Characterization of a Radiometer Window for Mars Aftbody Heating Including Ablation Product Deposition Using a Miniature Arc Jet

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Background

- **Mars Entry Descent and Landing Instrumentation 2 (MEDLI2)**
  - Characterize aerodynamic, aerothermodynamic, and TPS performance
  - Expands off MEDLI (Mars Science Laboratory, 2012)
  - Pressure Transducers, Thermal Plugs, Heat Flux Sensors, Radiometer

**MEDLI2 (Mars 2020)**

Figure Credit: H. H. Hwang et al., 2016.
MEDLI2 Radiometer

• MEDLI2 radiometer consists of a heat flux sensor behind a sapphire window
• Measurement range: 0 - 15 W/cm²

MEDLI2 Radiometer

• Expected backshell heating for Mars 2020:
  - Radiative: ~ 4.5 W/cm²
  - Convective: ~ 1 W/cm²

• Spectral radiance for MSL entry from Electric Arc Shock Tube (EAST) experiments show peak radiance around 2.7 μm and 4.3 μm due to CO₂

![Figure Credit: B. A. Cruden et al., 2015.](image-url)
Radiometer Characterization

- Radiometer output

\[ V_{rad} \propto \int T(\lambda)A(\lambda)L(\lambda) \, d\lambda \]

- Radiometer output is not spectral, however characterization will be done spectrally

- \( L(\lambda) \): Spectral radiance of source (calibration or shock layer)
- \( T(\lambda) \): Spectral transmission of window
- \( A(\lambda) \): Spectral absorbance of heat flux sensor

\[ V_{rad} \propto \int T(\lambda)A(\lambda)L(\lambda) \, d\lambda \]
Transmission and Absorbance

Sapphire Window
- Transmission of ~88% up to 5.5 µm

Heat Flux Sensor
- Absorbance of ~95%
Measured Radiation

Heat Flux Sensor Absorbance, $A(\lambda)$
Radiometer Window Transmission, $T(\lambda)$

Radiance (W/cm$^2 \cdot$ sr.$\cdot$µm)
Transmission and Absorbance (%)

Wavelength (µm)
Measured Radiation

Percent Signal Loss:

\[ S_{\text{loss}} = \left( 1 - \frac{\int T(\lambda) A(\lambda) L(\lambda) \, d\lambda}{T_{\text{cal}} A_{\text{cal}} \int L(\lambda) \, d\lambda} \right) \times 100 \]
Measured Radiation

Percent Signal Loss:

\[
S_{loss} = \left(1 - \frac{\int T(\lambda)A(\lambda)L(\lambda)\,d\lambda}{T_{cal}A_{cal}\int L(\lambda)\,d\lambda}\right) \times 100
\]

- Measure of unaccounted for radiation due to variation in wavelength sensitivity

Diagram showing measured radiances and total radiances at different wavelengths, with transmission and absorbance plots.
Measured Radiation

Percent Signal Loss:

\[
S_{loss} = \left(1 - \frac{\int T(\lambda)A(\lambda)L(\lambda) \, d\lambda}{T_{cal}A_{cal}\int L(\lambda) \, d\lambda}\right) \times 100
\]

- Measure of unaccounted for radiation due to variation in wavelength sensitivity

- Assuming radiometer calibration corrects for 1 - 2 \mu m \rightarrow T_{cal}A_{cal} = 85%

\[
S_{loss} = 1.8\%
\]
Thermal Protection System (TPS) Ablation

- Radiometer will be embedded in backshell TPS
- TPS ablation products from heatshield or backshell could be deposited on the window

Backshell
SLA-561V
(Silicone resin with cork, phenolic microballoon, silica microballoon, and refractory fiber fillers*)

Heatshield
PICA
(Carbon Fiberform and phenolic resin**)

Image credit: NASA/JPL-Caltech

** H.K. Tran, et al., 1997.
Miniature Arc Jet (mARC) Facility

• mARC previously characterized in air*
  • Heat fluxes > 1000 W/cm²

• Expected Mars 2020 heat flux:
  - Heatshield: ~ 150 W/cm²
  - Backshell: ~ 5 W/cm²

• Characterize mARC in Mars flight relevant environment (90% CO₂, 10% N₂)

*A. Nawaz et al., 2016.
mARC Characterization Results

Flow rate of 0.1 g/s
→ Centerline heat flux: 250-400 W/cm²

Flow rate of 0.25 g/s
→ Centerline heat flux: 550-700 W/cm²

Test Conditions:
• 90% CO₂, 10% N₂ (by mass)
• Arc Current: 40 A
• Distance From Nozzle: 20 mm

See paper for detailed mARC characterization results.
Test Article and Expected Heat Rate

Computed surface heating rates for a wedge at various inclination angles

- Model inclination angle: 45°
  - ~140 W/cm² on TPS #1
  - ~5 W/cm² at the window
## Test Conditions:
- 90% CO₂, 10% N₂ (by mass)
- Mass Flow Rate: 0.1 g/s
- Arc Current: 40 A
- Distance From Nozzle: 20 mm
- Model Inclination Angle: 45°

### Test Matrix

<table>
<thead>
<tr>
<th>Run Number</th>
<th>Window Number</th>
<th>Duration (sec)</th>
<th>TPS #1/TPS #2</th>
<th>Copper Slug?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>55</td>
<td>PICA/PICA</td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>40</td>
<td>PICA/PICA</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>30</td>
<td>PICA/SLA</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>30</td>
<td>PICA/SLA</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>30</td>
<td>SLA/SLA</td>
<td>Yes</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>30</td>
<td>SLA/SLA</td>
<td>No</td>
</tr>
</tbody>
</table>
Radiometer Windows

- PICA/PICA, with Copper Slug, Window 1
- SLA/SLA, with Copper Slug, Window 2
- PICA/SLA, with Copper Slug, Window 3
- PICA/PICA, without Copper Slug, Window 1
- SLA/SLA, without Copper Slug, Window 2
- PICA/SLA, without Copper Slug, Window 3
- SLA/SLA, without Copper Slug, Window 4
- PICA/SLA, without Copper Slug, Window 5
- SLA/SLA, without Copper Slug, Window 6
Radiometer Window Transmission
Post-mARC Test

Transmission (%) vs. Wavelength (µm)

- Initial
- PICA/PICA Window 1
- PICA/PICA Window 4
- PICA/SLA Window 3
- PICA/SLA Window 6
- SLA/SLA Window 2
- SLA/SLA Window 5
Radiometer Window Transmission
Post-mARC Test

![Graphs showing transmission over wavelength for PICA/PICA, SLA/SLA, and PICA/SLA]
Comparison to EAST MSL Data

**Graphs:**
1. **PICA/PICA - Window 1**
   - Heat Flux Sensor Absorbance
   - Radiometer Window Transmission - Post-mARC
   - Wavelength (µm) on x-axis, Radiance (W/cm² sr-μm) on y-axis

2. **SLA/SLA - Window 2**
   - Heat Flux Sensor Absorbance
   - Radiometer Window Transmission - Post-mARC
   - Wavelength (µm) on x-axis, Radiance (W/cm² sr-μm) on y-axis

3. **PICA/SLA - Window 3**
   - Heat Flux Sensor Absorbance
   - Radiometer Window Transmission - Post-mARC
   - Wavelength (µm) on x-axis, Radiance (W/cm² sr-μm) on y-axis
### Percent Signal Loss

<table>
<thead>
<tr>
<th>Initial</th>
<th>PICA/PICA</th>
<th>PICA/PICA</th>
<th>SLA/SLA</th>
<th>SLA/SLA</th>
<th>PICA/SLA</th>
<th>PICA/SLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper Slug?</td>
<td>---</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Window Number</td>
<td>---</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Max $S_{loss}$ (%)</td>
<td>1.8</td>
<td>12.2</td>
<td>13.1</td>
<td>27.9</td>
<td>29.0</td>
<td>19.7</td>
</tr>
</tbody>
</table>

- Signal loss of 12 - 30% from ablation products coating the sapphire window in both 2.7 µm and 4.3 µm bands
  - SLA/SLA likely an over-test
  - PICA/SLA more representative with ~ 20% signal loss
Conclusions

- Initial
  - Transmission of radiometer window ~ 88% up to 5.5 µm
  - Absorbance of heat flux sensor ~ 95%
  - Radiometer measures about 85% of total expected radiation, which is correctable through calibration
  - About 1.8% loss due to variation in wavelength sensitivity

- Post-mARC Testing
  - Decreased radiometer window transmission at ~3 µm, ~4.5 µm, > 5.5 µm
  - 12 - 30% of signal lost due TPS ablation products
Future Work

• How “flight-like” were the conditions in the mARC?

  **Flight Matched Conditions**
  - Peak heatshield heat flux on TPS #1
  - Peak backshell heat flux at window location
  - Heat load

  **Not Flight Matched Conditions**
  - Heat profile
  - Length scale

• Other questions:
  - How does cold-soak during interplanetary transit impact window transmission and ablation product deposition?
  - How does window transmission degrade as a function of time during entry?

➢ Repeat flight and mARC test CFD
  ➢ Blowing boundary condition that matches the mass loss rate predicted by material response models
  ➢ Compare concentration of ablation products over the window
  ➢ If the flight concentration is less than the mARC test, these results will be treated as an over-test
Thank you!
Questions?
XPS Results – Atomic % (Average)

<table>
<thead>
<tr>
<th></th>
<th>PICA/PICA Window 4</th>
<th>SLA/SLA Window 2</th>
<th>PICA/SLA Window 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>C 1s</td>
<td>59.8%</td>
<td>54.7%</td>
<td>52.1%</td>
</tr>
<tr>
<td>O 1s</td>
<td>29.1%</td>
<td>27.9%</td>
<td>30.2%</td>
</tr>
<tr>
<td>Si 2p</td>
<td>4.5%</td>
<td>12.5%</td>
<td>11.1%</td>
</tr>
<tr>
<td>N 1s</td>
<td>3.7%</td>
<td>3.9%</td>
<td>4.8%</td>
</tr>
<tr>
<td>Cu 2p3</td>
<td>3.0%</td>
<td>1.0%</td>
<td>1.9%</td>
</tr>
</tbody>
</table>

- Identified elements (carbon, oxygen, and silicon) support conclusions from FTIR data
- Windows in PICA/PICA models contained the most carbon
- Windows in SLA/SLA models contained the most silicon
- Presence of silicon in PICA/PICA windows could be from RTV-560 used to adhere the TPS to the bracket or from insulating tape used inside the chamber
- Copper is assumed to come from the mARC electrodes as the arc erodes them