TFAWS Interdisciplinary Session Paper Session

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

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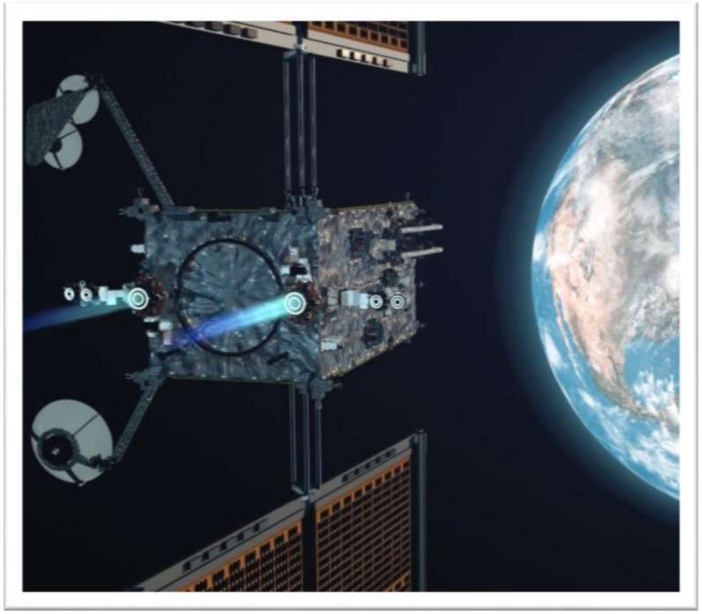


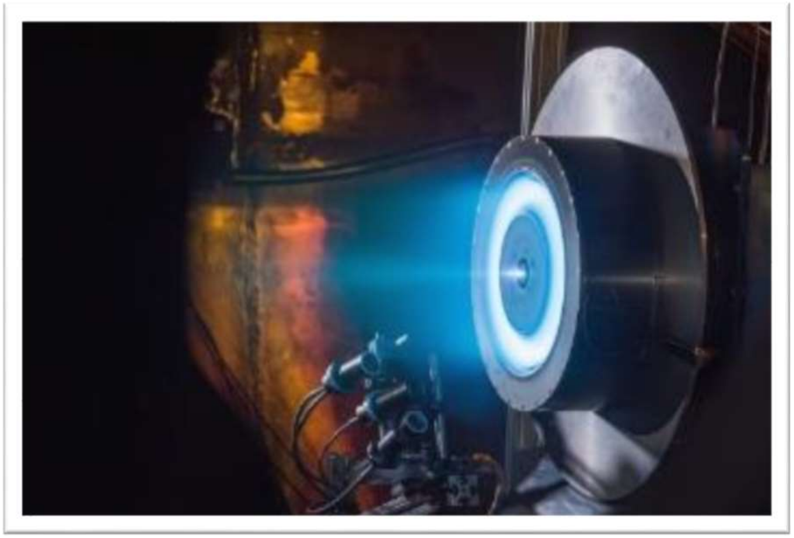
Gateway and the PPE (Power and Propulsion Element)

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.



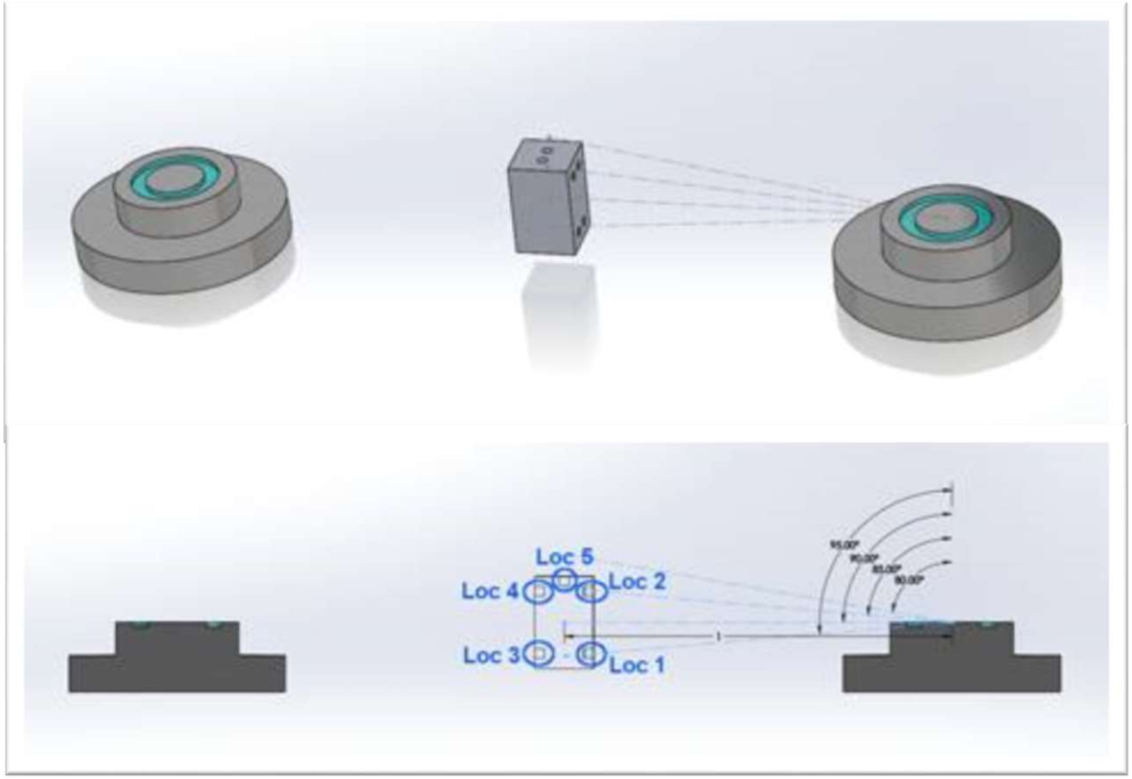
- The plume can have detrimental effects on the spacecraft and thruster.

- The plume behavior has been seen to be different in-flight then in ground testing.

- The plume is in need of further study.

PDP Background

- 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**

$$Q_{Total} = Q_{Rad} + Q_{Conv} + Q_{ElectronHeating}$$

$$Q_{Rad\_Thruster} + Q_{Rad\_Plume}$$

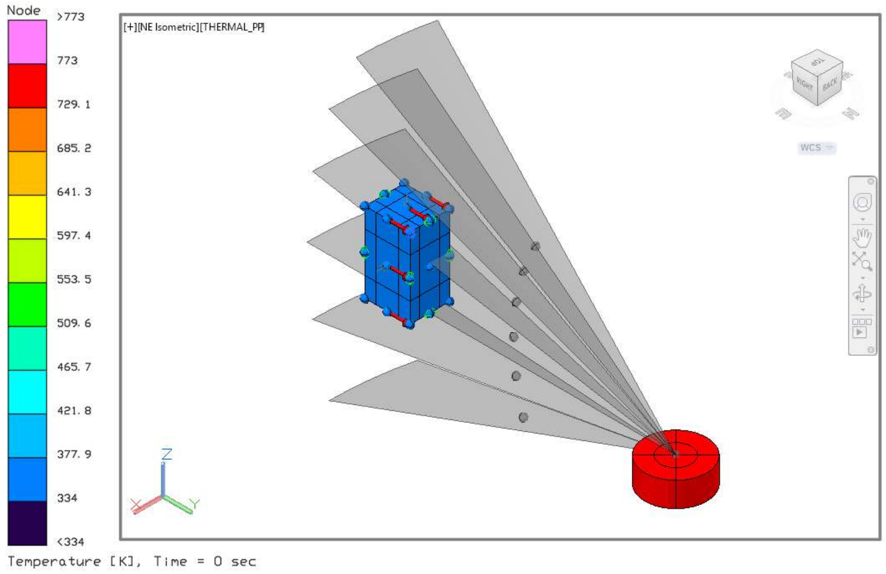
$$Q_{Conv\_Ions} + Q_{Conv\_NeuParticle}$$

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

Thruster Radiation

$$Q_{Rad\_Thruster}$$

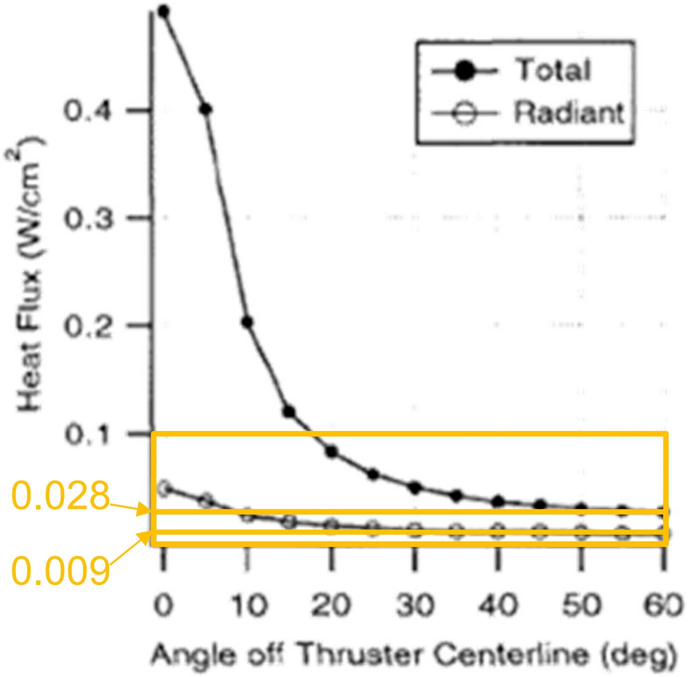
- Source:
  - TD Modeling – Surface to Surface radiation exchange
- Assumptions:
  - The thruster surface temperature of 400° C max and -130° C min
  - PDP is 1.0 meter from thruster
  - The angles to the thruster will vary from 60° to 110° from the thrust axis
- Margin:
  - Applied in proximity, angle, and temperature of the thruster



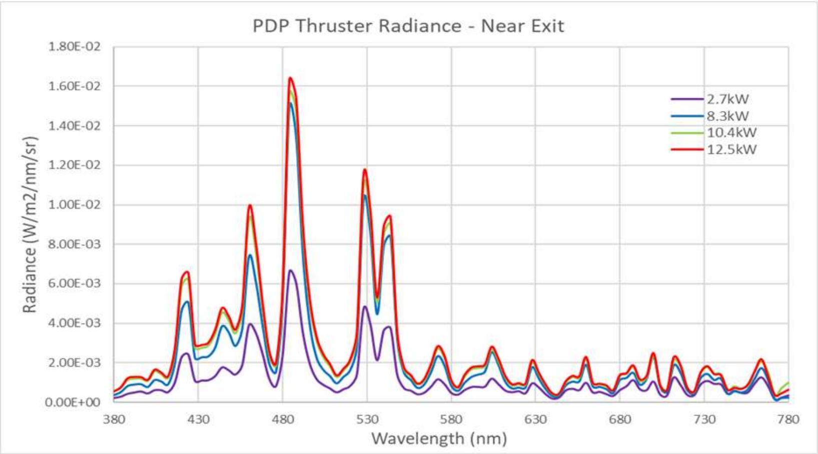
Plume Radiation

Q_{Rad_Plume}

- 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.



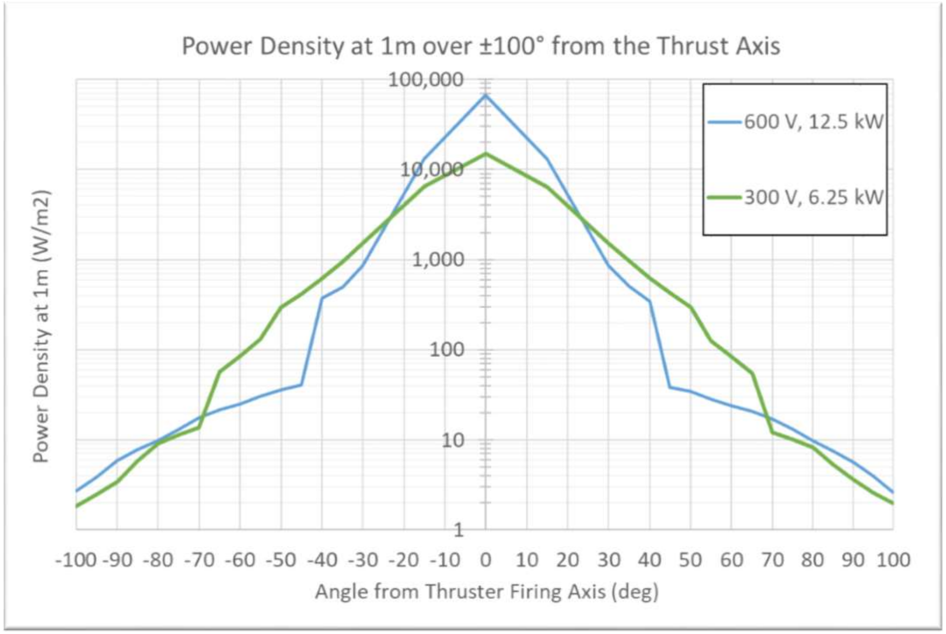
Ionic and neutral particle transport property measurements in the plume of an SPT-100, Lyon B. King



Convection From Ions

$$Q_{Conv\_Ions}$$

- Source:
  - Ion Power Density
    - V: Ion Charges Species with RPA
    - I: Current Density with Faraday Probe
    - $V \times I = Power\ Density$
- 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°

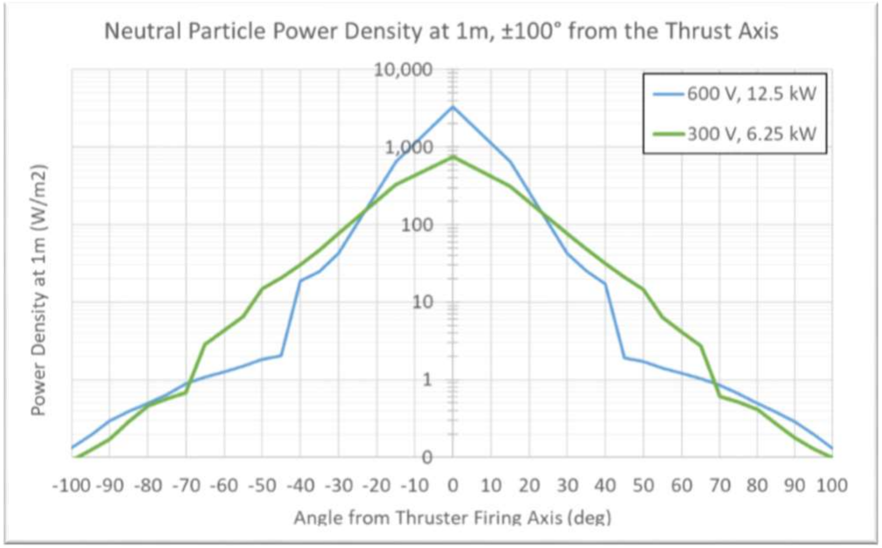


	600V		300V			
	Neg Angle (W/m^2)	Pos Angle (W/m^2)	Neg Angle (W/m^2)	Pos Angle (W/m^2)	600V Average (W/m^2)	300V Average (W/m^2)
60°-65°	25.2	24.2	86.0	83.4	**24.7**	**84.7**
70°-75°	17.6	17.1	13.7	12.2	**17.3**	**12.9**
80°-85°	9.8	9.9	9.1	8.2	**9.8**	**8.6**
90°-95°	5.9	5.7	3.4	3.6	**5.8**	**3.5**
100°	2.7	2.6	1.8	2.0	**2.7**	**1.9**

Convection From Neutral Particles

$$Q_{Conv\_Neutral\_Particle}$$

- Source:
  - Neutral particle heating will be 5% of the Q_{Conv_Ions}
  - $Power\ Density \times 0.05 = Q_{Conv\_NP}$
- 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.

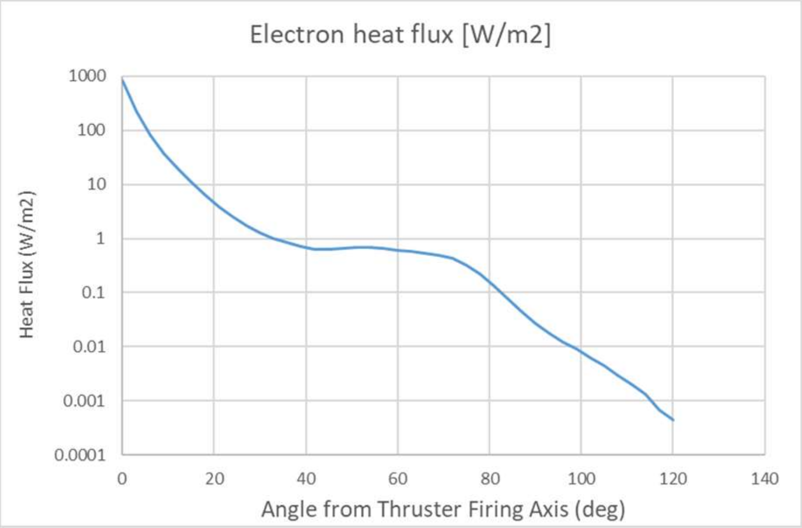


	600V		300V			
	Neg Angle (W/m^2)	Pos Angle (W/m^2)	Neg Angle (W/m^2)	Pos Angle (W/m^2)	600V Average (W/m^2)	300V Average (W/m^2)
60°-65°	1.26	1.21	4.30	4.17	**1.23**	**4.24**
70°-75°	0.88	0.85	0.68	0.61	**0.87**	**0.65**
80°-85°	0.49	0.49	0.45	0.41	**0.49**	**0.43**
90°-95°	0.29	0.28	0.17	0.18	**0.29**	**0.18**
100°	0.14	0.13	0.09	0.10	**0.13**	**0.10**

Electron Heating

$$Q_{ElectronHeating}$$

- Source:
  - Caused by electrons discharging energy into the incident surface.
    - V: Electron temperature
      - assume 1 eV electron temperature
    - I: Current Density with Faraday Probe
    - $V \times I = Power\ Density$
- 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 then 2.4x margin.
- Note
  - Overall Electron plume heating is negligible



Angle	Flux (W/m^2)	Flux + Margin (W/m^2)
60°-69°	0.613	1.472
70°-79°	0.438	1.052
80°-89°	0.133	0.320
90°-99°	0.027	0.064
100-109°	0.006	0.015
110-120°	0.002	0.005

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

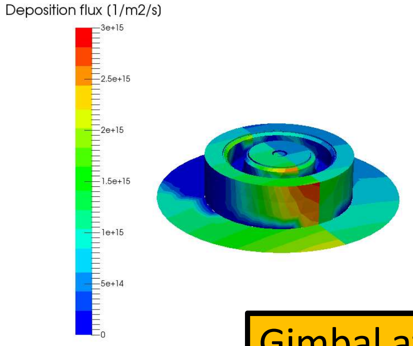
- Back-sputtering material to thruster
  - The thermal control coating will coat nearby components as the surface is sputtered away.
  - This can be detrimental to the thruster.

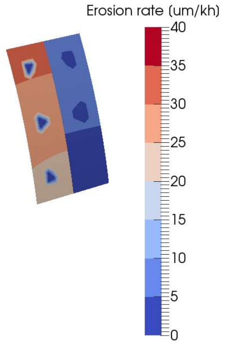
Effects of Ion Induced Erosion

- 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.

Erosion Analysis Results

- 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





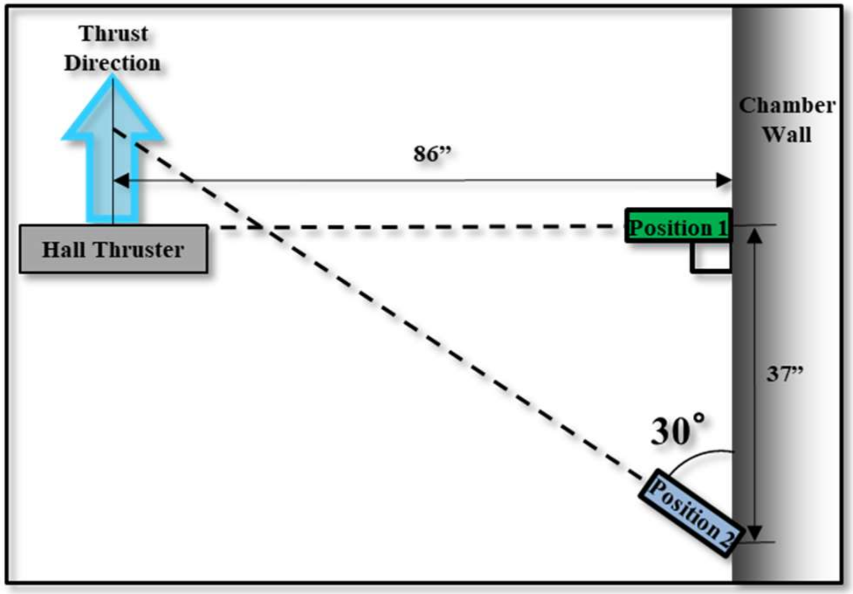
Gimbal at 20°

Gimbal angle	Max Eroded Thickness (@ 8khr), um					
	Graphite	Moly	Tungsten	Alumina	Aluminum	Titanium
20°	**24.24**	162.60	206.37	**37.52**	175.39	**81.74**
10°	**11.35**	75.78	95.87	**18.57**	85.08	**38.00**
0°	**6.58**	43.87	55.04	**11.80**	54.24	**21.97**

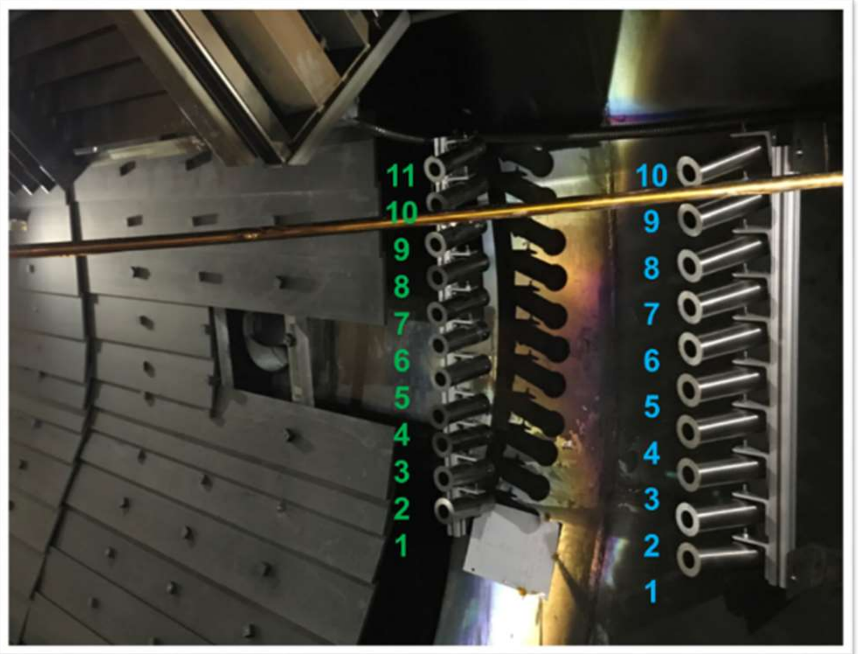
Erosion and sputtering analysis by John Yim at NASA GRC

Ion Plume Exposure Testing Setup

- 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.



Collimator Positioning (Top-Down)



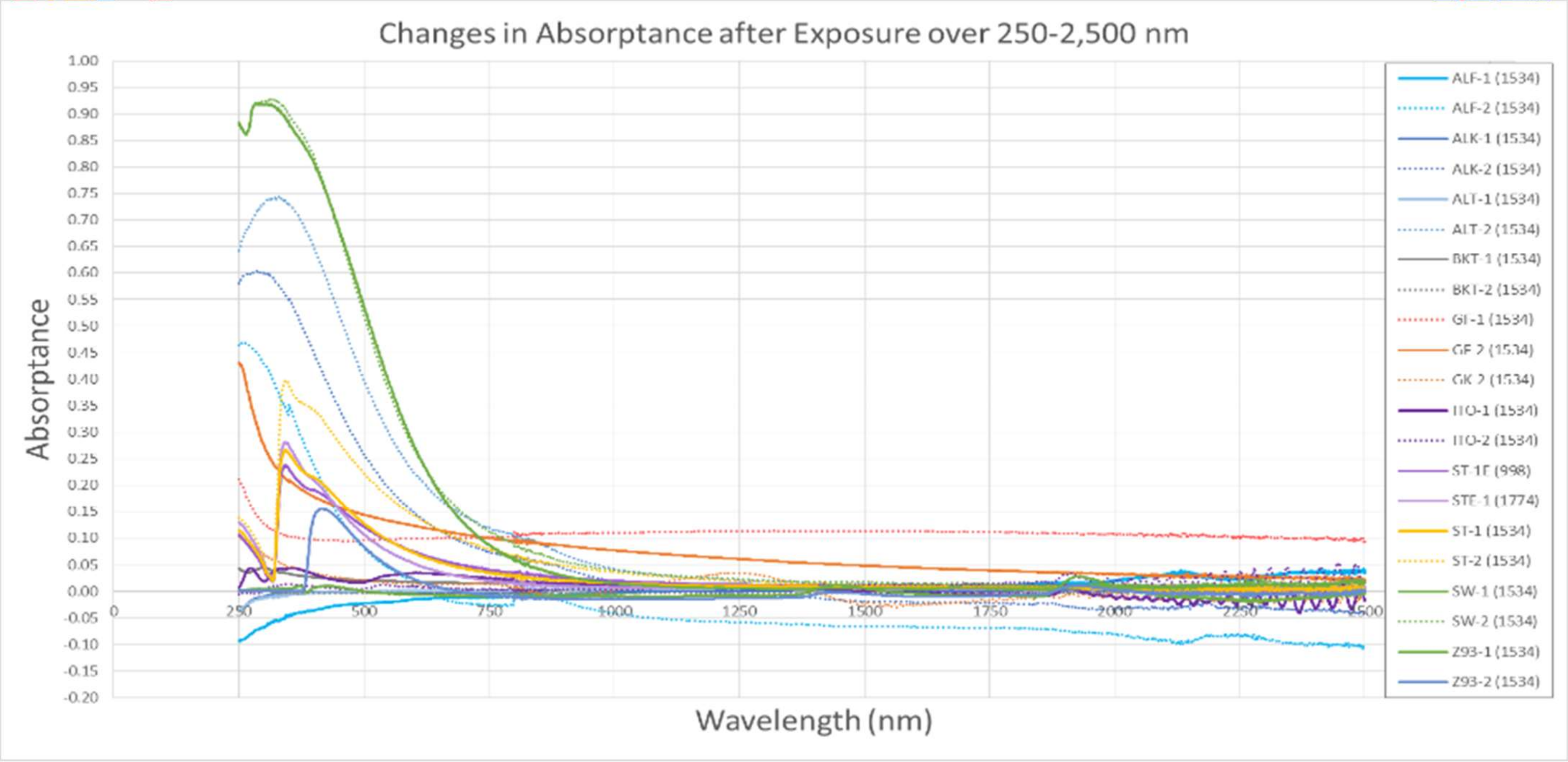
Test samples mounted in VF-5

Optical Properties after Plume Exposure

Nomenclature	Material	Location	Hemispherical Emittance (ƐH)	Solar Absorptance (α)	Emittance Change (536)	Emittance Change (1534)	Absorptance Change (536)	Absorptance Change (1534)
AlK-1	Aluminum x 2.0mil Kapton, 1st Surface Mirror	E90°	0.021	0.094	0.001	0.006	0.002	0.000
AlT-1	Aluminum Tape 0.5 mil	E90°	0.029	0.097	-0.007	-0.003	-0.001	0.001
AlF-1	Aluminum Foil	E90°	0.030	0.141	-0.001	0.007	-0.018	-0.013
ST-1	Silver Teflon 2nd Surface Mirror	E90°	0.404	0.083	0.018	-0.001	0.091	0.069
STE-1	Silver Teflon 2nd Surface Mirror (Exposed, 240hr)	E90°	0.404	0.079	0.007	0.004	0.038	0.059
Z93-1	White Paint Z-93	E90°	0.814	0.161	-0.043	-0.045	-0.006	-0.004
ST-2E	Silver Teflon 2nd Surface Mirror	E90°	0.403	0.081	N/A	0.001	N/A	0.068
ITO-1	ITO (1600 ohm/sq)x 2.0 mil Kapton x Al	E90°	0.499	0.394	-0.034	-0.033	0.013	0.019
BKT-1	Kapton Black tape	E90°	0.866	0.928	-0.005	0.006	0.001	0.017
GF-1	Graphite Foil	E90°	0.486	0.722	0.034	0.008	0.058	0.104
SW-1	Solar White	E90°	0.653	0.025	-0.120	-0.108	0.238	0.267
AlK-2	Aluminum x 2.0mil Kapton	E-30°	0.021	0.134	-0.003	0.013	0.083	0.149
AlT-2	Aluminum Tape 0.5 mil	E-30°	0.030	0.099	-0.008	-0.005	0.126	0.227
AlF-2	Aluminum Foil	E-30°	0.030	0.211	0.000	-0.008	0.123	0.034
ST-2	Silver Teflon 2nd Surface Mirror	E-30°	0.404	0.082	0.003	0.001	0.091	0.122
Z93-2	White Paint Z-93	E-30°	0.814	0.167	-0.048	-0.039	0.005	0.022
GK-2	Germanium (1500 Au) x 2.0 mil Kapton	E-30°	0.391	0.523	-0.021	-0.018	-0.002	0.014
ITO-2	ITO (1600 ohm/sq)x 2.0 mil Kapton x Al	E-30°	0.499	0.397	0.014	0.019	0.002	0.007
BKT-2	Kapton Black tape	E-30°	0.866	0.928	-0.005	-0.004	-0.002	-0.003
GF-2	Graphite Foil	E-30°	0.486	0.714	-0.003	0.066	0.016	0.111
SW-2	Solar White	E-30°	0.653	0.026	-0.016	-0.003	0.185	0.277

- 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

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

Back-Sputtering Material to Thruster

- Materials that erodes 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

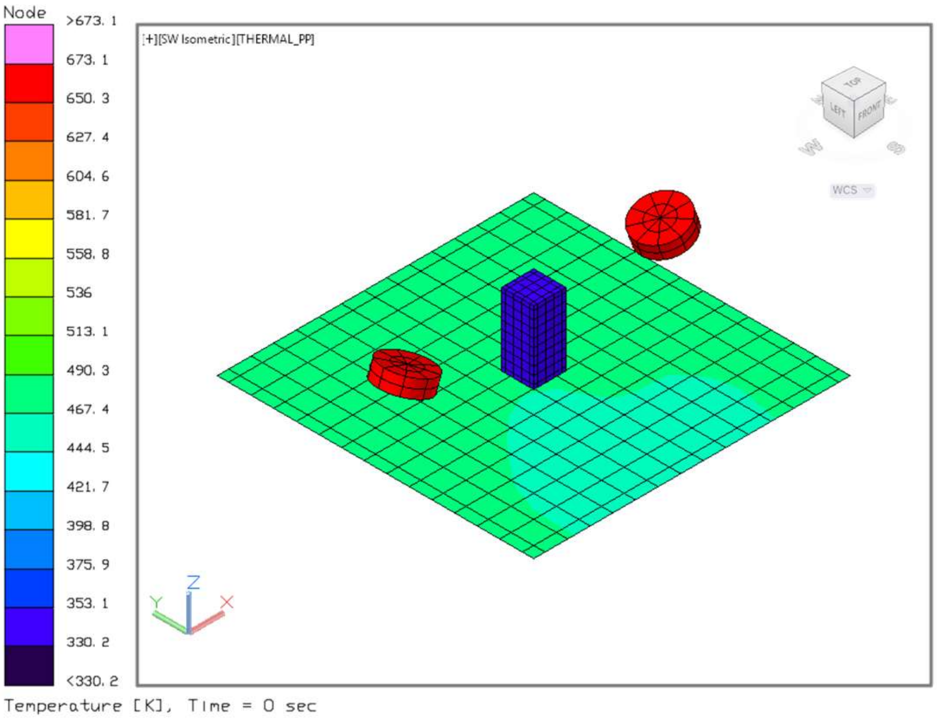
- For limiting PDP erosion, all 3 of these materials will work well.
- Rates are much lower than thruster tolerance requirement (2 um/khr) but is asymmetric
- Deposited thickness (after 8 khr) is thick enough to completely change the local optical properties but does not alter the electrical properties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

Gimbal angle	Max deposition rate, um/khr [Max deposition thickness after 8 khr, um]		
	Graphite	Titanium	Alumina
0°	0.028 [0.23]	0.089 [0.71]	0.063 [0.50]
10°	0.054 [0.43]	0.170 [1.36]	0.122 [0.97]
20°	0.061 [0.49]	0.193 [1.54]	0.139 [1.11]

Erosion and sputtering analysis by John Yim at NASA GRC

Thermal Control Solution for PDP

- 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.

PDP Coating	Alumina	Titanium	Graphite
Emissivity	0.25-0.6	0.3-0.55	0.34
Absorptivity	0.1-0.25	0.4-0.6	0.65
20° Gimbal Temperature (°C)	46 to 97	80 to 151	145
30° Gimbal Temperature (°C)	77 to 139	106 to 175	170

- 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)

PDP Substrate Material	Al-6061	SS-316	Ti-6
Thermal Conductivity (W/m-K)	167	16.3	6.7
CTE Mismatch Alumina (10^-6/K)	16	8.4	1.0

Recommendation and Future Work

- 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

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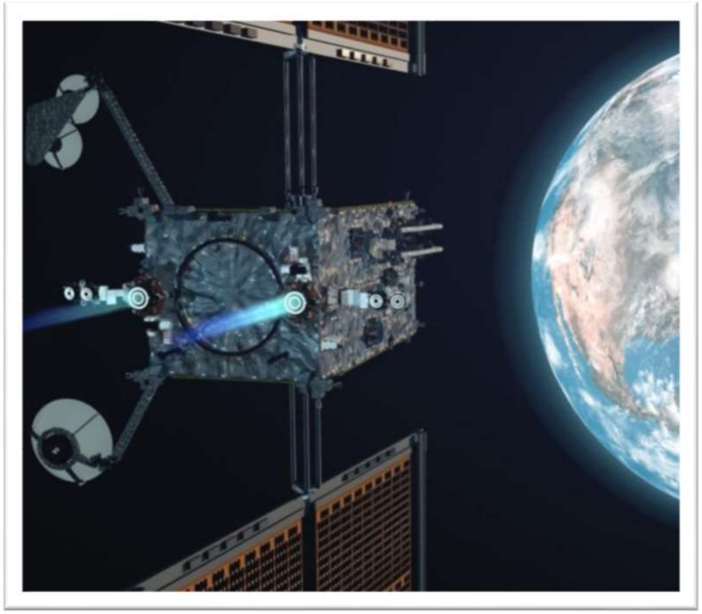

QUESTIONS?