet current is increased to higher values, the relative impingement current again rose quickly indicating that direct ion interception was occurring on the upstream edge of the accel hole barrels due to perveance (or space-charge) limitations. Figure 2a indicates that the safe operating range of the NEXIS gridlets was relatively large at 6.05 kV of total accelerating voltage (V_T) and the ratio of perveance to crossover beamlet currents was ~7. Figure 2b contains similar data collected over a wide range of net and total voltages where the ratio of perveance to crossover current remained between 7 and 7.2. Numerical simulations currently agree quite well with experimental perveance limits, however, they do not agree with experimentally measured crossover limits. This situation is shown in Fig. 2c where an impingement curve calculated using numerical simulation tools available at CSU is compared to experimental measurements made at a grid gap of 2.34 (relative to NSTAR). The numerically determined crossover limit was found to be 50% less than the experimentally determined value. More work is needed to determine why this difference occurs.

Fig. 2a Typical impingement data collected at V_T = 6.05 kV.
Fig. 2b   Impingement limit data collected over a wide range of net operating voltages.

Fig. 2c   Comparison of numerical simulation and experimentally determined impingement limit data at $V_N=2800$ V and 2.34 spacing (rel to NSTAR). The baseline of the experimental data was offset by 3% to simplify comparisons to the numerical simulation output that only identified directly (i.e., non-CEX) impinging ion current.
Many impingement limit curves similar to those shown in Fig. 2 were reduced to determine the crossover and perveance limits on beamlet current, and Fig. 3a shows the effect that grid-to-grid spacing had on the perveance limit over a range of total accelerating voltages, $V_T (V_T = V_N - V_A)$. The spacing was varied from the nominal value to 44% of nominal in five steps. In order to orient the reader familiar with conventional propulsion systems, it is noted that the LM NEXIS thruster has achieved a specific impulse of over 7500 sec at a net accelerating voltage of $V_N = 5400$ V. Three of the data sets in Fig. 3a were re-plotted in Fig. 3b, and the solid line located just above each curve represents the space-charge limited beamlet current given by Eq. (1):

$$J_{b,pl} = \frac{\pi \sigma_o}{9} \sqrt{\frac{2q}{m}} \frac{V_T^{3/2} d_s^2}{\ell_c^2}.$$  \hspace{1cm} (1)

In Eq. (1), $J_{b,pl}$ represents the beamlet current at the perveance limit, $\varepsilon_o$ permittivity of free space, $q$ charge on a singly ionized ion, $m$ mass of a xenon ion, $V_T$ total voltage difference between the screen and accelerator grids, $d_s$ screen hole diameter, and $\ell_c$ effective grid gap. The equation for beamlet current was derived from the Child-Langmuir expression for current density by multiplying by the cross-sectional area of a screen hole. The effective ion acceleration length, $\ell_c$, was calculated using the following equation.

$$\ell_c = \sqrt{(t_s + \ell_g)^2 + \frac{d_s^2}{4}}$$ \hspace{1cm} (2)

In Eq. (2), $t_s$ represents the screen grid thickness and the other parameters are described above and in Table 1. An interesting point to gleam from the data shown in Fig. 3a is that the experimental perveance limits are only 10% to 15% below their corresponding maximum theoretical values.

![Fig. 3a Effect of grid spacing on perveance limit.](image_url)
The NEXIS thruster was designed to have a peak beamlet current of about 1 mA/hole, and Fig. 3a shows that beamlet currents up to 2.6x higher are possible before direct beam ion impingement occurs on the accelerator grid due to perveance limitations. This de-rated operational condition was intentionally chosen for the NEXIS thruster to optimize lifetime and propellant throughput, which can be significantly reduced at higher beamlet currents and high total accelerating voltages due to the production of charge-exchange ions near the screen grid that can strike the accelerator grid with high energy and cause rapid sputter erosion.

Figure 3b shows the effect of grid spacing on crossover limits over the same range of total voltage plotted in Figs. 3a and 3b. At $V_T=5900$ V (i.e., $V_N=5400$ V, $V_A=-500$ V) for the nominal spacing, the crossover beamlet current limit was ~0.4 mA/hole. To operate without direct crossover impingement, the highly de-rated NEXIS thruster must have all beamlets operate at an ion current greater than this limit (at $V_T=5900$ V). The LM NEXIS thruster has a very flat density profile, and flatness parameters of 0.82 have been documented. The peak beamlet current for the LM NEXIS thruster operating at a total beam current of 3.82 A was ~1 mA/hole and the minimum beamlet current was estimated to be roughly

![Image](image-url)
1/2 to 1/3 of this value (or ~0.5 to 0.33 mA/hole) from current density measurements made just upstream and downstream of the accelerator grid. The nominal spacing of the LM NEXIS thruster was 4.12 times larger than the NSTAR gap (and ~15% larger than the nominal gap used in this study), which is believed to be adequate to eliminate direct impingement due to crossover ions for the LM thruster. An interesting point to gleam from the data shown in Fig. 3c is the dependence of the crossover limit on total voltage raised to the power of ~1.5 as indicated by the curve fits shown in the figure. This behavior suggests that the crossover impingement process that occurs at low beamlet currents may be related to space-charge limited processes.

Figures 4a and 4b contain pervane and crossover limit data, respectively, when the accel hole diameter was increased from the nominal value to a value 22% larger. As expected, the pervane limit increased with accel hole diameter and the crossover limit decreased. Although attractive for increasing safe beamlet current operational ranges, increases in accelerator hole diameter can increase the backstreaming limit (as described below) and can decrease the propellant utilization due to higher unionized propellant loss. Other advantages and disadvantages exist regarding accelerator hole size changes, and further work is required to optimize the selection of the accelerator hole diameter (and hole shape).

Figures 5a though 5d present backstreaming limit data collected on the NEXIS gridlets. Figure 5a is a plot of apparent beamlet current as the accelerator voltage magnitude was varied from 600 V to 200 V when the beamlet current (due to ion flow) was fixed at 3 mA at the -600 V accelerator grid bias. The increase in apparent beamlet current at 350 V is due to beam plasma electrons that backstream though the grids and deposit their energy into the ion source discharge chamber. Voltage magnitudes larger than this limit must be applied to the NEXIS accelerator grid to avoid excessive electron backstreaming and potentially harmful heat deposition into the discharge chamber. For the purposes of this paper, we will define the onset of backstreaming to occur when the apparent beamlet current rises 2% above the minimum current, which is at 350 V for the operating conditions listed in Fig. 5a. Many data sets like the one shown in Fig. 5a were collected at different operating conditions, and Fig. 5b contains backstreaming limit measurements derived from these data that were obtained over a range of beamlet

![Fig. 4a Effect of accel hole size on pervane limit.](image1)

![Fig. 4b Effect of accel hole size on crossover limit.](image2)

![Fig. 5a Typical indicated beamlet current versus accelerator voltage plot used to determine backstreaming limit.](image3)
currents from slightly above the crossover limit current to slightly below the perveance limit. The maximum backstreaming limit typically occurred at beamlet currents that were about midway between the crossover and perveance limits.

Figures 5c and 5d contain maximum backstreaming limit data that were collected over a range of grid-to-grid spacing values and over a range of accelerator hole diameter values that were measured as a function of net accelerating voltage. As expected, increases in net accelerating voltage increased the backstreaming limit as did increases in accelerator hole diameter. Also expected was the trend of increased backstreaming limit when the grid spacing was reduced. The backstreaming margin at the nominal spacing condition and $V_N = 5400$ V was measured to be 428 V, which is less than 75 V from the nominal accelerator voltage magnitude (i.e., only 75 V of margin against backstreaming). However, it is pointed out that this measurement was made at the midway point between the crossover and perveance limits, which is higher than the maximum beamlet current expected for the NEXIS thruster. The analytical model of Williams, Goebel, and Wilbur was used to estimate the backstreaming limit variation with beamlet current for the $V_N = 5400$ V operating condition at the nominal spacing and accelerator hole diameter and the results of this effort are shown in Fig. 6. At ~1 mA, the backstreaming limit was estimated to be 350 V, which corresponds to a 150 V margin to backstreaming onset when the nominal accelerator grid voltage of -500 V is applied. The assumptions made to generate the curve shown in Fig. 6 include a beam plasma electron temperature ($T_e$) of 5 eV, a beam plasma potential ($V_{bp}$) of 20 V relative to neutralizer common, and an onset definition of 1% electron backstreaming current. These estimates were made by best fitting the adjustable parameters in the model to several backstreaming curves obtained at different operating conditions. Future work is planned to measure the beam plasma properties in the gridlet test facility. Additional assumptions in the analytical model were that the ratio of the average beamlet-to-accelerator hole diameter varied smoothly with parabolic behavior from ~0.6 at the crossover limit to a tightly focused minimum of 0.35 at ~1 mA to 0.9 at the perveance limit.
B. Accelerated Gridlet Wear Testing Facility

Agere, Inc. donated a dual ion beam deposition system to Colorado State University, which is being prepared for use in performing accelerated wear testing of gridlet assemblies. Photographs of the ion beam deposition facility and ion beam diagnostic equipment are shown in Fig. 1. Ion current density profiles were measured downstream of the 16-cm diameter RF ion source (shown in the lower left photograph of Fig. 1). Most of the current density profiles recorded to date were taken at ~40 cm downstream of the plasma source where gridlets will be placed during long-term sputter exposure runs. The lower right photograph shows an ion beam striking a test sample that was mounted to the 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.

A typical current density profile is shown in Fig. 8 for conditions where the ion source was operated on xenon with a beam voltage of 750 eV and a beam current of 250 mA. To date, the ion source has been operated at beam voltages ranging from 100 V to 1,500 V and beam currents from 50 mA to 600 mA. In addition, long term
sputter tests (of ~10 hr duration) have been completed in the facility at several different beam voltages (as low as 100 V) under fully autonomous control. It is noted that exposures at 1000 eV and 45° incidence will cause erosion rates that are in excess of 50 times those expected in the pit and groove regions of the accelerator grid on a NEXIS thruster operated under deep space conditions (see additional details below).

The current density data shown in Fig. 8 were taken using 2.5 mm steps starting at a reference location of 7 cm and stopping at 40 cm. The centerline of the ion beam indicated at 23.5 cm in Fig. 8 was found by measuring the midpoint distance between the two wings of the ion beam profile. The centerline position of 23.5 cm was close to the geometrical centerline position of 23.2 cm, which was measured with the use of a fixture that mounts within the ion source ground shroud and fires a laser pointer along the axis of the ion source. The probe positioning system is based on a Danaher SuperSlide™ drive-screw actuator that uses a Trio™ stepper motor controller to drive an Oriental Motors™ stepper motor mounted on a cooling plate within the vacuum facility. The motor is equipped with a built-in position indexer that allows feedback control of the probe location. The resolution of the probe actuator system was verified to be ±0.1 mm.

The ion current density data shown in Fig. 8 was measured using a Faraday probe whose entrance aperture (d=5.1 mm) was covered with a transparent nickel mesh (70x70 holes per inch and 90% open transparency). The probe body and screen were held at -30 V relative to the facility ground and the ion collecting cup located inside the Faraday cage was biased at +30 V to repel low energy charge exchange ions and to prevent secondary electron emission from the current sensing surface.

Integration of the current density data contained in Fig. 8 yielded a beam current of 129 mA which was significantly lower than the measured beam current of 250 mA. The integrated beam current obtained from the data shown in Fig. 8 is mostly comprised of energetic ions that have successfully transited from the ion source to the probe location (z=40 cm) without suffering charge exchange or (greater than ~40°) ion-neutral scattering collisions. The total current density of ions and fast neutrals that make it to the probe can be estimated by calculating the CEX mean-free path and using it in the survival equation to determine an enhancement factor of 1.67 (the value used to multiply the measured current density data shown in Fig. 8 in order to obtain the curve labeled “Total Ion and Fast Neutral Current Density”). Integration of the total current density curve results in a total equivalent current of 216 mA, which is 13.7 % lower than the measured current of 250 mA. If all of the difference between the total equivalent current and measured current is assumed to be due to scattering, it is possible to calculate the ratio of scattered ion current (250 - 216 mA) to CEX ion current (216 - 129 mA) to be 0.4. In other words, the scattering cross section appears to be ~40% of the CEX cross section at this energy. Although this calculation is quite sensitive to the assumed/measured values of (a) the CEX cross section and (b) neutral density within the region between the ion source and the target, it appears to be higher than expected. However, it is pointed out that a rough estimate of the scattering cross section (i.e., the area corresponding to a circle with a radius that is equal to twice the radii of a neutral xenon atom) is close to 40% of the CEX cross section at 750 eV ($\sigma_{\text{CEX}} (750 \text{ eV}) = 36\times10^{-20} \text{ m}^2$).

An analysis was performed to estimate how fast the NEXIS gridlets will be worn in the facility described above relative to the wear rate that will occur under deep space conditions, and the results of this analysis are summarized below. The NEXIS accelerator current that will be expected in the vacuum conditions of deep space has been estimated to be 0.5% of the beam current.5 If this current is assumed to fall onto the downstream surface of the accelerator grid in pit and groove locations that are 0.7 mm wide, an average current density of ~0.04 mA/cm² would be expected over the 57 cm diameter NEXIS accelerator grid. Note that the pit and groove area assumed in the analysis corresponds to ~25% of the accelerator grid webbing. The recession rate of the ion bombarded surface would be expected to be 9 nm/hr under 500 eV xenon ion bombardment at normal incidence (assuming a carbon-carbon sputter yield of 0.11 atoms/ion from Williams et al6). The recession rate under 500 eV ion bombardment at normal incidence in our sputter facility would be ~0.14 μm/hr if the beam current were set to 250 mA. Increasing the beam current to 500 mA, the ion energy to 1000 eV, and setting the angle of incidence to 45° would increase the etch rate to 0.9 μm/hr. When two masks are used to generate the pit and groove pattern in separate sputter exposure runs, the average etch rate would be reduced to 0.45 μm/hr. This etch rate is 50x higher than the erosion rates under deep space conditions. The pyrolytic coating applied to the NEXIS CC composite material is ~40 μm thick. This coating would be eroded through under in-space conditions in ~4500 hrs (on average). The same amount of wear could be realized in the sputtering facility described above in 90 hrs (about 4 days) of beam operational time (45 hrs with one mask and 45 hrs with another to generate full pit and groove patterns). In order to orient the reader, it is noted that wear testing in ground based test facilities (similar to the JPL “patio” chamber) would erode through the pyrolytic coating in ~1500 to 2000 hrs if the material that is back-sputtered from the target onto the accelerator grid.
surface could be neglected. Unfortunately, the back-sputtered material is probably not negligible due to the very powerful NEXIS ion beam that causes ~10 to 12 Aeq of back-sputtered target material.

Fig. 7 Photographs of ion beam deposition facility to be used for performing accelerated wear tests.

Fig. 8 Xenon ion and fast neutral flux profile measured 40 cm downstream of the 16 cm diameter ion source.
C. Gridlet Electric Field Breakdown Testing

In order to avoid unintentional arc damage of sensitive CC composite surfaces, the electric-field breakdown tests planned for the NEXIS gridlets processed in the accelerated wear test facility must be performed using advanced arc suppression power supplies. Results of gridlet breakdown testing are presented in Fig. 9 that were obtained with both a laboratory power supply and a power supply based on three-phase-switching converter technology that was developed by Colorado Power Electronics.\textsuperscript{9} As indicated in Fig. 9, significant (>100x) reductions in charge transfer were achieved over laboratory power supplies equipped with arc suppression circuits. Figure 10 contains a comparison of impingement data collected with the two different power supplies, which were found to be in good agreement. It is noted from the data in Fig. 10 that the NEXIS thruster could be safely operated at beamlet currents up to 3 mA at the 3200 V screen voltage condition. This lower net accelerating voltage operating point is attractive for missions requiring higher thrust and lower specific impulse operation to lift spacecraft out of regions surrounding planets. If the threat of arc damage could be avoided through the use of a 3-phase-converter power supply system, and a discharge chamber could be designed to deliver this much beamlet current, the data in Fig. 10 suggest that the 57-cm NEXIS thruster could be operated at a power level approaching 40 kW at a specific impulse of 5800 sec. It is noted that efficiency measurements made on the prototype 3-phase-converter power supply were 95.2% over a range of output voltage, and, furthermore, this type of power conversion topology is inherently easier to maintain high efficiency over output voltages ranges from nominal to 50% of nominal.\textsuperscript{3}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig9.png}
\caption{Screen voltage and current waveforms during gridlet-to-gridlet arcs recorded with arc-suppression-equipped laboratory power supply and advanced 3-phase-converter-based power supply. Note that the arc current waveform of the 3-phase-convertor supply was nearly undetectable on the scale used for the laboratory supply.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig10.png}
\caption{Comparison of impingement limit data collected with laboratory and advanced 3-phase-converter-based power supplies.}
\end{figure}
IV. Conclusions

Sub-scale ion optics testing was completed on NEXIS-like ion optics geometry over wide ranges of net and total accelerating voltage, accelerator hole diameter, and grid spacing. Wide margins to backstreaming and perveance limits were observed, however, experimental crossover limits were recorded that indicate relatively small margins exist at small grid spacing or high total voltage. Numerical simulations agree with perveance limit measurements, but underestimate the crossover limits, and more work is necessary to resolve this issue. It is noted that spacing the grids further apart would increase the crossover margin, which is quite sensitive to grid spacing. A facility was described where accelerated gridlet wear tests could be conducted that would allow electrical breakdown phenomena to be characterized in only 2000 hrs that would be equivalent to an in-space operational time of 100 khr. In regard to electrical breakdown testing, very promising results were obtained in minimizing the current transfer that occurs between the grids during an arc when a 3-phase-converter-based power supply was used to conduct tests. A screen/ accel power supply combination based on this technology will enable electric field breakdown measurements to be conducted on gridlets subjected to accelerated wear testing without fear of damaging the pyrolytic coating applied to the carbon-carbon composite surface.

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