Thermal Design Challenges for In-Flight Exposure to an Electric Propulsion Plasma Plume Environment

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Presented By
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The Gateway is a manned lunar orbiting space station under development. The station will be assembled in multiple stages, while in orbit, starting with the launch of PPE in 2022. The power and propulsion element (PPE) is a high-power, 50-kilowatt class solar electric propulsion spacecraft. It will be responsible for providing power generation and propulsion for the Gateway. Its primary propulsion is done using multiple hall effect thrusters.
Ion Propulsion Background

- An ion thruster ionizes a neutral gas and uses electrostatic forces to accelerate it in the direction of desired thrust.
- The byproduct of this action is a high energy plasma plume.
- The plume can have detrimental effects on the spacecraft and thruster.
- The plume behavior has been seen to be different in-flight then in ground testing.
- The plume is in need of further study.
PDP Objective

- Provide a diagnostics package to characterize high-power solar electric propulsion on-orbit operating characteristics and assess plasma interactions.
Plume Environment Effects

- How does the plume effect objects in close proximity?

  - **Plume Induced heating**
    - **Convection** from high energy particles
    - **Radiation** from high temperature plume and thruster
    - **Electron Heating**

  \[
  Q_{Total} = Q_{Rad} + Q_{Conv} + Q_{ElectronHeating}
  \]

  \[
  Q_{Rad_{Thruster}} + Q_{Rad_{Plume}} + Q_{Conv_{Ions}} + Q_{Conv_{NeuParticle}}
  \]

- **Surface Erosion**
  - High energy particles that impinge the surface will erode away material.
  - Erosion can cause changes to the thermal optical properties
Thruster Radiation

\[ Q_{Rad\_Thruster} \]

- **Source:**
  - TD Modeling – Surface to Surface radiation exchange
- **Assumptions:**
  - The thruster surface temperature of 400° C max and -130° C min
  - PDP is 1.0 meter from thruster
  - The angles to the thruster will vary from 60° to 110° from the thrust axis
- **Margin:**
  - Applied in proximity, angle, and temperature of the thruster
• Source
  – Estimated ~30% of total convective heat sources at 60°
    • $Q_{Conv} \times \frac{1}{3} = Q_{Rad\_Plume}$
• Assumption:
  – Assume ideal black body absorption
• Margin
  – Based on worst case 60° angle, black body absorption, and margin of $Q_{Conv}$.
• Notes:
  – A more accurate estimate of $Q_{Rad\_Plume}$ will be done based of xenon plasma radiance and the spectral absorptivity of the final coating of PDP can be done.
Convection From Ions

$Q_{\text{Conv}_\text{Ions}}$

- **Source:**
  - Ion Power Density
    - $V$: Ion Charges Species with RPA
    - $I$: Current Density with Faraday Probe
    - $V \times I = \text{Power Density}$

- **Assumptions:**
  - 100% of the Ion energies are imparted to the incident surface with no losses.

- **Margin:**
  - Margin will be applied based on the uncertainty of the plume behavior in space. This comes to 2.4x.

- **Note:**
  - There is less uncertainty in the power density the closer to the firing axis a measurement is made.
  - The Power density is higher at 300V at 60°
**Source:**
- Neutral particle heating will be 5% of the $Q_{\text{Conv}_\text{Ions}}$
- $\text{Power Density} \times 0.05 = Q_{\text{Conv}_\text{NP}}$

**Assumptions:**
- 100% of the Neutral Particle energies are imparted to the incident surface with no losses.
- The 5% of the power density estimate comes from an estimate of 95% propellant utilization.
- The energy contained in the neutral particles are equal to the energy of the ions.

**Margin:**
- Applied the same 2.4x margin to this as the power density.
Electron Heating

$Q_{\text{Electron Heating}}$

• **Source:**
  – Caused by electrons discharging energy into the incident surface.
    • $V$: Electron temperature
      – Assume 1 eV electron temperature
    • $I$: Current Density with Faraday Probe
    • $V \times I = \text{Power Density}$

• **Assumptions:**
  – Assuming about a 1.0 eV electron temperature
  – Assume electron heating is applied over every exposed surface.

• **Margin:**
  – Applied the same 2.4x margin to this as the power density.
    • The uncertainty in plume mechanics at this location for the electrons is less than 2.4x margin.

• **Note**
  – Overall Electron plume heating is negligible
Unique Design Challenges

• Uncertainty of plume behavior in flight
  – Based on limited in-flight performance data, the plume behavior has been observed to be substantially different than ground data

• Ion induced erosion
  – Erosion will remove the surface of the thermal control coating
  – Erosion will alter the thermal optical properties of exposed surfaces

• Back-sputtering material to thruster
  – The thermal control coating will coat nearby components as the surface is sputtered away.
  – This can be detrimental to the thruster.
Effects of Ion Induced Erosion

• Erosion will remove the surface of the thermal control coating
  – Materials with low erosion rates are preferred given the long (15 year) life of the hardware.
  – Analysis has been done to predict lifetime erosion rates.

• Erosion will alter the thermal optical properties of exposed surface.
  – Some testing has been done to understand these effects of erosion on absorptivity and emissivity.
Analysis has been performed to predict the expected lifetime erosion rates for some materials.

Many common thermal control surfaces have not been measured.
  - This limits the selection of possible thermal control material options.

There is uncertainty to how these materials will behave as thermal control surfaces when exposed an Ion Plume.

<table>
<thead>
<tr>
<th>Gimbal angle</th>
<th>Graphite</th>
<th>Moly</th>
<th>Tungsten</th>
<th>Alumina</th>
<th>Aluminum</th>
<th>Titanium</th>
</tr>
</thead>
<tbody>
<tr>
<td>20°</td>
<td>24.24</td>
<td>162.60</td>
<td>206.37</td>
<td>37.52</td>
<td>175.39</td>
<td>81.74</td>
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<td>10°</td>
<td>11.35</td>
<td>75.78</td>
<td>95.87</td>
<td>18.57</td>
<td>85.08</td>
<td>38.00</td>
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<tr>
<td>0°</td>
<td>6.58</td>
<td>43.87</td>
<td>55.04</td>
<td>11.80</td>
<td>54.24</td>
<td>21.97</td>
</tr>
</tbody>
</table>
• A total of 10 different materials were selected for long duration exposure testing to the thrust plume of the TDU-3 hall thruster Long Duration Wear Test.

• Two locations were chosen to represent realistic exposure to an actual spacecraft
  • 90° & 115° from the thrust axis

• The samples were mounted in collimators to remove other sources of contamination within the chamber, such as back sputter.

• The emissivity and absorptivity were measured before, during, and after the test.
### Optical Properties after Plume Exposure

Most samples showed a decrease in Hemispherical Emittance and an increase in Solar Absorptance. Many of the changes did not increase or decrease significantly with exposure time.

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>AIK-1</td>
<td>Aluminum x 2.0mil Kapton, 1st Surface Mirror</td>
<td>E90°</td>
<td>0.021</td>
<td>0.094</td>
<td>0.001</td>
<td>0.006</td>
<td>0.002</td>
<td>0.000</td>
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<tr>
<td>AIT-1</td>
<td>Aluminum Tape 0.5 mil</td>
<td>E90°</td>
<td>0.029</td>
<td>0.097</td>
<td>-0.007</td>
<td>-0.003</td>
<td>-0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>AIF-1</td>
<td>Aluminum Foil</td>
<td>E90°</td>
<td>0.030</td>
<td>0.141</td>
<td>-0.001</td>
<td>0.007</td>
<td>-0.018</td>
<td>-0.013</td>
</tr>
<tr>
<td>ST-1</td>
<td>Silver Teflon 2nd Surface Mirror</td>
<td>E90°</td>
<td>0.404</td>
<td>0.083</td>
<td>0.018</td>
<td>-0.001</td>
<td>0.091</td>
<td>0.069</td>
</tr>
<tr>
<td>STE-1</td>
<td>Silver Teflon 2nd Surface Mirror (Exposed, 240hr)</td>
<td>E90°</td>
<td>0.404</td>
<td>0.079</td>
<td>0.007</td>
<td>0.004</td>
<td>0.038</td>
<td>0.059</td>
</tr>
<tr>
<td>Z93-1</td>
<td>White Paint Z-93</td>
<td>E90°</td>
<td>0.814</td>
<td>0.161</td>
<td>-0.043</td>
<td>-0.045</td>
<td>-0.006</td>
<td>-0.004</td>
</tr>
<tr>
<td>ST-2E</td>
<td>Silver Teflon 2nd Surface Mirror</td>
<td>E90°</td>
<td>0.403</td>
<td>0.081</td>
<td>N/A</td>
<td>0.001</td>
<td>N/A</td>
<td>0.068</td>
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<tr>
<td>ITO-1</td>
<td>ITO (1600 ohm/sq)x 2.0 mil Kapton x Al</td>
<td>E90°</td>
<td>0.499</td>
<td>0.394</td>
<td>-0.034</td>
<td>-0.033</td>
<td>0.013</td>
<td>0.019</td>
</tr>
<tr>
<td>BKT-1</td>
<td>Kapton Black tape</td>
<td>E90°</td>
<td>0.866</td>
<td>0.928</td>
<td>-0.005</td>
<td>0.006</td>
<td>0.001</td>
<td>0.017</td>
</tr>
<tr>
<td>GF-1</td>
<td>Graphite Foil</td>
<td>E90°</td>
<td>0.486</td>
<td>0.722</td>
<td>0.034</td>
<td>0.008</td>
<td>0.058</td>
<td>0.104</td>
</tr>
<tr>
<td>SW-1</td>
<td>Solar White</td>
<td>E90°</td>
<td>0.653</td>
<td>0.025</td>
<td>-0.120</td>
<td>-0.108</td>
<td>0.238</td>
<td>0.267</td>
</tr>
<tr>
<td>AIK-2</td>
<td>Aluminum x 2.0mil Kapton</td>
<td>E-30°</td>
<td>0.021</td>
<td>0.134</td>
<td>-0.003</td>
<td>0.013</td>
<td>0.083</td>
<td>0.149</td>
</tr>
<tr>
<td>AIT-2</td>
<td>Aluminum Tape 0.5 mil</td>
<td>E-30°</td>
<td>0.030</td>
<td>0.099</td>
<td>-0.008</td>
<td>-0.005</td>
<td>0.126</td>
<td>0.227</td>
</tr>
<tr>
<td>AIF-2</td>
<td>Aluminum Foil</td>
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<td>0.030</td>
<td>0.211</td>
<td>0.000</td>
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<td>0.123</td>
<td>0.034</td>
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<td>Silver Teflon 2nd Surface Mirror</td>
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<td>0.003</td>
<td>0.001</td>
<td>0.091</td>
<td>0.122</td>
</tr>
<tr>
<td>Z93-2</td>
<td>White Paint Z-93</td>
<td>E-30°</td>
<td>0.814</td>
<td>0.167</td>
<td>-0.048</td>
<td>-0.039</td>
<td>0.005</td>
<td>0.022</td>
</tr>
<tr>
<td>GK-2</td>
<td>Germanium (1500 Au) x 2.0 mil Kapton</td>
<td>E-30°</td>
<td>0.391</td>
<td>0.523</td>
<td>-0.021</td>
<td>-0.018</td>
<td>-0.002</td>
<td>0.014</td>
</tr>
<tr>
<td>ITO-2</td>
<td>ITO (1600 ohm/sq)x 2.0 mil Kapton x Al</td>
<td>E-30°</td>
<td>0.499</td>
<td>0.397</td>
<td>0.014</td>
<td>0.019</td>
<td>0.002</td>
<td>0.007</td>
</tr>
<tr>
<td>BKT-2</td>
<td>Kapton Black tape</td>
<td>E-30°</td>
<td>0.866</td>
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</tr>
<tr>
<td>GF-2</td>
<td>Graphite Foil</td>
<td>E-30°</td>
<td>0.486</td>
<td>0.714</td>
<td>-0.003</td>
<td>0.066</td>
<td>0.016</td>
<td>0.111</td>
</tr>
<tr>
<td>SW-2</td>
<td>Solar White</td>
<td>E-30°</td>
<td>0.653</td>
<td>0.026</td>
<td>-0.016</td>
<td>-0.003</td>
<td>0.185</td>
<td>0.277</td>
</tr>
</tbody>
</table>
Results after 1534 Hours of Exposure

- Chart shows the change in measured solar absorptance over the range of wavelength for all samples tested
- Overall, most of the samples showed an increase in absorptance with the largest increase in the 250-750nm range
• Materials that erode from the thruster can redeposit onto the surface of the thruster.

• Redeposited material can cause electrical shorting inside the thruster.
  – It is desirable to chose a thermal control surface that is dielectric

• Sufficiently thick redeposited material will alter the optical thermal properties of the thruster
Back-Sputtering Material to Thruster

- For limiting PDP erosion, all 3 of these materials will work well.
- Rates are much lower than thruster tolerance requirement (2 um/khr) but is asymmetric
- Deposited thickness (after 8 khr) is thick enough to completely change the local optical properties but does not alter the electrical properties
  - Thruster team is currently analyzing the asymmetric thermal effects

<table>
<thead>
<tr>
<th>Gimbal angle</th>
<th>Max deposition rate, um/khr [Max deposition thickness after 8 khr, um]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Graphite</td>
</tr>
<tr>
<td>0°</td>
<td>0.028 [0.23]</td>
</tr>
<tr>
<td>10°</td>
<td>0.054 [0.43]</td>
</tr>
<tr>
<td>20°</td>
<td>0.061 [0.49]</td>
</tr>
</tbody>
</table>

Erosion and sputtering analysis by John Yim at NASA GRC
Based on the available information on erosion/sputter rates, we reduced our possible material choices to 3 candidates:
- Alumina Spray coating
  - On Al, SS, & Ti
- Titanium
- Graphite

Through modeling, we traded the available information on thermal optical properties to develop recommendations for the PDP material selection.
Thermal Trade Results

• PDP Coating
  – Note: There is much uncertainty in the optical properties of the material candidates.
  – Alumina offers much better thermal performance.

<table>
<thead>
<tr>
<th>PDP Coating</th>
<th>Alumina</th>
<th>Titanium</th>
<th>Graphite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emissivity</td>
<td>0.25-0.6</td>
<td>0.3-0.55</td>
<td>0.34</td>
</tr>
<tr>
<td>Absorptivity</td>
<td>0.1-0.25</td>
<td>0.4-0.6</td>
<td>0.65</td>
</tr>
<tr>
<td>20° Gimbal Temperature (°C)</td>
<td>46 to 97</td>
<td>80 to 151</td>
<td>145</td>
</tr>
<tr>
<td>30° Gimbal Temperature (°C)</td>
<td>77 to 139</td>
<td>106 to 175</td>
<td>170</td>
</tr>
</tbody>
</table>

• PDP Substrate Material
  – CTE mismatch could result in failure during coating process
    • Coating thickness limitations are only validated via testing
  – Thermal conductivity decreases temperature gradient across box (worst case)
    • ~45 C (For SS)
    • ~10 C (For Al)
• Our recommendation is to use an alumina spray coating on an aluminum 6061 substrate.
• Further testing is needed to reduce uncertainty and risk

**Testing:**

1. **Coating Process and Optical Property Testing**
   - Coating variables:
     • Porosity
     • Thickness
   - Measure:
     • Adherence to substrate
     • Optical property variation

2. **Ion Source Erosion Testing**
   - Measure:
     • Erosion rates
     • Changes to optical properties
     • Sputter redeposition rates

3. **Coating Delamination Testing**
   - Thermal shock delamination of alumina
Acknowledgements

• Penni Dalton – NASA, GRC
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  – Materials Expert
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  – Providing materials samples
• Jim Myers – NASA, GRC
  – Emissivity Measurements
• Miria Finckeror & Brian O’Connor – NASA, MSFC
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• Robert Youngquist & Tracy Gibson – NASA, KSC
  – Providing materials samples