WEAR TESTING OF THE HERMeS THRUSTER
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Outline

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• Objectives
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  – Test Article
  – Test Configuration
• Wear Test Segments
• Trends in data
  – Deposition on BN
  – Performance
  – Pole Cover Wear
  – Other Wear
• Summary
• Current Status
Context and Motivation

Asteroid Redirect Robotic Mission (ARRM)
- 50 kW-class SEP spacecraft
- SEP Technology Demonstration Mission

Ion Propulsion System: High-power HET
- Heliocentric transfer from Earth to asteroid
- Orbit capture at asteroid
- Transfer to low-asteroid orbit
- Planetary-defense demonstration
- Departure and escape from asteroid
- Heliocentric transfer from asteroid to lunar orbit
- Insertion into a lunar distant retrograde orbit
- Pitch and yaw control throughout


Artists conception of the ARRM spacecraft

12.5 kW HERMeS operation in VF-5 at GRC
# Wear Test Objectives

**Objective 1:** Quantify wear trends over and extended period of TDU operation to identify unknown failure modes and support validation of service-life models

<table>
<thead>
<tr>
<th>Objective/metric</th>
<th>Category</th>
<th>Measurement</th>
<th>Measurement Method</th>
<th>When</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component erosion</td>
<td>Primary</td>
<td>Surface height profile</td>
<td>Optical profilometry</td>
<td>Pre/post-test (pre/post-test segment)</td>
</tr>
<tr>
<td>Anomalous (visible) erosion</td>
<td>Primary</td>
<td>Digital images of TDU surfaces</td>
<td>Digital cameras</td>
<td>On-demand</td>
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<tr>
<td>Real-time assessment of B &amp; C fluxes</td>
<td>Secondary</td>
<td>Relative density of sputtered atoms</td>
<td>Optical emission spectra</td>
<td>On-demand</td>
</tr>
<tr>
<td>Cathode depletion</td>
<td>Primary</td>
<td>Weight of insert</td>
<td>High-resolution balance</td>
<td>Pre/post-test</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Orifice Plate Temperature</td>
<td>Thermocouple</td>
<td>Continuous</td>
</tr>
<tr>
<td>Thermal deformation</td>
<td>Primary</td>
<td>TDU component temperatures</td>
<td>Thermocouple</td>
<td>Continuous</td>
</tr>
<tr>
<td>Emitter temperature</td>
<td>Secondary</td>
<td>HCA orifice plate temperature</td>
<td>Thermocouple</td>
<td>Continuous</td>
</tr>
</tbody>
</table>

Potential wear sites (& mitigation):
- Outer pole cover (graphite covered)
- Inner pole cover (graphite covered)
- HCA orifice (orifice sizing)
- HCA keeper (graphite)
- Inner and outer discharge chamfers (magnetic shielding)
### Wear Test Objectives

**Objective 2:** Quantify performance trends over and extended period of TDU operation to identify unknown failure modes and support validation of service-life models

<table>
<thead>
<tr>
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<th>Category</th>
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<th>Measurement Method</th>
<th>When</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nominal Operating Point</strong></td>
<td>Primary</td>
<td>Thrust</td>
<td>Calibrated thrust stand</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Flow rate</td>
<td>Calibrated flow meters</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Currents and Voltages</td>
<td>Calibrated shunts and probes</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thruster Telemetry (stability)</td>
<td>IVB sweep</td>
<td>At regular intervals</td>
</tr>
<tr>
<td><strong>Ref. Operating Points</strong></td>
<td>Primary</td>
<td>As with nominal point</td>
<td>As with nominal point</td>
<td>At regular intervals</td>
</tr>
<tr>
<td><strong>Plume characterization</strong></td>
<td>Primary</td>
<td>Ion current density</td>
<td>Faraday probe on probe arm</td>
<td>At regular intervals</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ion energy distribution</td>
<td>RPA on probe arm</td>
<td>At regular intervals</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Electron Temp. &amp; Plasma Pot.</td>
<td>Langmuir probe on probe arm</td>
<td>At regular intervals</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Charge-dependent current flux</td>
<td>ExB probe on probe arm</td>
<td>At regular intervals</td>
</tr>
<tr>
<td><strong>Thermal trends</strong></td>
<td>Primary</td>
<td>TDU component temps</td>
<td>Thermocouples</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td>Tertiary</td>
<td>Anode and BN surface temps</td>
<td>IR camera</td>
<td>On demand</td>
</tr>
<tr>
<td><strong>HCA emitter Temperature</strong></td>
<td>Secondary</td>
<td>HCA orifice plate temperature</td>
<td>Thermocouple</td>
<td>Continuous</td>
</tr>
<tr>
<td><strong>HCA insert health</strong></td>
<td>Primary</td>
<td>Keeper IV trace for 3 mass flows</td>
<td>IV trace</td>
<td>At regular intervals</td>
</tr>
<tr>
<td><strong>HCA plume mode onset</strong></td>
<td>Secondary</td>
<td>A/C component of keeper voltage</td>
<td>IV trace</td>
<td>At regular intervals</td>
</tr>
<tr>
<td><strong>TDU plume structure</strong></td>
<td>Tertiary</td>
<td>Plume structure of Xe I and Xe II</td>
<td>Single-frequency images</td>
<td>On demand</td>
</tr>
</tbody>
</table>
Wear Test Objectives

Objective 3: Quantify deposition rate of back-sputtered facility material to identify the impact of deposition on thruster surfaces, to validate facility modeling, and to inform facility configuration for future tests.

<table>
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<tr>
<th>Objective/metric</th>
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<th>Measurement Method</th>
<th>When</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back-sputter rate</td>
<td>Primary</td>
<td>Mass of back-sputtered deposition</td>
<td>QCM</td>
<td>Continuous</td>
</tr>
<tr>
<td>Back-sputter composition</td>
<td>Primary</td>
<td>Mass-spec of deposition</td>
<td>SEM / XDAS</td>
<td>Post-test</td>
</tr>
<tr>
<td>Impact of deposition</td>
<td>Primary</td>
<td>Resistance at voltage/temperature</td>
<td>“Meggering”</td>
<td>Periodic</td>
</tr>
<tr>
<td>Spatially resolved sputter yields</td>
<td>Secondary</td>
<td>Thickness and composition of BSM</td>
<td>Witness plates</td>
<td>Post test</td>
</tr>
</tbody>
</table>

- Three QCMs near thruster plane
- Monitor horizontal, vertical symmetry of deposition
- Modeling predicts uniform flux at thruster position

Long term diagnosis
- Ta foil coupons on sides of panel graphite nuts facing beam dump
- Multiple (24) locations
- Provide spatial (z, θ) resolution of total carbon deposition throughout tank

Objective 4: Provide guidance for future long-duration testing by identifying best practices and unknown issues associated with facility operation and configuration
The HERMeS Technology Demonstration Unit One (TDU-1) has reached the level of maturity where long-duration wear testing is required

- Extensive Performance Testing During 2015
  - Demonstrated Nominal Performance Goals
  - Incorporated a Series of Minor Design Modifications
  - Correlated with Detailed Plasma Modeling of the Near-Feld Plume

- Extensive Thermal and Structural Modeling Tied to Experimental Data

- High-confidence that a TDU-based design will meet ARRM thruster requirements


• All TDU-1 operation is in GRC’s Vacuum Facility Five (VF-5)
  – Configuration identical to that of 2015 TDU performance testing base pressure \( \sim 1 \cdot 10^{-7} \) Torr. Pressure near TDU \( \sim 4.4 \cdot 10^{-6} \) Torr (Xe)
• Operation on laboratory power supplies/power console
• Operation on laboratory Xe feed system
Graphite Installation

- Graphite paneling protects all surfaces downstream of thruster
- 10 degree and 30 degree angling of beam dump plates
- Aperture introduced for IR camera
- Beam dump can be biased as part of test-like-you-fly analysis/assessment
# Wear Test Segments

<table>
<thead>
<tr>
<th>Test</th>
<th>Segment</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV (underway)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective particular to the Segment</td>
<td></td>
<td>Measure TDU performance with graphite pole covers</td>
<td>Measure erosion of graphite pole covers,</td>
<td>Measure erosion and performance with Al\textsubscript{2}O\textsubscript{3} pole covers</td>
<td>Measure erosion and performance over an extended period</td>
</tr>
<tr>
<td>Image</td>
<td></td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>Inner Pole Cover Configuration</td>
<td>Graphite, no masks, for 100 h No cover for 22 h</td>
<td>Polished graphite with Mo masks</td>
<td>Alumina with alumina masks</td>
<td>Same pole cover as Segment II with graphite masks</td>
<td></td>
</tr>
<tr>
<td>Outer Pole Cover Configuration</td>
<td>Graphite, no masks, for 100 h No cover for 22 h</td>
<td>Same pole cover as segment I</td>
<td>Alumina with no masks</td>
<td>New, polished graphite with graphite masks</td>
<td></td>
</tr>
<tr>
<td>Electrical Configuration</td>
<td>Varied</td>
<td>Cathode-tied</td>
<td>Floating</td>
<td>Cathode-tied</td>
<td></td>
</tr>
<tr>
<td>Duration, h</td>
<td>122</td>
<td>246</td>
<td>360</td>
<td>~1272 (670 completed)</td>
<td></td>
</tr>
<tr>
<td>Time-on-HCA and BN at end of segment, h</td>
<td>122</td>
<td>368</td>
<td>728</td>
<td>~2000 (1398 completed)</td>
<td></td>
</tr>
</tbody>
</table>
Overview

• Configuration
  – Thruster body tied to cathode in segments I, II, and IV
  – Thruster body floated in segment III

• Wear Test Operating Point
  – 600 V, 12.5 kW
  – Magnetic field settings determined by performance characterization in Segment I

• Typical Values for Various Parameters (vary slightly with configuration)
  – Jb: 1.9 A (≡ 0 during segment III)
  – Jd peak-to-peak: 14 A
  – Vd peak-to-peak: 12 V
  – Vcg peak-to-peak: 30 V
Deposition on BN Discharge Channel

Magnetic shielding has yielded net deposition on BN channel—no evidence of BN erosion

- Deposition estimated to be ~ 1 μm after 728 h (measured < 1 μm for 360 h)
- Surface resistance measured at 35 Ω
- No change in thruster performance noted over first 50 h during coating

BN witness plates confirm QCM measurements are mostly carbon

Performance trends at 600 V, 12.5 kW

- Discharge current steady during wear testing
  - Manual flow control—no changes required
  - Variations observed are largely thermally-induced due to various restarts.
- Thrust also varies due to thermal drift, but is largely constant.
  - 3.4 % higher with graphite pole covers
- Total current also largely constant
  - Body current included in total current
Performance trends at 20.8 A

- Reference firing conditions measured periodically
  - Capture changes in performance for conditions other than the wear test operating point
- For 20.8 A, no changes observed in thrust with time for 300 V, 400 V, or 600 V operation.
- The slight improvement in performance at 600 V with graphite pole covers remains constant. No improvement at lower discharge voltages.
Assessment of Sputter Erosion

- Optical profilometry of inner front pole covers
  - Referenced to protected region under masks (Mo or Al₂O₃)
  - Two measurements at each radial location, each average over a bit
- Sputtered surface is textured, adds a few µm uncertainty
- Mo masks had Mo masks of their own
- Al₂O₃ masks were un-masked.
Sputter-erosion of graphite inner pole cover

- **Graphite:**
  - Erosion rate of 45 μm/kh
  - Maximize near edges
  - Nominal pole covers sufficient

- **Molybdenum:**
  - Maximum rate of 600 μm/kh
  - Appears to follow same trends...but doesn’t!

- **OES data suggest erosion increased between 20 and 75 h. Change in B-field at 20 h**
• Maximum $\text{Al}_2\text{O}_3$ rate of 135 $\mu$m/kh
  – Thick covers required to meet ARRM mission
• Fundamentally different erosion pattern
• OES data again suggest erosion was roughly constant (within uncertainty of measurement)
Correlation of inner pole cover erosion trends

- Ratio of Mo and Al\(_2\)O\(_3\) to graphite erosion rates
  - Intended to shed light on energy of sputtering ions
  - Reveals Mo and Al\(_2\)O\(_3\) are eroding in similar regards wrt graphite
    (Mo rates being roughly 3x Al\(_2\)O\(_3\) rates across the radius)
- Suggests erosion patterns are dominated by ions’ angles of incidence rather than energy levels. (Cf. Oyarzabal, AIAA-2005-3525)
  - Ions between 75 eV and 125 eV
  - 15 degree variation in angle of incidence
Other Components

- **Outer pole cover**
  - Possible erosion observed near outer radius of graphite outer pole cover (44 μm/kh). Lack of reference (thruster not removed from chamber) makes absolute measurements difficult.
  - No erosion observed on the alumina outer pole cover—but no deposition either....

- **Discharge cathode**
  - No erosion observed on cathode keeper or orifice plate after 728 h (removed for inspection before Segment IV).
  - No change in ignition or cathode-only behavior observed.
Summary

• Test Campaign
  – Three of four test segments completed
    • Extensive performance testing
    • Measurement of inner pole cover wear for two potential thruster configurations
    • Demonstration of magnetic shielding over extended operation
  – Segment IV underway incorporating lessons learned

• Component Wear
  – No BN channel erosion
  – Graphite pole cover erosion of 45 μm/kh yields < 50% of the volumetric erosion of alumina (including outer pole cover).
  – OES appears to yield real-time assessment of rates..

• TDU Performance
  – No variation in performance observed with thruster operating time
  – Performance gain associated with graphite (conducting) pole / cathode-tied configuration could be significant for long duration missions
Current Status

• Back-sputter characterization
  – Back sputter rates of 1.8 μm/kh measured by QCMs
  – No impact observed on thruster performance
  – Graphite paneling has significantly reduced back-sputter onto the thruster

• Data suggest best configuration
  – Graphite pole covers with body tied to cathode
    • Lower erosion
    • Better performance
    • Acceptably worse beam divergence and spread of higher energy ions
  – Segment IV initiated to identify unknown issues associated with this configuration over extended (> 1000 h) operation
    • Graphite covers, with body tied to cathode potential (cathode floats wrt ground)
    • 670 h to date
    • No variation in thruster performance.
    • No anomalies noted through external visual inspection