Post-test Inspection of NASA’s Evolutionary Xenon Thruster Long Duration Test Hardware: Ion Optics

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Introduction

• NEXT Long Duration Test (LDT) conducted as part of service life verification approach

• LDT thruster operated from June 2005 to February 2014, after which test was voluntarily terminated
  – 918 kg propellant throughput
  – 51,184 h operation
  – 35.5 MN·s

• LDT thruster vented to atmosphere April 2014 for inspection
  – Ion optics inspection nearly completed
  – Paper presents ion optics results to date

<table>
<thead>
<tr>
<th>Operating Condition</th>
<th>Segment Duration, h</th>
<th>Post-Segment Duration, h</th>
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<tr>
<td>3.52 A, 1800 V</td>
<td>13,042</td>
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<td>3.52 A, 1179 V</td>
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Optics Inspection Objectives & Plan

• Measure wear of & deposition on critical surfaces to verify & update service life models
  – Screen grid wear of upstream surface
  – Accelerator grid wear of downstream surface & aperture walls
  – Deposition on both grids (potential source for grid short)

• Verify in situ erosion measurements
  – Grid aperture diameters, center cold grid gap, groove depth

• Resolve thruster-related issues encountered during test
  – Impedance degradation, unanticipated performance trends, sources of rogue holes, and differences between models & observed erosion

• Verify design changes made prior to LDT had desired impacts
  – Grid masking, accelerator aperture diameter increase & control, compensation change

• Identify any unanticipated thruster life-limiting phenomena
Test Hardware

- **EM3 thruster**
  - Much of design & design approach evolved from NSTAR
  - Prototype model ion optics utilized
    - Manufactured by Aerojet
    - Two grid, convex electrodes

- **PM optics design includes:**
  - 36 cm beam extraction diameter for reduced outer aperture erosion
  - Improved manufacturing of electrodes for tighter aperture tolerances & reduced cusp profile
  - Improved mounting design that reduced stresses for gap stabilization

- **Comparisons with NSTAR electrodes**
  - NEXT screen grid aperture diameters, center-to-center hole spacing, & thickness are same
  - NEXT accelerator grid aperture diameters & thickness are 11% & 50% larger, respectively
  - NEXT cold grid gap 8% larger at center
  - NSTAR beam extraction diameter 28.4 cm
Cold Grid Gap
Cold Grid Gap

- Post-test cold grid gap
  - Measured with gages
  - Corrected for downstream screen surface deposition

- Change in cold grid gap (% pretest center gap):
  - Center = -4%
  - Average = -7%
  - NSTAR ELT = -30%

- Efforts to stabilize NEXT cold grid gap were largely successful

- In situ diagnostic (center cold grid gap) correlates with post-test measurement within uncertainties
Screen Grid
Screen Grid Overall Condition

- Net erosion of upstream screen grid surface
Screen Grid Upstream Erosion

- Upstream grid exhibited chamfered erosion pattern
  - Pronounced near grid center, faded away with increasing radius
  - *Very similar to NSTAR ELT erosion pattern*

- Worst case screen webbing erosion was close to center of a ridge for screen grid service life assessment
Screen Grid Thickness

- Webbing cross-sectioned
  - Radius B selected because along probe path & highest $j_b$
  - Photomicrographs show eroded pattern & deposition
- Minimum screen grid thickness was 86% of pretest (off-center)
- Screen grid has substantial service life remaining
Screen Grid Deposition

- Deposition on aperture walls & downstream surface
- Deposition composed of grid material & C with trace O & trapped Xe
  - Grid material from accelerator aperture erosion
  - C likely back-sputtered
- Backscattered electron image shows:
  - Broad discolored bands, likely from operation at different throttled levels
  - Whitish lines, likely from perveance measurements

\[ r = 0.4 \text{ cm} \]
Screen Grid Aperture Wall Deposition

- Aperture wall deposition was thicker on webbing surface closest to grid center at large radii, which increased with radius
  - Due to non-uniform accelerator wall erosion
- Deposition led to average 2.2% decrease in screen aperture diameters
  - Reduces open area by 4.4% & likely contributed to reduced screen grid ion transparencies during test
Screen Grid Downstream Deposition

- Downstream webbing deposition was small percentage of cold grid gap
- Little evidence of deposition spalling
- Deposition increased with increasing radius & was thickest closest to optics center
  - Due to non-uniform accelerator aperture wall erosion
Accelerator Grid
Accelerator Grid Overall Condition

• Net carbon deposition was observed throughout most of grid perforated region

• Net carbon deposition expected within aperture walls
  – Removal rate of back-sputtered carbon decreases as aperture enlarges

• Net carbon deposition within pit & groove erosion pattern unexpected
  – Investigation revealed that erosion persisted until 36.5 kh (621 kg throughput)
Accelerator Grid Downstream Erosion

- Pit & groove erosion pattern
  - Evident and fades away at larger radii due to masking by back-sputtered carbon
  - Grooves that are deeper than pits
- Chamfering of downstream accelerator apertures evident
  - Measured with in situ diagnostics at three radial locations
  - Transitions to hexagonal star-shaped pattern at outer radii
Accelerator Grid Upstream Aperture Erosion

- Slight chamfering of upstream aperture is evident
- At larger radii, chamfering is preferentially towards grid outer radius
- Erosion is result of minor systemic aperture misalignment, leading to preferential erosion of surfaces closest to deflected beamlet
- This erosion likely caused:
  - Uneven deposition on screen aperture walls & upstream surfaces
  - Slightly more collimated beam profiles at EOL
- Resolution is straightforward - adjust aperture alignment during manufacture
Accelerator Grid Pit & Groove Erosion

• Webbing cross-sectioned
  – Radius selected because along probe path & highest $j_b$
  – Photomicrographs show eroded pattern & deposition

• Groove depths were 27-35% of grid thickness within 6 cm radius, then decreased
  – Transition from net erosion to net deposition at full power appear consistent with post-test measurements

• Max groove depth was half that measured in situ diagnostics
  – Due to changes in reference plane locations
  – More recent measurements show groove depths as large as 45% thickness
Accelerator Grid Aperture Enlargement

- Minimum aperture diameters without deposition increased by ~5-7% of pretest measurements
  - In situ measurements indicate that minimum diameter increases occurred during throttled power operation (13.0-29.2 kh)
- Smaller than NSTAR ELT changes, which was as large as 24% of pretest
  - In addition to different operating voltages, lower peak beam current density & 11% larger BOL diameter
- In situ measurements compared favorably with post-test
  - Within measurement uncertainties
Accelerator Grid Aperture Erosion

- Downstream aperture diameters without deposition increased by 24-33% of pretest diameter
  - In situ measurements indicate that that increase occurred predominantly during 1st full power segment (up to 13 kh)
- Grid geometric changes (36 cm, large diameter, & better tolerance control) reduced degree of erosion at larger radii
- Upstream diameter increased by as much as 17% of pretest diameter
- Impact on ion optics performance requires further assessment
  - Affect perveance, electron backstreaming, & accelerator current
Summary

• Average change in cold grid gap was -7% of pretest center gap
  – Efforts to stabilize NEXT cold grid gap were largely successful

• Screen grid
  – Upstream erosion exhibited chamfered erosion pattern with minimum grid thickness at 86% of pretest thickness
    • Screen grid has substantial service life remaining
  – Deposition
    • Composed of grid material from accelerator aperture erosion & back-sputtered carbon
    • On aperture walls: Thicknesses up to 1.9% of nominal diameter
      – Average aperture diameter decreased by 2.2% from deposition
    • On downstream surfaces: Thicknesses up to 5% of center grid gap
    • Little evidence of spalling
Summary

• Accelerator grid
  – Net carbon deposition within pit & groove erosion pattern
    • Investigation revealed that erosion persisted until 36.5 kh (621 kg throughput)
  – Downstream erosion
    • Groove depths deeper than pits
    • Groove depths were 27-35% of grid thickness for 6 cm radius, then decreased
  – Aperture erosion
    • Slight upstream aperture chamfering is evident and preferentially towards grid outer radius at larger radii
      – Erosion is result of minor systemic aperture misalignment that can be corrected
    • Minimum aperture diameters increased by ~5-7% of pretest measurements
    • Downstream aperture diameters increased by 24-33% of pretest diameter
    • Upstream diameter increased by as much as 17% of pretest diameter
Future Work

- Make additional measurements
- Complete correlation of inspections results with test data
  - Understand impact of back-sputtered carbon on test results
- Verify/update service life models
Backup
Recent Groove Measurements

- Groove depths as deep as 45% of grid thickness
- Transition from net erosion to net deposition at 14-16 cm
Pit Measurements

- Pit depths as deep as 27% of grid thickness
  - Less than groove depths
Screen Grid Deposition

- Partial ring deposition
  - Non-uniformly distributed azimuthally
  - Center of ring aligned with outer radius
  - Coverage increased from 90° at mid-radius to 240° at r = 18 cm
  - Maximum protrusion into aperture was 4% of nominal diameter

- Backscatter electron image shows that ring predominantly formed during second full power segment (after 29 kh)

- Although cause unknown, likely a facility effect that only modestly reduced open area (~2.5%)
Accelerator Grid Net Deposition

• In situ images show net erosion evident 35.6 kh
  – Imaging system failed
• Long range images
  – Net erosion to 36.5 kh (621 kg throughput), but net deposition by 41.5 kh
  – 36.5 kh image shows changes have just begun to occur
• Root cause presently unknown
  – At 41.5 kh (2\textsuperscript{nd} full power segment), annular net erosion pattern evident
  – Only known mechanism is redistribution of accelerator current
Grid Masses

- **Screen grid**
  - Net mass loss of 0.8 gm
  - Deposition would have masked mass loss due to erosion
  - Based on erosion measurements, preliminary mass loss from erosion estimated to be 5.2 gm
    - Mass of deposition difficult to estimate
  - NSTAR ELT mass loss due to erosion was 3.2 gm
    - Difference due to longer duration & higher beam currents of LDT

- **Accelerator grid**
  - Net mass loss of 29.5 gm
  - Deposition mass was 12.4 gm based on measurement & analysis
  - Based on deposition mass, preliminary mass loss from erosion estimated to be 42 gm
    - Does not include deposition on unperforated region
  - NSTAR ELT mass loss due to erosion was 33.7 gm
    - Difference due to longer duration & higher beam currents of LDT
Accelerator Grid Rogue Holes

- Four rogue holes identified on accelerator grid during LDT
- Source of rogue holes (e.g. deposition on screen apertures) was not found
Accelerator Grid Aperture Enlargement

- Minimum aperture diameters without deposition increased by ~5-7% of pretest measurements
  - In situ measurements indicate that minimum diameter increases occurred during throttled power operation (13.0-29.2 kh)
- Smaller than NSTAR changes, which was as large as 24% of pretest
  - In addition to different operating voltages, lower peak beam current density & 11% larger BOL diameter
- With deposition, diameters decreased due to back-sputtered carbon
  - In situ measurements detected minimum diameter decrease at 38-42 kh