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Results of a 1000-hour Wear Test of 30-cm Carbon-Carbon Ion Optics

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The success of the NSTAR ion engine on the Deep Space 1 spacecraft coupled with the recent success of the ground-based life test of the flight spare engine has paved the way for implementation of ion thrusters on NASA science missions. Even with the long life demonstrated during the flight spare test, greater propellant throughput is still desired. One relatively simple way to increase thruster life is to use carbon-based ion optics, which are much more resistant to erosion than molybdenum optics. Carbon-carbon ion optics have recently been demonstrated to meet performance requirements and withstand launch loads. The present paper discusses the results of a 1000-hour wear test intended to determine the erosion resistance and voltage standoff capability of the optics in a relevant environment, i.e. duration testing on an NSTAR-like thruster. The wear test was conducted for 1029 hours at a beam voltage of 1800 V and a beam current of 1.76 A. Ion optics performance was stable throughout the test with slight decreases observed in the perveance limit. Accelerator grid erosion was characterized by measuring the pits and grooves erosion profile at the center of the grid. Erosion rates of 27 μm/hr in the pits were determined. Erosion data were compared to calculations using a 3D ion optics code with excellent results. The ion optics operated at the nominal test voltages for the duration of the test with recycle rates initially as low as 0.2 per hour, and less than five per hour for the bulk of the test. Field emission currents between the grids were observed and were identified as occurring at the edge of the optics assembly in a region of electric field stress in excess of the material threshold. This problem can be easily eliminated in future developments by a simple design change which does not impact thruster performance. Carbon-carbon ion optics technology is now ready for the next phase of development, flight qualification, and implementation on NASA science mission.

I. Introduction

The success of the NSTAR ion engine[1] on NASA's Deep Space 1 spacecraft coupled with the recent success of the ground-based Extended Life Test (ELT) of the NSTAR flight spare[2] has paved the way for implementation of ion thrusters on future science missions such as Dawn.[3] Even though the ELT demonstrated more than 30,000 hours of operation and a throughput in excess of 235 kg of xenon, far in excess of the design lifetime, flight programs are clamoring for greater thruster life. A relatively simple way to increase thruster life is to replace the molybdenum-based ion optics with a material that is more erosion resistant. Carbon-carbon (CC) has shown to be an excellent candidate for ion thruster optics because of its low sputter yield (desirable for erosion resistance), high strength (desirable for vibration tolerance), and low coefficient of thermal expansion (desirable for control of grid gap).[4] Although carbon-carbon materials have been subject to sputter erosion measurements and wear testing in developments of the past decade, none of those programs strived to produce a relatively large diameter ion optics design capable of meeting performance requirements, passing vibration testing, and demonstrating reduced erosion resistance compared to molybdenum.[4] JPL has recently designed and fabricated 30-cm-dia. carbon-carbon ion optics to meet these goals under the Carbon-Based Ion Optics (CBIO) project, and those grids have already demonstrated the ability to meet performance and vibration testing requirements.[5,6] Although this recent work has answered some fundamental questions about the viability of 30-cm carbon-carbon ion optics, it is also necessary to demonstrate that such optics can provide the long-term voltage standoff capability and reduced wear required for high-Isp, long-life thrusters.

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Several long-duration thruster tests have been performed with carbon-carbon grids to characterize grid wear and voltage standoff capability (though not necessarily explicitly stated for the latter). Most tests have demonstrated reduced erosion rates compared to molybdenum optics and the ability of CC optics to hold off voltage for the duration of the test. Mueller et al.[7] characterized aperture diameter enlargement and mass loss for a 15-cm three-grid system operated for 700 hours. Meserole[8] compared pits-and-grooves erosion of 10-cm CC and molybdenum optics and determined that the erosion rate of the CC accelerator grid was one-eighth to one-ninth that of the molybdenum grid. Hayakawa et al.[9] terminated an endurance test after 3814 hours because of excessive arcing, likely due to the significant surface damage resulting from the arcing.[10] The longest duration test of CC optics was the 18,000-hour test of a 10-cm, three-grid system[11] for the HAYABUSA mission which has achieved more than 10,000 hours of flight operation of CC grids.[12] These optics were operated at a relatively high electric field (3.6 kV/mm) and moderate beam current density (1.4 mA/cm^2) for the bulk of the test. There were no reported problems with voltage standoff and no change in thruster performance over the course of the test. Erosion rates, characterized by mass loss and aperture diameter measurement, were low.

The results of tests performed to date are encouraging, but additional work is necessary to determine the performance of CC materials required for high-power, high-Isp thrusters with larger beam diameters necessary for missions such as the proposed Jupiter Icy Moons Orbiter.[13] The sputter yield of different types of CC composites can be quite different[4] and voltage standoff capability strongly depends on the material and surface features[10] so it is important to characterize the materials of interest. The carbon-carbon ion optics developed by JPL for 30-cm and larger thrusters employ high-modulus fibers for grid stiffness and vibration tolerance.[14] The sputter yield[15] and high-voltage breakdown[10] characteristics of these materials have been thoroughly characterized.

The goals of the wear test reported herein are threefold: to characterize accelerator grid erosion on an operating NSTAR-class thruster, to use the data to validate grid life models, and to demonstrate extended operation of CC grids (e.g. voltage standoff and recycle behavior). Discussion of the design of the CBIO 30-cm ion optics, performance test results, and vibration modeling and test results may be found in Refs. 5 and 6.

II. Test Setup

Selection of the ion optics test article from the available sets was driven by the desire to maximize the probability of achieving the test goals. Although eight complete sets of grids were produced, many of the grids were affected by problems during the manufacturing process[6] (these issues were identified and corrected for a subsequent optics fabrication[14]). In order to achieve the primary goal of characterizing erosion, the options were limited to the two optics assemblies capable of extracting the full 1.76 A from the ion engine, with Set 104B preferred because of the larger design grid gap and thus reduced operational risk due to manufacturing issues. This grid set was successfully operated without difficulty in earlier testing with one of the lowest recycle rates of the grids tested.[6] Ion optics set 104B is shown mounted on the wear test thruster in Fig. 1. Pre-test visual inspection of the conditions of the screen and accelerator grids yielded no significant findings other than minor damage to some of the screen grid webbings which had been identified earlier. Seven webs located from 2 to 4 cm from the outer edge of the active grid area were broken, with little-to-no displacement in the through-plane direction as seen in Fig. 2.

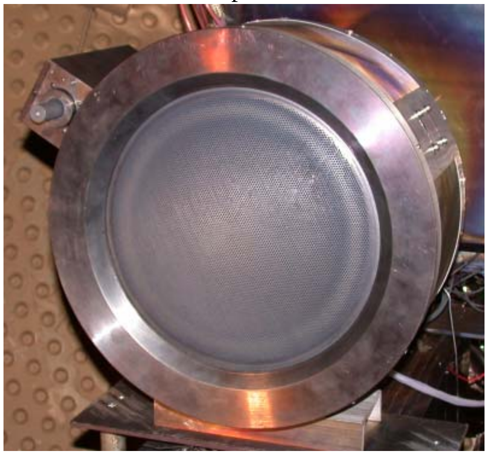


Fig. 1. Carbon-Carbon Grids Installed on NSTAR-Class Thruster for Wear Test.

Dimensional inspection of the ion optics prior to the wear test was performed with a non-contact optical measurement inspection system. Grid gap, aperture alignment, and accelerator grid aperture diameters were all determined with the system. The centerline grid gap was set to within 0.5% of the design value, although the gap at the periphery was 11% larger due an incorrect design of the mold used during fabrication.[6] The alignment between screen and accelerator grid apertures was measured for nineteen hole-pairs at the center region of the grid and was determined to be better than 1.4% of the aperture center-to-center spacing. The full set of pre-test inspection data are compared to post-test inspection data in Section IIIB.

The ion optics wear test was conducted on the NKO2 thruster (NSTAR-Knock-Off #2) designed and built at JPL to be functionally equivalent to the NSTAR 30-cm ion thruster. The discharge chamber magnetic field, thruster

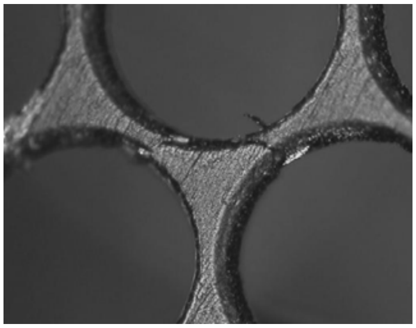


Fig. 2. Photograph of Screen Grid Broken Webbings Identified in Pre-Test Inspection.

performance, and beamlet current density were all directly measured and found to be essentially the same as for the NSTAR thruster. The NKO2 thruster was also used for all performance testing of the CBIO ion optics.

The wear test was performed in a 5.8-m long, 2.4-m diameter cryopumped vacuum facility with base pressure less than 10^{-7} Torr and a pumping speed on Xe of 50,000 L/s. Ion gauges calibrated on xenon were located on the vacuum tank wall just downstream of the thruster exit plane and inside the vacuum tank mounted 40 cm behind and 40 cm radially from the center of the accelerator grid. NIST-traceable mass flow and electrical calibrations were performed prior to the test.

The facility was instrumented with several diagnostics for the wear test. An in-situ camera system with resolution of 30 µm was used for grid aperture imaging. A quartz-crystal microbalance was located in the thruster exit plane 12 cm from the edge of the accelerator grid to record facility backsputter rates. Finally, a 23-mm-dia. tungsten-coated Faraday probe was traversed across a thruster diameter at a distance of 25 mm from the accelerator grid apex to record beam current density profiles.

A Spellman model SR6 rated at 3 kV and 2 A was used for the beam supply; the accelerator grid power supply was a Glassman model FC1N120 rated at 1kV and 120 mA. The recycle circuit used for the wear test was developed before charge-transfer limits for the carbon-carbon material were established.[10] Recycles were initiated on grid power supply overcurrents exceeding 100 ms. Under these conditions, arc charge transfers exceeded the recommendations derived from materials testing.[10] Autonomous thruster control and monitoring were provided by a LabView-based software program which recorded all thruster and facility telemetry and could shutdown the thruster in the event of a facility problem or an out-of-bounds condition.

Requirements for the CBIO project were developed from the 40-cm-dia. NASA Evolutionary Xenon Thruster (NEXT) program.[17] Operating conditions for CBIO testing were derived from NEXT operating conditions. The ion optics wear test was performed at a nominal condition of 1.76 A beam current with screen and accelerator grid voltages of +1800 V and -200 V, respectively. At regular intervals the optics performance was characterized at the nominal test condition as well as at the three other CBIO beam currents of 1.01, 0.75, and 0.34 A at the same grid voltages.[6] Thruster mass flow rates were determined directly from the NSTAR engine throttle table[1] at the equivalent beam currents. Perveance measurements were made by holding the beam current and accelerator grid voltage constant while varying the screen grid voltage and recording the accelerator grid current. The discharge current was adjusted in this case to maintain constant beam current. The perveance limit was defined as the point at which the rate-of-change of accelerator grid current was 0.02 mA/V. Electron backstreaming (EBS) onset was determined by reducing the magnitude of the accelerator grid voltage at constant discharge current and monitoring the beam ion energy cost, a 1% change in which defined the EBS limit. Finally, the screen grid transparency to ions was measured by biasing the screen grid negative of the cathode by twenty volts and recording the bias current. The ratio of the screen power supply current to the total screen current (i.e. bias current plus screen supply current) yielded the transparency. In addition to the optics performance measurements, beam current density profiles were recorded with a standard Faraday probe at each operating point. Finally, a pulse counter was used to record the number of recycles during the test.

III. Results and Discussion

The wear test was voluntarily terminated after 1029 hours of beam extraction. The beam current, shown in Fig. 3, was controlled to within ± 0.02 A although some outlier points were captured by the data system during performance tests, recycles, and thruster re-starts. Voltages measured on the ion optics were within 1790 ± 5 V and -200 ± 1 V, respectively, for the screen and accelerator grids throughout the test. The tank pressure measured at the thruster was nominally 8.3×10^{-6} Torr and was within about ±5% of this value over the course of the test. There were two significant interruptions during the test. The first interruption was caused by a broken cryopump head unit that necessitated opening of the vacuum chamber for repair and

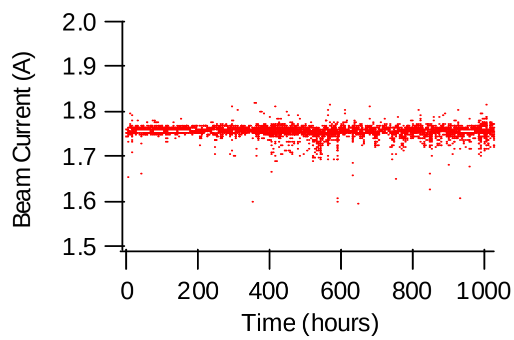


Fig. 3. Beam Current Extracted From Ion Optics Over Course of Wear Test.

replacement at the 588-hour point. At that point the opportunity was taken to remove the ion optics from the thruster for inspection but not disassembly. A second test interruption occurred at the 847-hour point for cyropump regeneration. Vacuum was not broken at that time.

A. Ion Optics Performance

Beam current density profiles measured at the beginning and end of the test are compared in Fig. 4 for three of the four operating conditions. The nominal test operating point shows the typical NSTAR profile.[16] There are slight differences in the beginning-of-test and end-of-test profiles, especially at the higher powers, but the differences in the peak beam currents are similar to those seen in the NEXT wear test[17] and the NSTAR ELT.[16]

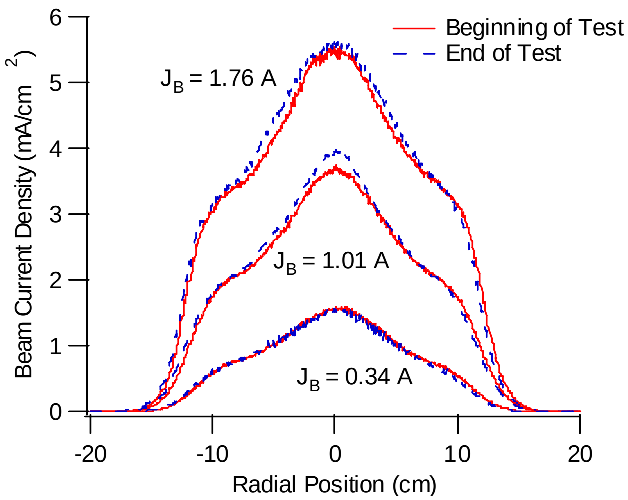


Fig. 4. Comparison of Beam Current Densities at Beginning and End of Test.

Trends in screen grid transparency, perveance limit, and EBS limit are shown in Fig. 5. The screen grid ion transparencies were essentially unchanged throughout the test. At each power level the transparency varied by no more than 0.005 from the average. Measurements of the perveance limit, however, showed slight decreases at the higher powers. At full power, the perveance limit decreased by 77 V. This is slightly more than the decreases observed in the first 1000 hours of the NEXT wear test[17] and the NSTAR LDT[18] at full power. Limits at the two intermediate powers decreased by a more modest 30-40 V and there was no change at the lowest power. Improvements in the perveance limit of the optics set were likely due to enlargement of the accelerator grid apertures (see Section B).

It was more difficult to determine trends in the EBS limit data due to data scatter. Error in interpretation of the EBS limit is much greater than the error for the transparency or perveance limits. The largest difference between beginning-of-test and end-of-test values was 20 V at the 1.01-A beam current condition. There does not appear to be a significant, stable trend in the EBS limit for this short-duration test, however, and the limits are all well below the nominal -200 V wear test operating point.

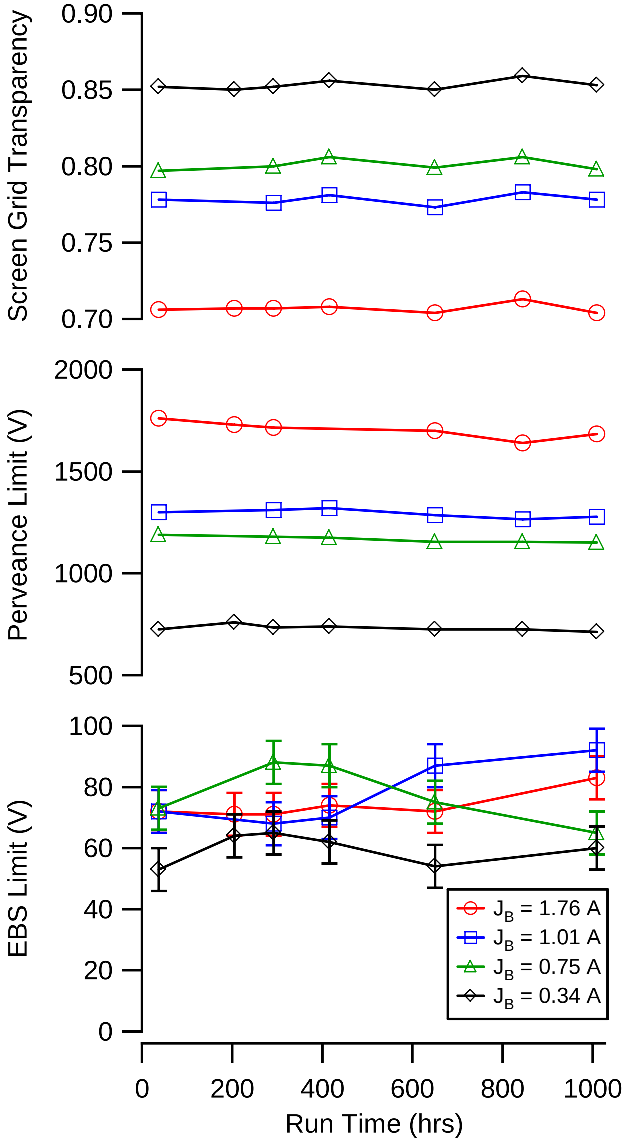


Fig. 5. Ion Optics Performance Trends.

Although the ion optics voltages and the beam current were steady throughout the wear test, the accelerator grid current displayed anomalous behavior. As seen in Fig. 6, the current at the beginning of the test was 15 mA (a relatively high value for NSTAR-class thrusters,[18] likely a result of the low tank pumping speed), reached levels as high as 57 mA, and showed correlation in time with the vacuum tank cryopump

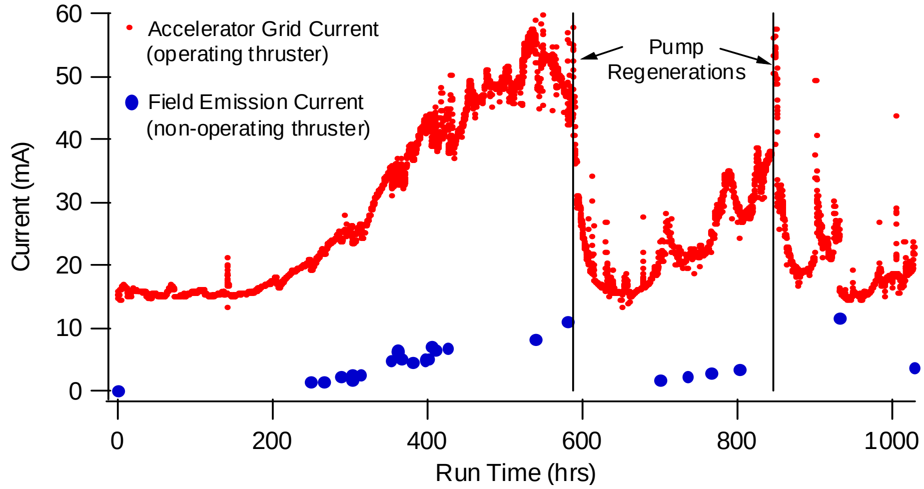


Fig. 6. Accelerator Grid and Field Emission Current Behavior Observed During Wear Test.

regenerations and levels of field emission current between the grids which were first observed at about 250 hours into the test. Smaller variations in accel grid current were also known to be related to temperature fluctuations in cryopump surfaces (e.g. at 70, 140, 610, 910, and 930 hours) and with thruster restarts after periods of non-operation, in which the vacuum facility had cooled and the pumping speed was slightly improved (e.g. at 205, 250, 305, and 830 hrs).

The field emission currents shown in Fig. 6 were measured with the thruster turned off and with a total voltage between grids of 2000 V. It was confirmed that the currents were field emission, not insulator leakage, when data collected over a range of voltages were plotted in the typical Fowler-Nordheim fashion,[19] as shown in Fig. 7, and showed the linear trend characteristic of field emission. The field emission current was periodically monitored throughout the test with the engine off and reached values as high as 11 mA at 580 and 930 hours for a total voltage of 2000 V. In general, the measured vacuum field emission currents did not account for the difference between increased accelerator grid currents in the operating thruster compared to the beginning-of-test value of 15 mA, suggesting enhancement of the current carried between the grids by the presence of plasma during thruster operation.

The trends in accelerator grid current with time are likely related to changes in surface morphology and environment at the field emitter sites during the test. Electron field emission at a given voltage depends exponentially on both the geometry of the emitting surface and its electronic state, which can be modified by adsorbed gases.[19] Surface geometry can be changed nearly instantaneously by arc damage[10] and over longer periods by Joule heating of emitter tips by the emission current.[19] Surface adsorbates affect field emission largely through modification of the local surface work function. Exposure of the carbon-carbon ion optics to atmosphere at the 588-hour mark and to ~1 Torr during cyropump regeneration at 847 hours caused such adsorbates to form on field-emitting surfaces. Studies have shown that exposure of carbon nanotube emitters to oxygen temporarily decreases field emission at a given voltage by two orders of magnitude, followed by complete recovery after removal of the contaminant gas source and operation for some tens of hours.[20] Such behavior is remarkably similar to the observed trend in field emission and accelerator grid currents after pump regenerations seen in Fig. 6. Although not a conclusive explanation of these trends, the effects of surface modification and adsorbate formation that occurred during the wear test are known to cause similar behavior.

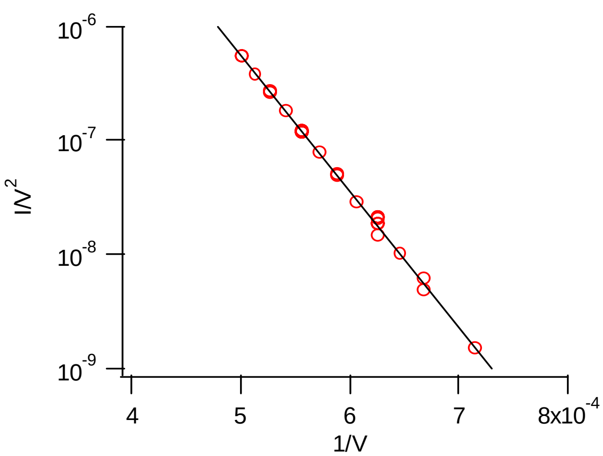


Fig. 7. Fowler-Nordheim Plot of Vacuum Current Between Screen and Accelerator Grids as a Function of Total Voltage.

Thruster and facility data were also analyzed to look for other possible explanations of the larger trends in accelerator grid current. Changes in collection of charge-exchange current from downstream of the accelerator grid were ruled out because of the stability of tank pressure and thruster operating conditions with time. Changes in direct ion impingement on the accelerator grid were ruled out for similar reasons. Post-test inspection of the optics (see Section IIIB) also failed to provide evidence for alternate explanations. Post-test inspection and electrostatic modeling, however, did provide conclusive evidence to support the presence of field emission.

The ion optics recycle rate, shown in Fig. 8, shows similar trends to the accelerator grid current. The increase in recycle rate observed from 300 to 590 hours, for example, is likely related to increased breakdowns in the region of increasing field emission. The rate of recycles was generally less than 5/hr for the duration of the test except for periods just after cyropump regeneration. The rate was as low as 0.22/hr (1 every 4.5 hours) before the field emission was first observed. The total number of recycles for the 1000-hour wear test was 2043. For comparison with molybdenum grids, the first 1000 hours of the NSTAR ELT saw just over 2000 recycles, the bulk of which occurred in the first 50 hours of the test. The NEXT wear test experienced about 3000 recycles over the same period, over half of which occurred during the first 250 hours of the test.[17] Both of these tests settled to rates on the order of one to three per hour. The recycle rate for the CBIO optics was also in the range of one to three per hour, except during the times when field emission contributions were particularly high. It is important to note that, even with broken webbings and field-emission-induced breakdown in non-active grid areas, the carbon-carbon grids in this wear test exhibited similar or better recycle behavior than molybdenum grids in other recent tests.

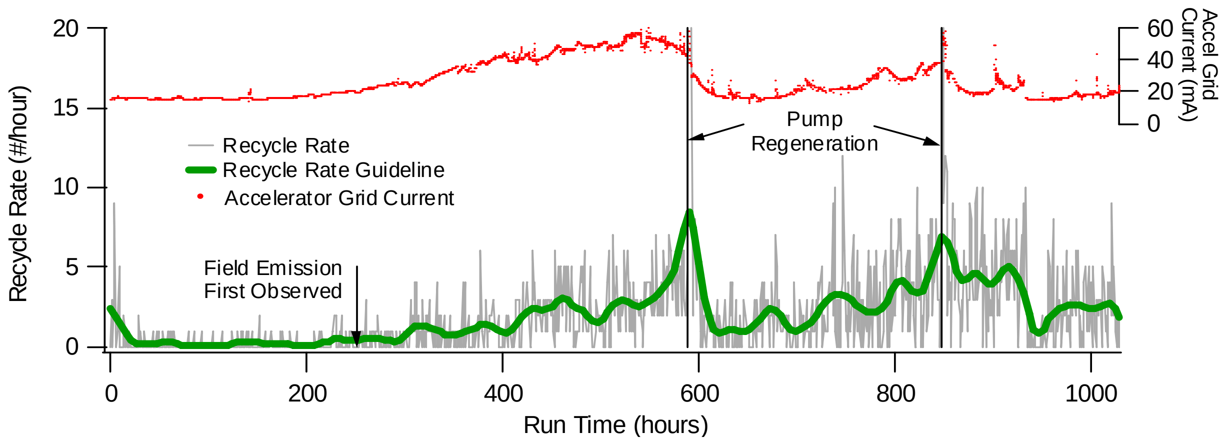


Fig. 8. Comparison of Ion Optics Recycle Rate and Accelerator Grid Current.

B. Post-Test Inspection

Following removal from the thruster, the optics assembly was visually inspected and photographed, then grid gap, aperture alignment, and accelerator grid hole diameters were measured using the same inspection system and method as prior to the test. The grids where then disassembled and their physical condition inspected. The insulator assemblies were clean and free of sputtered material; there was no loose or flaking material between the grids. No arc spots were observed on the active intra-grid surface of either the screen or accelerator grid. Twenty-five small arcs spots on non-active intra-grid surfaces were identified. Comparison of high-magnification photographs of the screen grid broken webbings identified before the wear test, like that shown in Fig. 2, showed no change in the condition of the webbings, e.g. no dislocation of webbings, no separation of intra-laminar plies, and no stray fibers. Apart from facility carbon backsputter on the downstream surface of the accelerator grid, there was little if any indication that the optics had been operated for an extended period of time.

The upstream surface of the accelerator grid was thoroughly inspected for signs of localized direct ion impingement and field emission. No anomalous erosion was observed on the upstream surface of the accelerator grid, even opposite the damaged screen grid webbings which would have been an indication of misaligned beamlets. Inspection of the edge of the screen grid assembly, however, showed three regions of localized discoloration and arcing, one of which is shown in Fig. 9, at the edge of the screen grid assembly that was not present in the pre-test photographs. There was no corresponding damage observed on the edges of the accelerator grid. The damaged areas roughly coincided with the locations where the measured edge grid gap, i.e. the gap measured at the circumference of the assembly, was at a minimum.

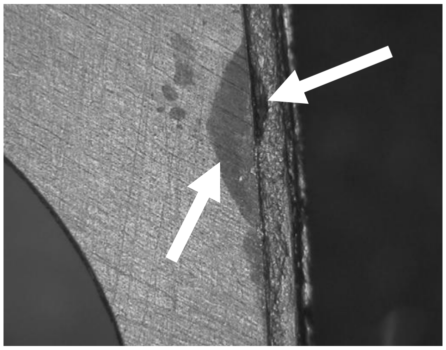


Fig. 9. Screen Grid Surface Damage at Location of High Electric Field Strength.

Electrostatic modeling of the assembly was performed to determine the electric fields at the grid edges, using the measured grid geometries and voltages. Corner radii of curvature were estimated by comparison to calibrated gauges under magnification. An example field map is shown in Fig. 10, where the maximum electric field of 5.1 kV/mm occurs at the edge inside of the outer diameter of the screen grid assembly, i.e. the region of damage in Fig. 9. Electric field is also concentrated at the corner of the accelerator grid and was 3.7 kV/mm for the field map of Fig. 10. The maximum calculated electric field strength at the accelerator grid edge is shown in Fig. 11 for edge gaps measured around the circumference of the grid assembly, where the spread in the field strength is representative of the uncertainty in the radius of curvature of the edge. Note that the locations of screen grid damage directly correspond to regions where the electric field exceeded the threshold for field emission of electrons from undamaged surfaces.[10] Accelerator grid surface roughening through arcing can reduce the threshold fields to less than 3 kV/mm.[10] Hence, it is clear that the correct environment for field emission was present, and was worst at the locations of the observed damage. The damage was caused by a combination of arcing and collection of electrons with energies of 2 keV and greater. In retrospect, small gaps at the edge of the optics assembly should have been identified earlier in the CBIO project as a technical risk. There is no need for high electric-field strengths in non-active areas of the grids, so this problem can be easily remedied by designing optics assemblies with larger non-active gaps as has been done for the NEXIS ion optics.[14]

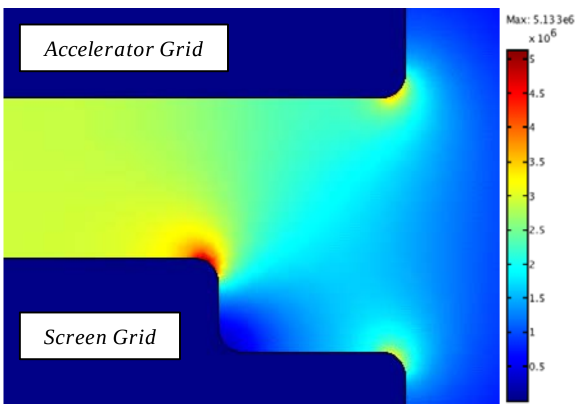


Fig. 10. Calculated Electric Fields at Edge of Optics Assembly.

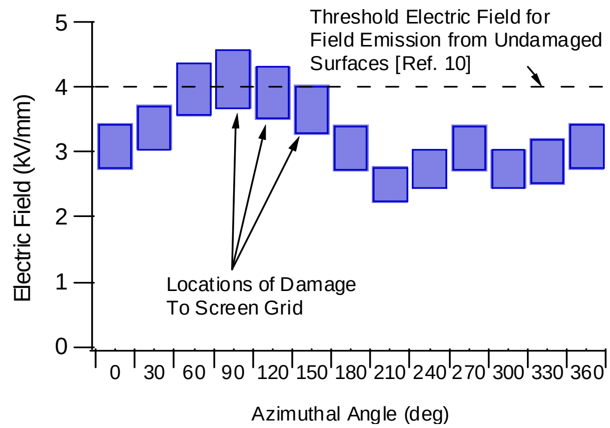


Fig. 11. Maximum Electric Field Calculated on Edge of Accelerator Grid.

Metrological inspection of the ion optics assembly was performed in the same manner as the pre-test inspections. There were no measurable changes in grid gap, as shown in Table 1, nor in aperture alignment. Accelerator grid aperture diameter measurements are compared in Fig. 12 for four apertures at the center of the grid. Diameter increases of 3 to 5% were recorded with this optical non-contact method. The bulk of the increase is likely related to removal of sooty residue inside the aperture leftover from the manufacturing process,[6] as suggested in Fig. 13. Center aperture diameter measurements with laser profilometry showed only a 0.2% diameter increase at 30μm below the downstream surface of the grid and no increase at 175 μm below the surface.

Table 1. Comparison of Pre- and Post-Test Normalized Grid Gap.

Location	Pre-Test	Post-Test
Centerline	1.00 ± 0.05	0.95 ± 0.07
Periphery	1.11 ± 0.10	1.12 ± 0.08

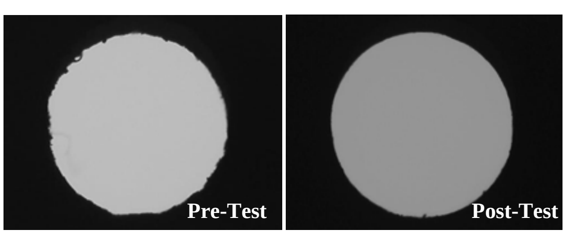


Fig. 13. Comparison of Accelerator Grid Center Aperture Before and After Wear Test.

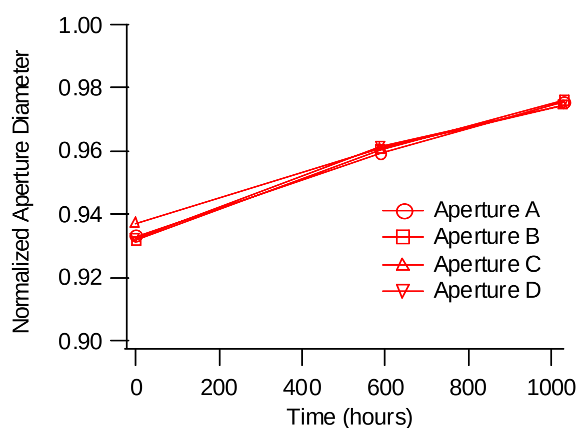
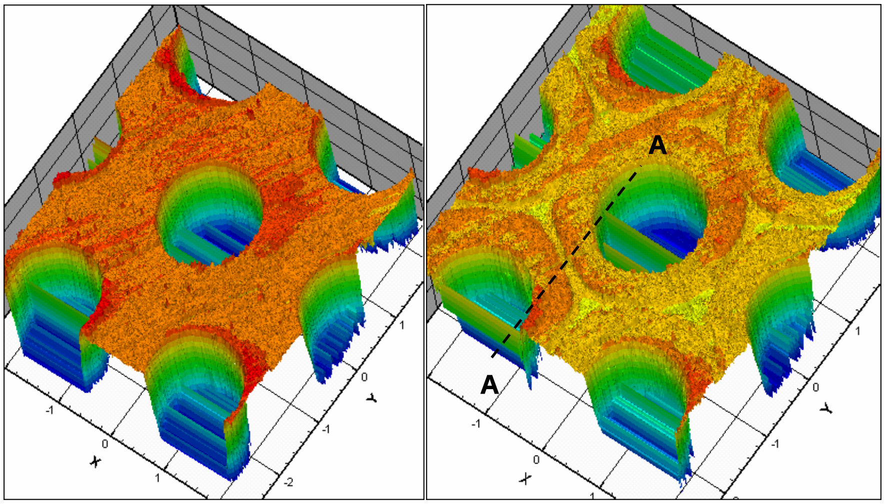


Fig. 12. Accelerator Grid Aperture Diameter Measurements.

C. Erosion Characterization for Accelerator Grid Downstream Surface

Erosion of the downstream surface of the accelerator grid surface by charge-exchange ion impingement was measured using laser profilometry. The laser, with a 2-µm spot size and 0.1-µm resolution, was rastered over an area surrounding the center aperture in step sizes of 13 µm to collect the data shown in Fig. 14. Pits-and-grooves cuts of the post-test data were extracted for each of the six hexagonal sides surrounding the center aperture. The pre-test and post-test cuts for section A-A are shown in Fig. 15. As depicted in the figure, pit depth was measured from the mesas surrounding the apertures to the bottom of the pits. Note that the bridge between pits of Fig. 15 did not experience net erosion, which was the case for half of the six cuts. The average depth for the six pits surrounding the center aperture was determined to be 27 ± 4 µm. Assuming that the facility backsputter rate of 4 µm/khr was distributed evenly across the face of the grid and that the mesa erosion rate was much less than the backsputter rate, a pit erosion rate of 27 µm/khr is determined from the data.



(a) Pre-Test. **(b) Post-Test.**

Fig. 14. Laser Profilometer Measurements of Accelerator Grid Area Surrounding Center Aperture.

A major goal of the wear test was to use erosion data to validate life models. Hence, measured erosion rates were compared to calculations performed with the JPL CEX3D code.[21] Recent understanding of neutral density distributions in NSTAR-class thrusters has improved the correlation between pit erosion rate calculations and test data using this code. Thruster and facility operational data from the wear test, the ion optics geometry, and sputter yield measurements for the carbon-carbon material used to fabricate the grids[15] were input to the code. Calculated and measured pits-and-grooves profiles are compared in Fig. 16. The agreement between the two results is very good. The code predicted a pit erosion rate of 22 µm/khr compared to the measured 27 µm/khr. Calculations for molybdenum grids under the same operating conditions yielded a pit erosion rate of 186 µm/khr, a factor of 8.5 greater erosion than for carbon-carbon grids.

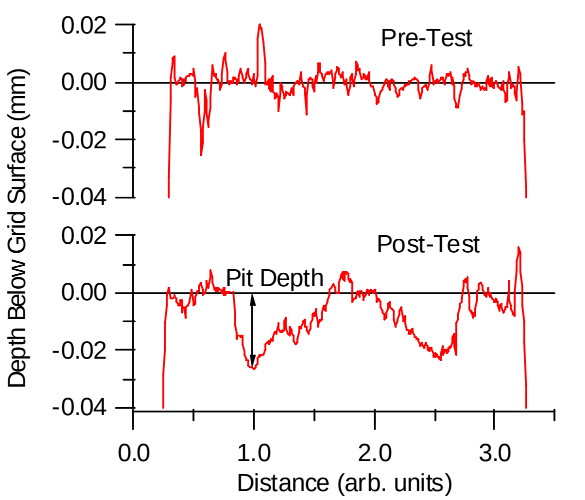


Fig. 15. Comparison of Pre- and Post-Test "Pits and Grooves" Scans for Cut A-A.

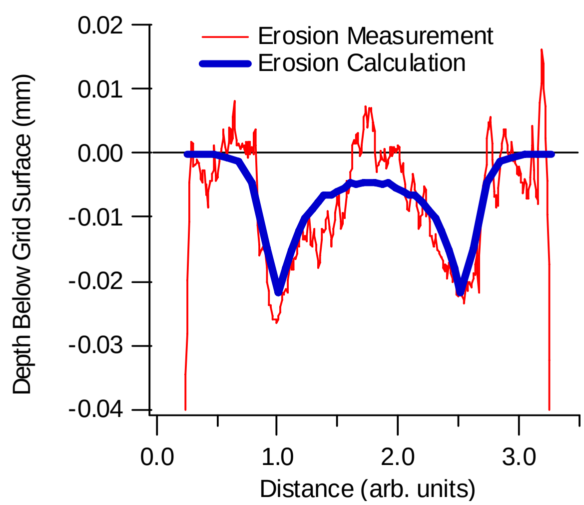


Fig. 16. Comparison of Measured and Calculated Pits-and-Grooves Erosion at Accelerator Grid Centerline.

The measurements and calculations presented herein have provided valuable data for validation of grid life models and enabled confidence in their use as design tools. When coupled with the agreement between predictions and calculations for molybdenum grids, these results confirm that carbon-carbon are much more erosion resistant than molybdenum grids.

IV. Conclusion

A 1029-hour wear test of 30-cm carbon-carbon ion optics was successfully completed and the test goals of demonstrating the erosion resistance, validating grid life models, and demonstrating voltage standoff and low recycle rates were achieved. The performance of the ion optics over the duration of the test was stable. Slight decreases in the perveance limit seen at higher powers were likely due to slight increases in accelerator grid aperture diameters. Pit erosion rates of 27 µm/khr were measured at the center of the accelerator grid. Calculated erosion rates were in good agreement with measurements, validating the use of the grid life codes as design tools. Equivalent erosion rates calculated for molybdenum optics under the same operating conditions were 186 µm/khr, a factor of 8.5 greater than for carbon-carbon.

The accelerator grid current displayed anomalous behavior over the course of the test, believed to result from time-varying field emission. The field emission electron currents detected between the screen and accelerator grids were determined to result from electric field stresses at the edge of the optics assembly that exceeded the material threshold for field emission. This problem can be easily avoided with a simple design change that would have no effect on thruster performance. There was no evidence to support other mechanisms for the observed long-term trends in accelerator grid current. Ion optics recycle rates, even with broken screen grid webbings and field-emission-induced breakdown, were as low or lower than for recent tests with molybdenum optics.

The Carbon-Based Ion Optics project has developed 30-cm carbon-carbon ion thruster grids and demonstrated their ability to meet performance requirements, to pass vibration testing, and to significantly surpass the lifetimes of molybdenum ion optics. The technology is now proven and ready for the next phase of development, flight qualification, and implementation on NASA science spacecraft.

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References

1. J.R. Brophy, "NASA's Deep Space 1 Ion Engine," Review of Scientific Instruments, Vol. 73, No. 2, Feb. 2002, pps. 1071-1078.

2. A. Sengupta, J.R. Brophy, J.R. Anderson, C. Garner, K. de Groh, T. Karniotis, B. Banks, "An Overview of the Results from the 30,000 Hr Life Test of Deep Space 1 Flight Spare Engine," AIAA 2004-3608, 40th Joint Propulsion Conference, Fort Lauderdale, FL, July 2004.

3. J.R. Brophy, G.B. Ganapathi, C.E. Garner, J. Gates, J. Lo, M.G. Marcucci, and B. Nakazono, "Status of the Dawn Ion Propulsion System," AIAA 2004-3433, 40th Joint Propulsion Conference, Fort Lauderdale, FL, July 2004.

4. J.S. Snyder, "Review of Carbon-Based Grid Development Activities for Ion Thruster," AIAA 2003-4715, 39th Joint Propulsion Conference, Huntsville, AL, July 2003.

5. J.S. Snyder, J.R. Brophy, D.M. Goebel, and J.S. Beatty, "Development and Testing of Carbon-Based Ion Optics for 30-cm Ion Thrusters," AIAA 2003-4716, 39th Joint Propulsion Conference, Huntsville, AL, July 2003.

6. J.S.Snyder and J.R.Brophy, "Performance Characterization and Vibration Testing of 30-cm Carbon-Carbon Ion Optics," AIAA 2004-3959, 40th Joint Propulsion Conference, Fort Lauderdale, FL, July 2004.

7. J. Mueller, J.R. Brophy, and D.K. Brown, "Endurance Testing and Fabrication of Advanced 15-cm and 30-cm Carbon-Carbon Composite Grids," AIAA 95-2660, 31st Joint Propulsion Conference, San Diego, CA, July 1995.

8. J.S. Meserole, "Erosion Resistance of Carbon-Carbon Ion Optics," Journal of Propulsion and Power, Vol. 17, No. 1, Jan-Feb 2001, pps. 12-18.

9. Y. Hayakawa, S. Kitamura, and K. Miyazaki, "Endurance Test of C/C Grids for 14-cm Xenon Ion Thrusters," AIAA 2002-3958, 38th Joint Propulsion Conference, Indianapolis, IN, July 2002.

10. D.M. Goebel, "High Voltage Breakdown Limits of Molybdenum and Carbon-based Grids for Ion Thrusters," AIAA 2005-4257, to be presented at the 41st Joint Propulsion Conference, Tucson, AZ, July 2005.

11. I. Funaki, H. Kuninaka, K. Toki, Y. Shimizu, K. Nishiyama, and Y. Horiuchi, "Verification Tests of Carbon-Carbon Composite Grids for Microwave Discharge Ion Thruster," J. of Propulsion and Power, Vol. 18, No. 1, Jan-Feb 2002, pps. 169-175.

12. H. Kuninaka, K. Nishiyama, Y. Shimizu, and K. Toki, "Flight Status of Cathode-Less Microwave Discharge Ion Engines Onboard HAYABUSA Asteroid Explorer," AIAA 2004-3438, 40th Joint Propulsion Conference, Fort Lauderdale, FL, July 2004.

13. Randolph, T.M. and J.E.Polk, "An Overview of the Nuclear Electric Xenon Ion System (NEXIS) Activity," AIAA 2004-5909, Space 2004 Conference and Exhibit, San Diego, CA, Sept. 2004.

14. Beatty, J.S., J.S. Snyder, and W. Shih, "Manufacturing of 57cm Carbon-Carbon Composite Ion Optics for the NEXIS Ion Engine," AIAA 2005-4411, to be presented at the 41st Joint Propulsion Conference, Tucson, AZ, July 2005.

15. J.D. Williams, M.L. Johnson, and D.D. Williams, "Differential Sputtering Behavior of Pyrolytic Graphite and Carbon-Carbon Composite Under Xenon Bombardment," AIAA 2004-3788, 40th Joint Propulsion Conference, Ft. Lauderdale, FL, July 2004.

16. A. Sengupta, J.R. Brophy, and K.D. Goodfellow, "Status of the Extended Life Test of the Deep Space 1 Flight Spare Ion Engine After 30,352 Hours of Operation," 39th Joint Propulsion Conference, Huntsville, AL, July 2003.

17. G.C. Soulas, H. Kamhawi, M.J. Patterson, M.A. Britton, and M.M. Frandina, "NEXT Ion Engine 2000 Hour Wear Test Results," AIAA 2004-3791, 40th Joint Propulsion Conference, Fort Lauderdale, FL, July 2004.

18. J.E. Polk, J.R. Anderson, J.R.Brophy, V.K. Rawlin, M.J. Patterson, J. Sovey, and J. Hamley, "An Overview of the Results from an 8200 Hour Wear Test of the NSTAR Ion Thruster," AIAA 99-2446, 35th Joint Propulsion Conference, Los Angeles, CA, June 1999.

19. P.R. Schwoebel and I. Brodie, "Surface-Science aspects of vacuum microelectronics," J. Vac. Sci. Technol. B, Vol 13(4), July/Aug 1995, pps. 1391-1410.

20. A. Wadhawan, R.E. Stallcup II, K.F. Stephens II, J.M. Perez, and I.A. Akwani, "Effects of O2, Ar, and H2 gases on the field emission properties of single-walled and multi-walled carbon nanotubes," Applied Physics Letters, Vol. 79(12), Sept. 2001, pps. 1867-1869.

21. J.R. Anderson, I. Katz, and D. Goebel, "Numerical Simulation of Two-Grid Ion Optics Using a 3D Code," AIAA 2004-3782, 40th Joint Propulsion Conference, Fort Lauderdale, FL, July 2004.