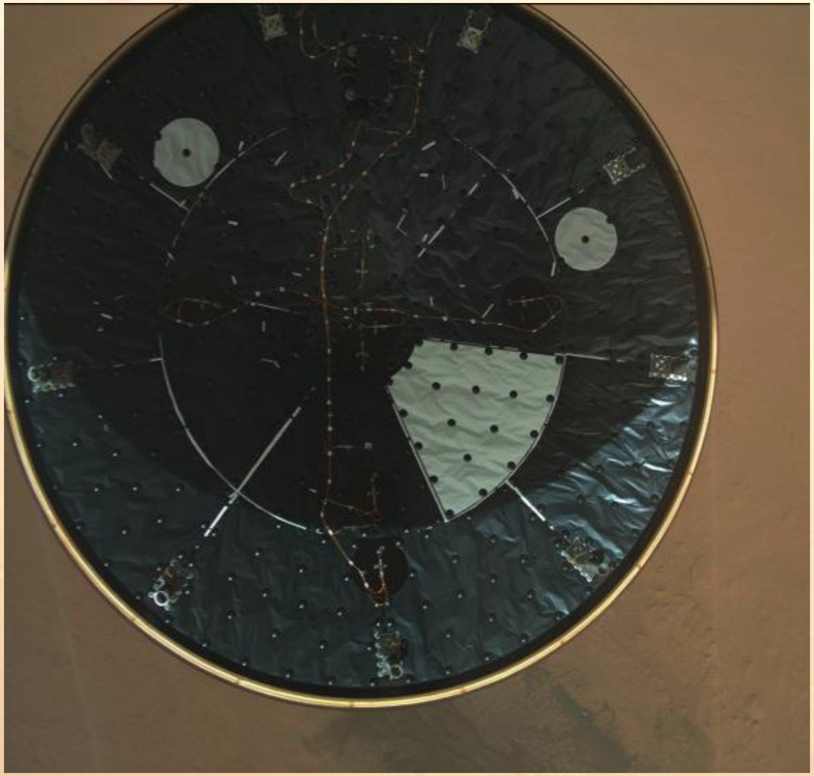

Characterization of a Radiometer Window for Mars Aftbody Heating Including Ablation Product Deposition Using a Miniature Arc Jet

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Chun Tang, Mark S. McGlaughlin, Todd R. White, NASA Ames Research Center

Thanh S. Ho, Megan MacDonald, Jacobs Technology at NASA Ames Research Center

Brett A. Cruden, AMA Inc. at NASA Ames Research Center

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

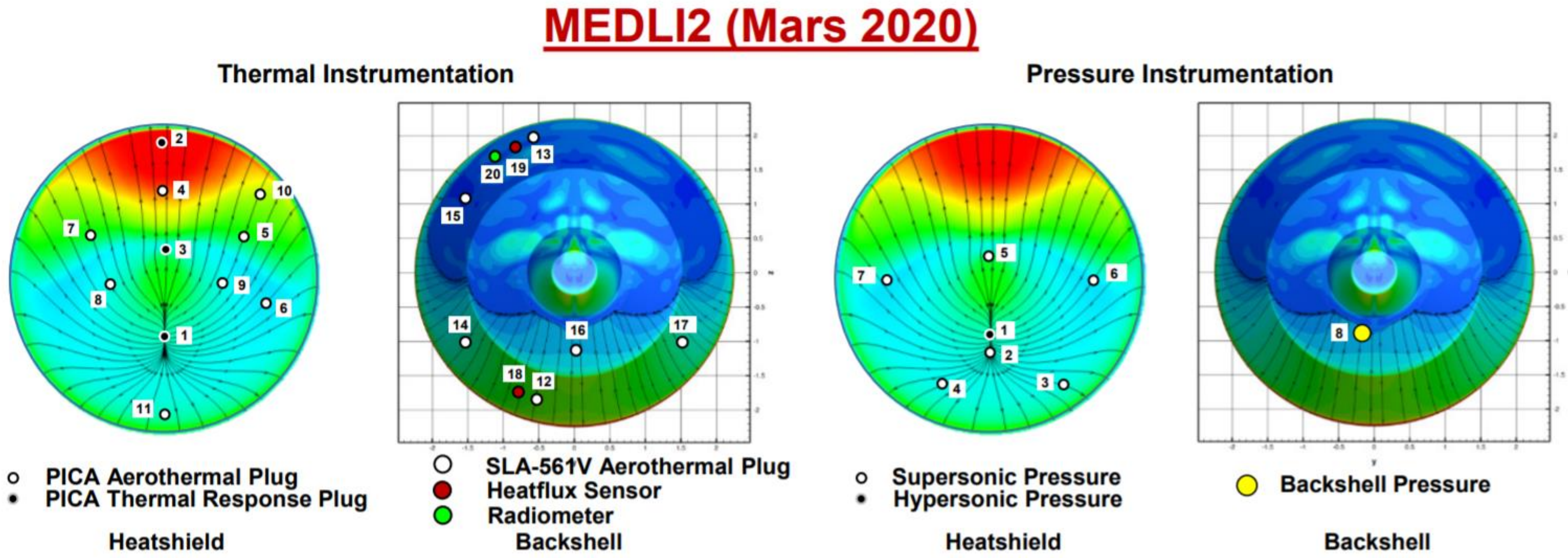
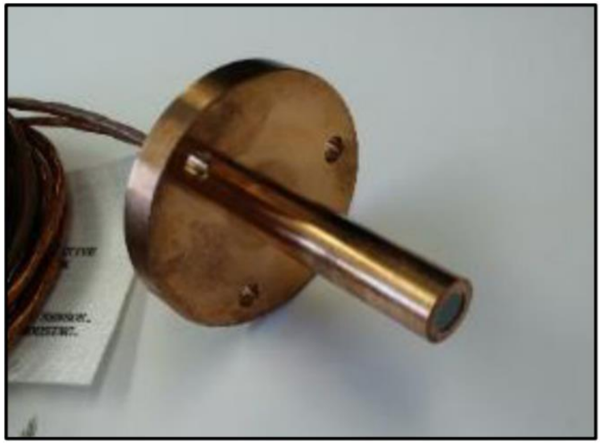


Figure Credit: H. H. Hwang et al., 2016.

MEDLI2 Radiometer

- MEDLI2 radiometer consists of a heat flux sensor behind a sapphire window
- Measurement range: 0 - 15 W/cm^2

MEDLI2 Radiometer



- Expected backshell heating for Mars 2020:
  - Radiative: ~ 4.5 W/cm^2
  - Convective: ~ 1 W/cm^2

- 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 CO_2

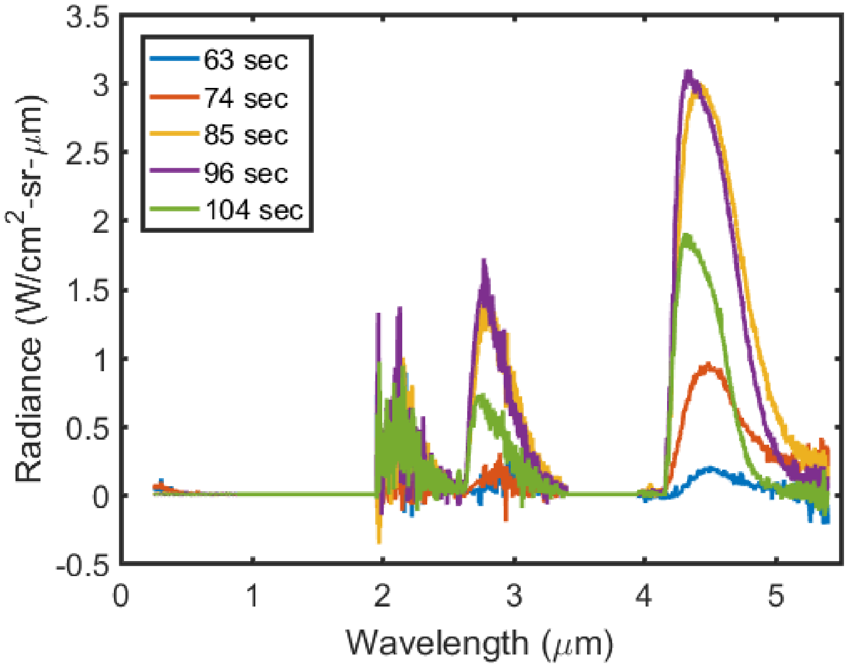


Figure Credit: B. A. Cruden et al., 2015.

Radiometer Characterization

- Radiometer output

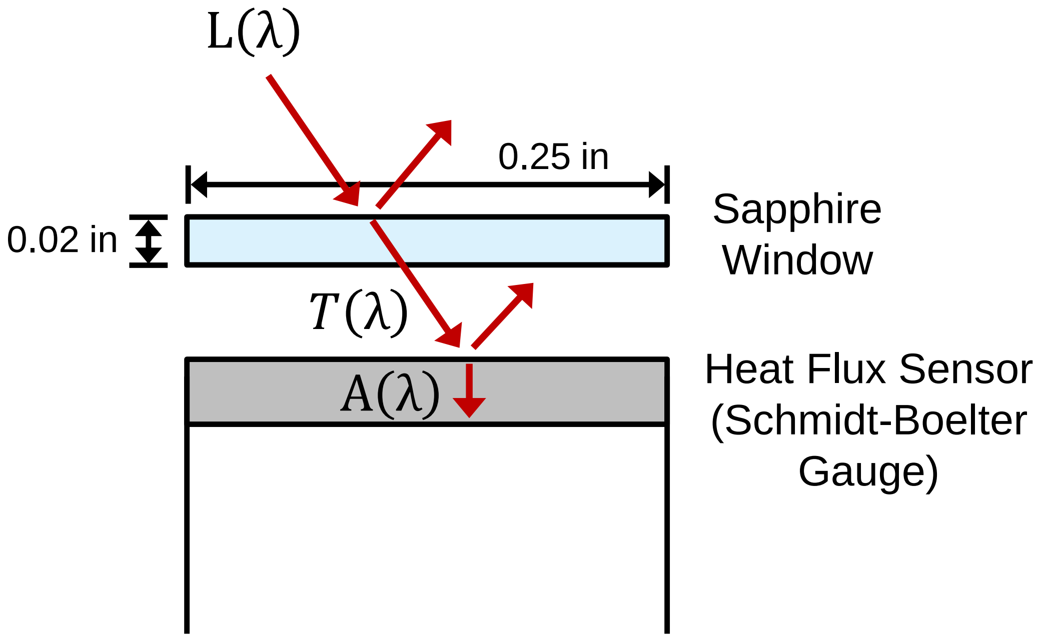
$$V_{rad} \propto \int T(\lambda)A(\lambda)L(\lambda)\,d\lambda$$

$L(\lambda)$: Spectral radiance of source (calibration or shock layer)

$T(\lambda)$: Spectral transmission of window

$A(\lambda)$: Spectral absorbance of heat flux sensor

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

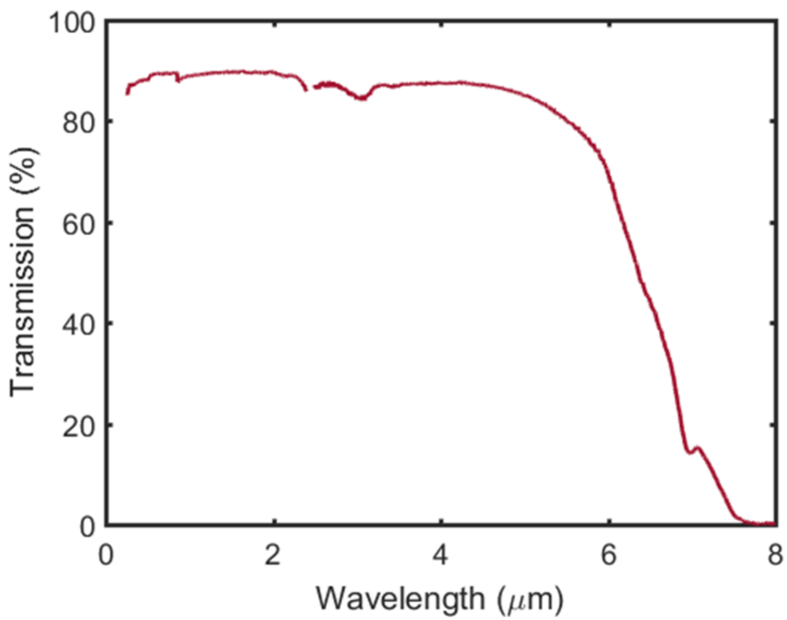


MEDLI2 Radiometer Cross-Section

Transmission and Absorbance

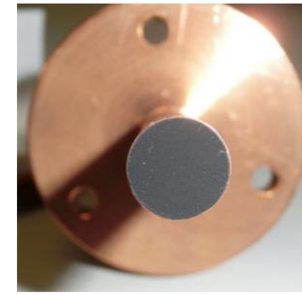
Sapphire Window

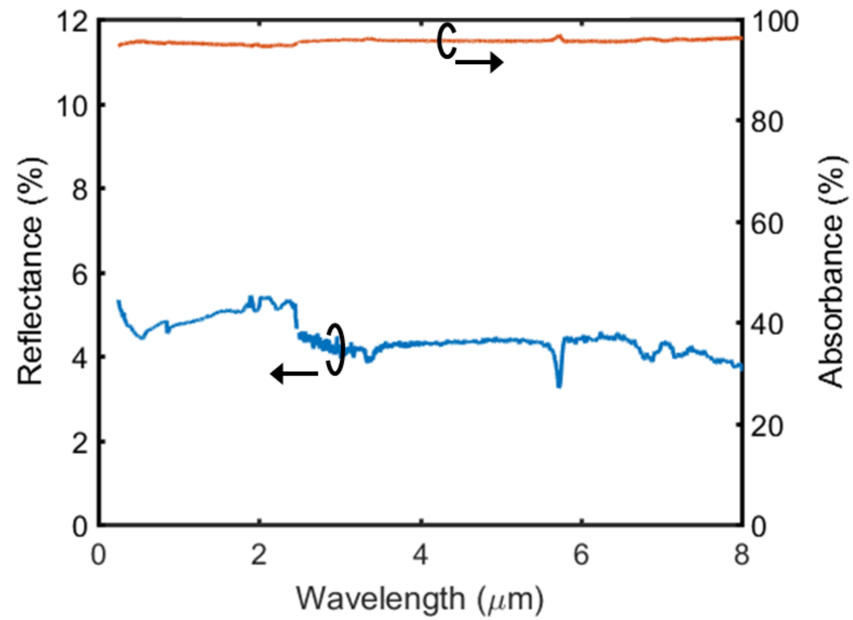
- Transmission of ~88% up to 5.5 µm



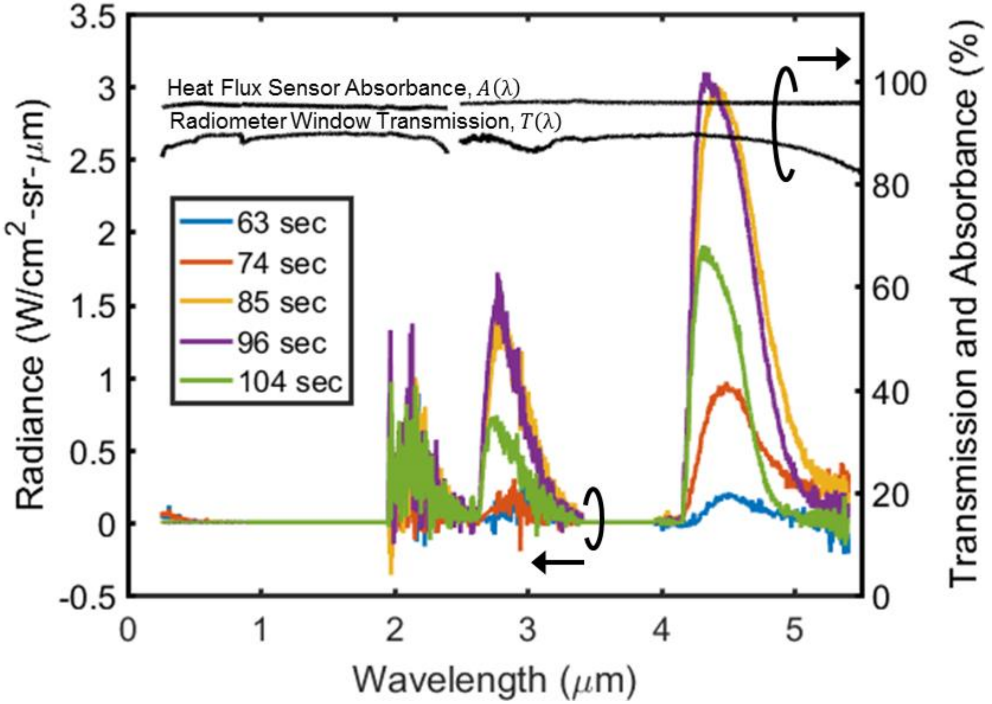
Heat Flux Sensor

- Absorbance of ~95%





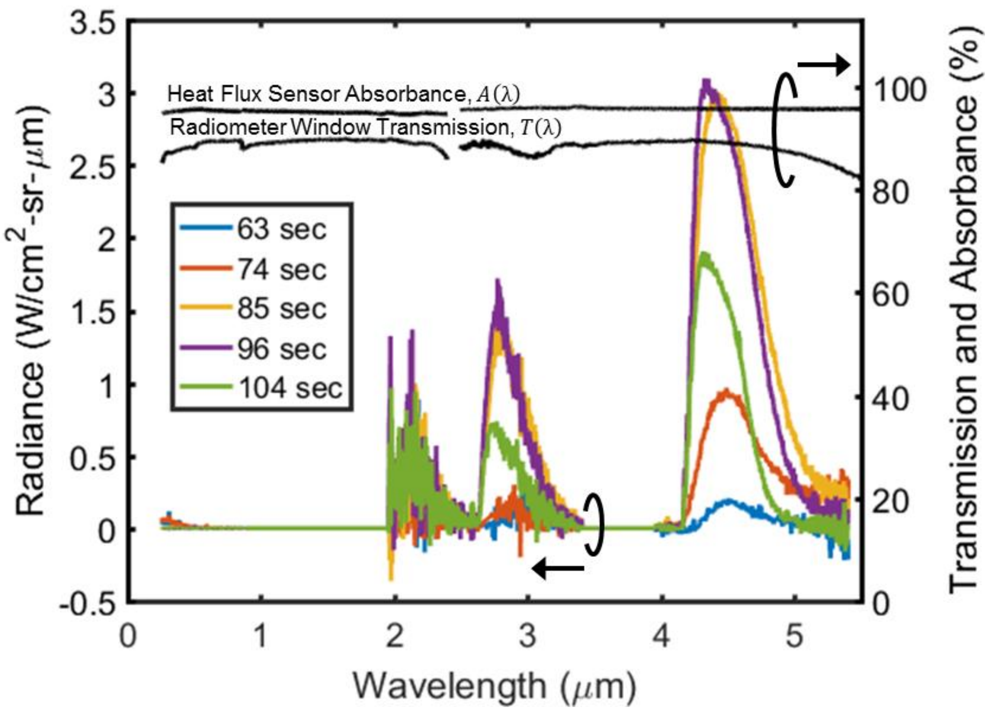
Measured Radiation



Measured Radiation

Percent Signal Loss:

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



Measured Radiation

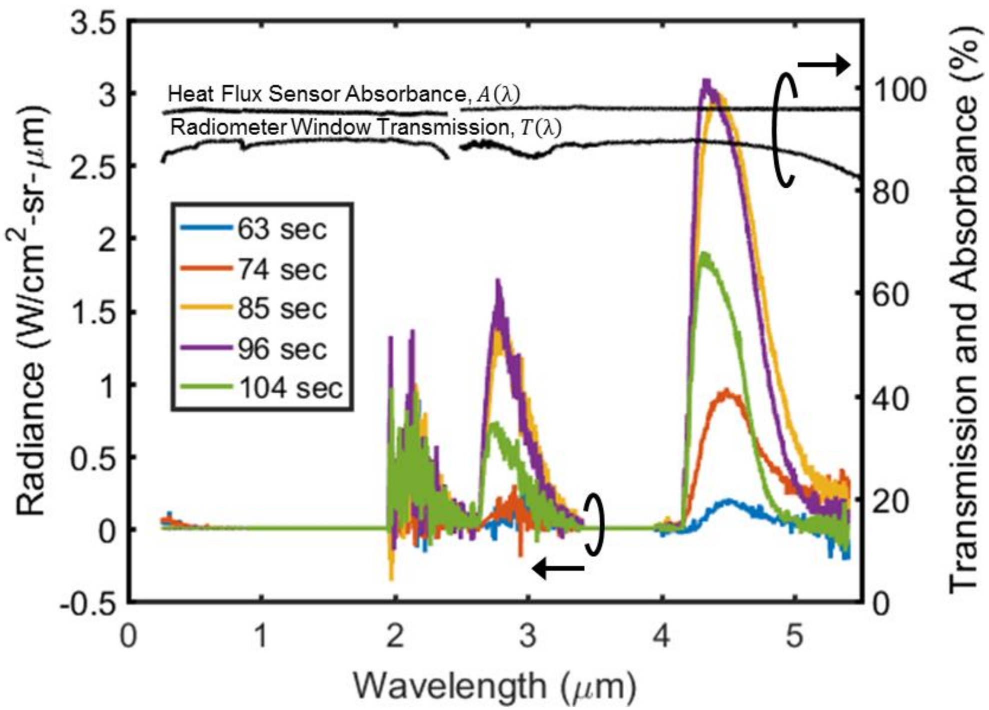
Percent Signal Loss:

Measured Radiance

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

Total Radiance

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



Measured Radiation

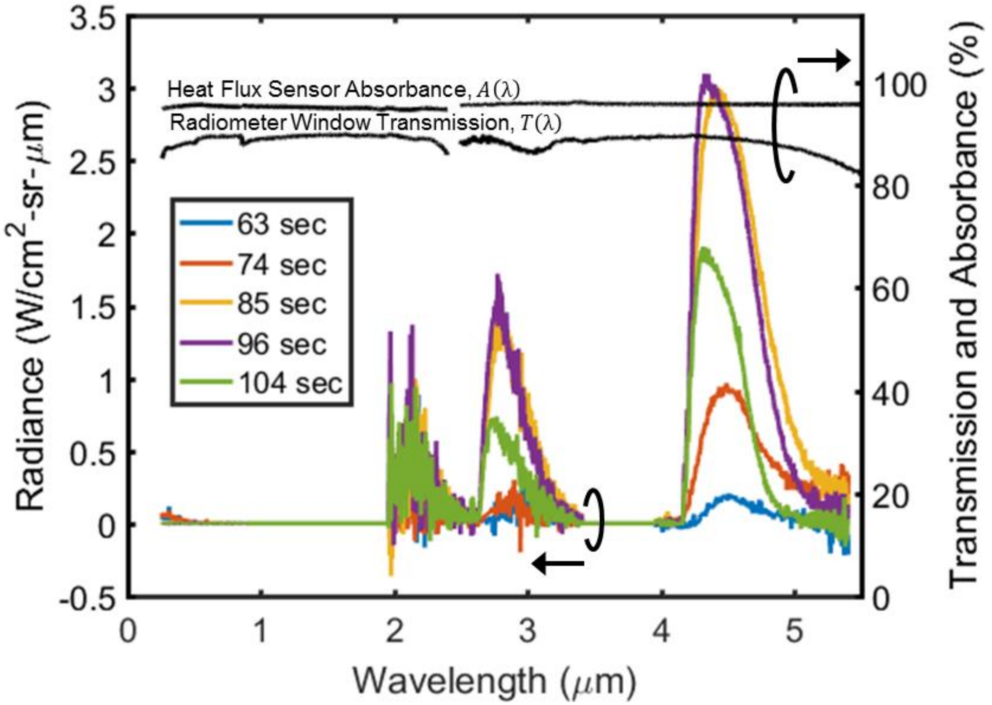
Percent Signal Loss:

Measured Radiance

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

Total Radiance

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



- Assuming radiometer calibration corrects for 1 - 2 µm → $T_{cal}A_{cal} = 85\%$
  - $S_{loss} = 1.8\%!$

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

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

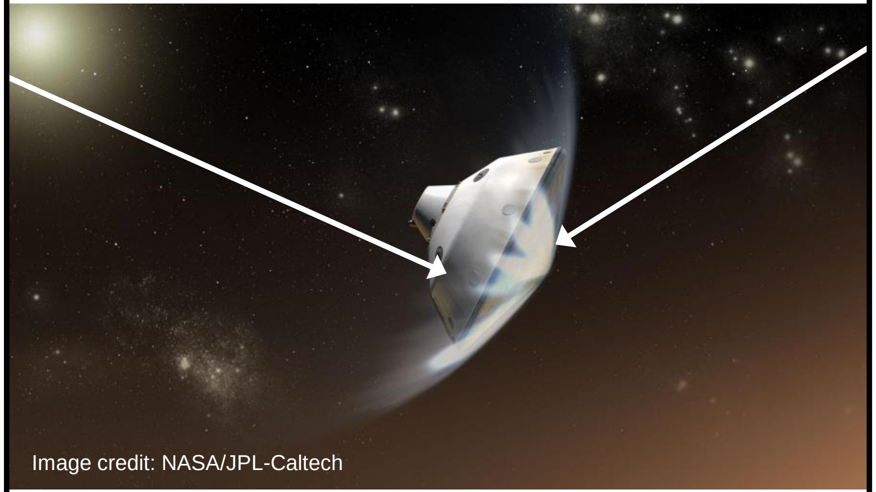
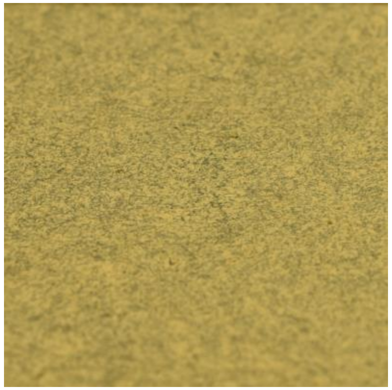


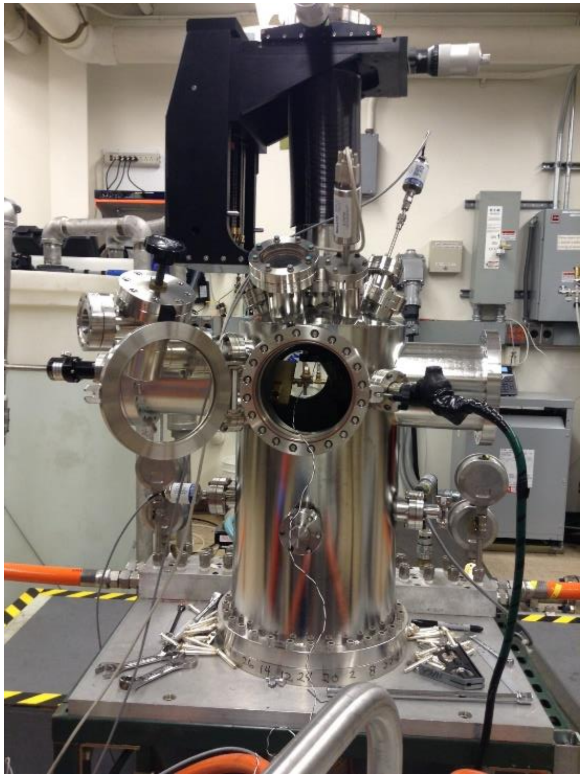
Image credit: NASA/JPL-Caltech

<u>Heatshield</u>
PICA
(Carbon Fiberform and phenolic resin**)



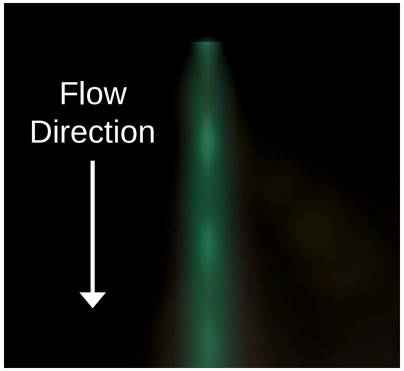
*E. L. Strauss, 1967.
** H.K. Tran, et al., 1997.

Miniature Arc Jet (mARC) Facility

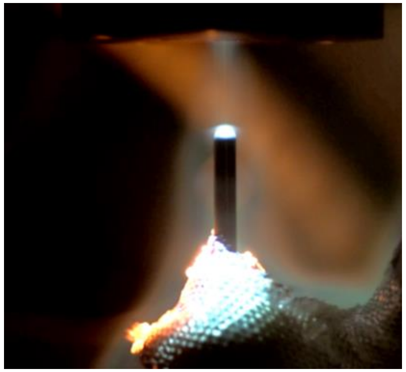


- mARC previously characterized in air*
  - Heat fluxes > 1000 W/cm^2
- Expected Mars 2020 heat flux:
  - Heatshield: ~ 150 W/cm^2
  - Backshell: ~ 5 W/cm^2
- Characterize mARC in Mars flight relevant environment (90% CO_2, 10% N_2)

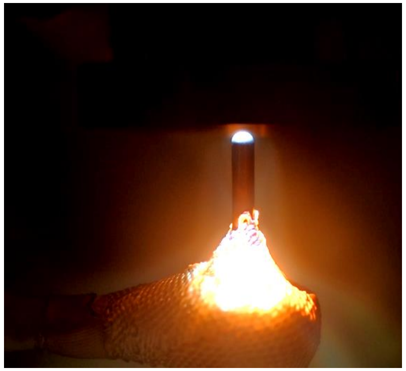
mARC Flow



Pitot Probe at 20 mm from Nozzle

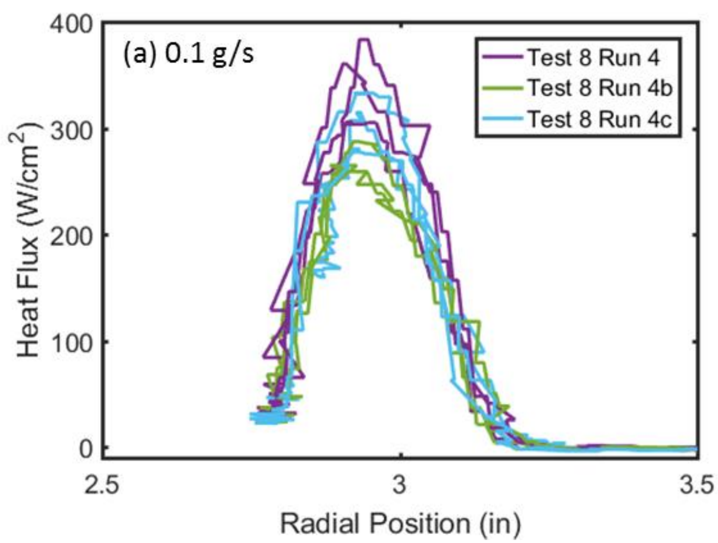


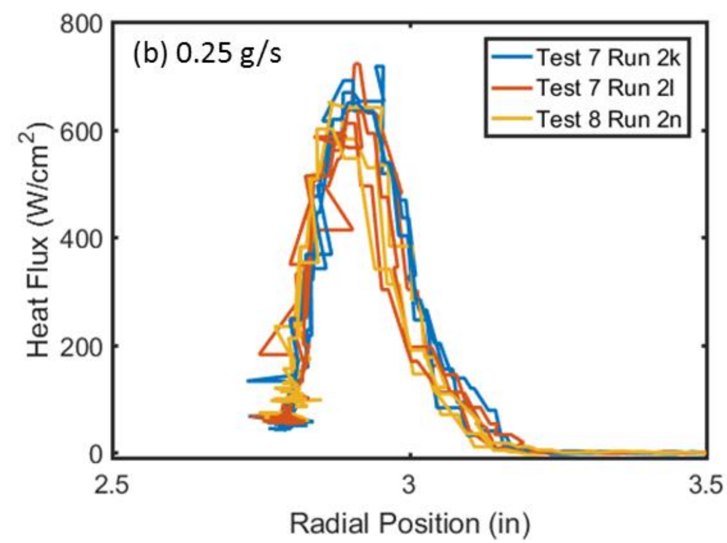
Gardon Gauge at 2 mm from Nozzle



*A. Nawaz et al., 2016.

mARC Characterization Results





Flow rate of 0.1 g/s
→ Centerline heat flux: 250-400 W/cm^2

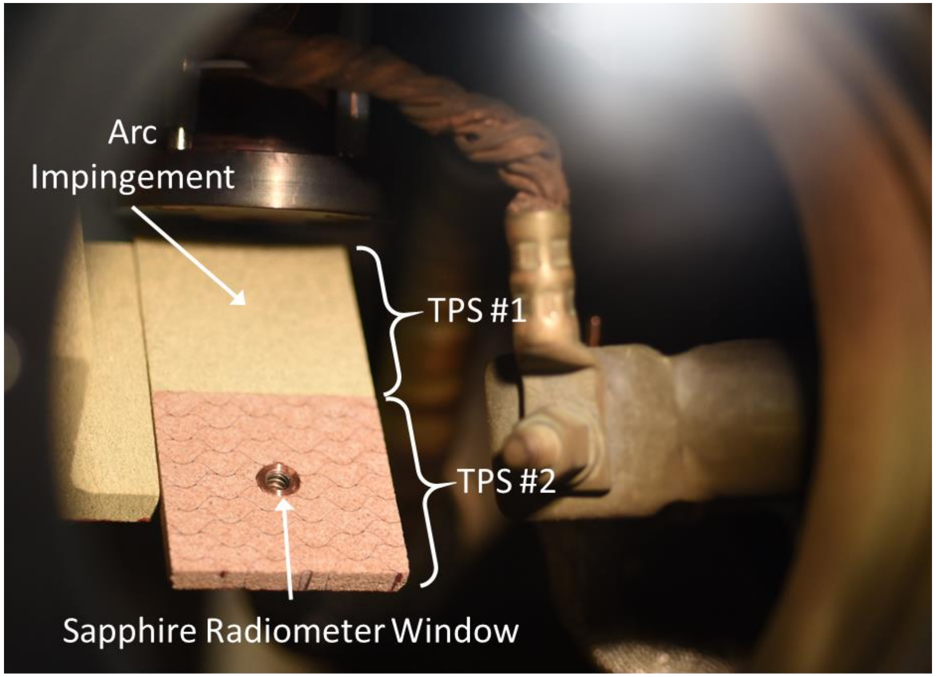
Flow rate of 0.25 g/s
→ Centerline heat flux: 550-700 W/cm^2

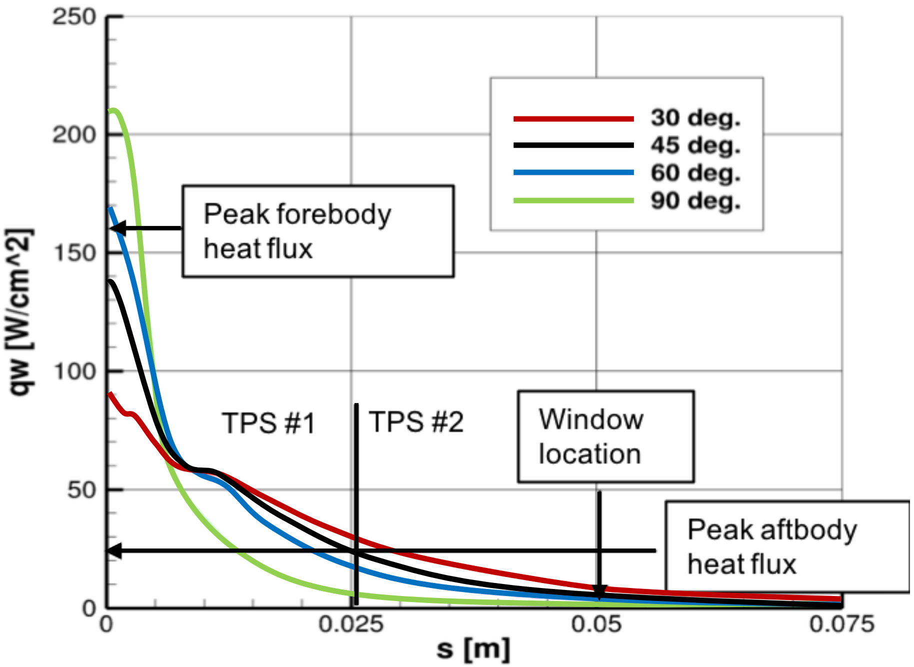
Test Conditions:

- 90% CO_2, 10% N_2 (by mass)
- Arc Current: 40 A
- Distance From Nozzle: 20 mm

See paper for detailed mARC characterization results.

Test Article and Expected Heat Rate



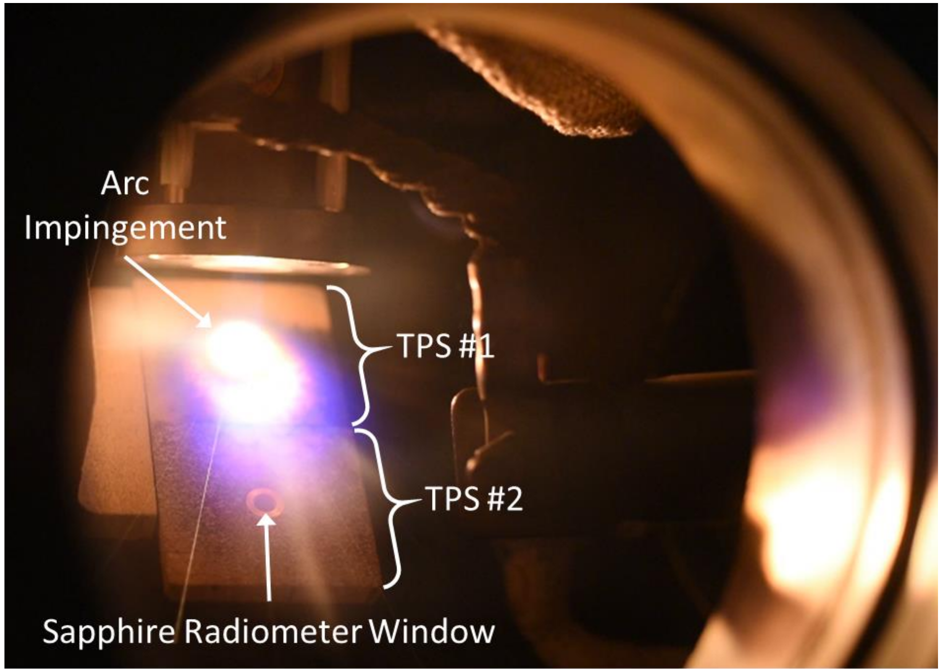


Computed surface heating rates for a wedge at various inclination angles

Model inclination angle: 45°

- ~140 W/cm^2 on TPS #1
- ~5 W/cm^2 at the window

Test Matrix

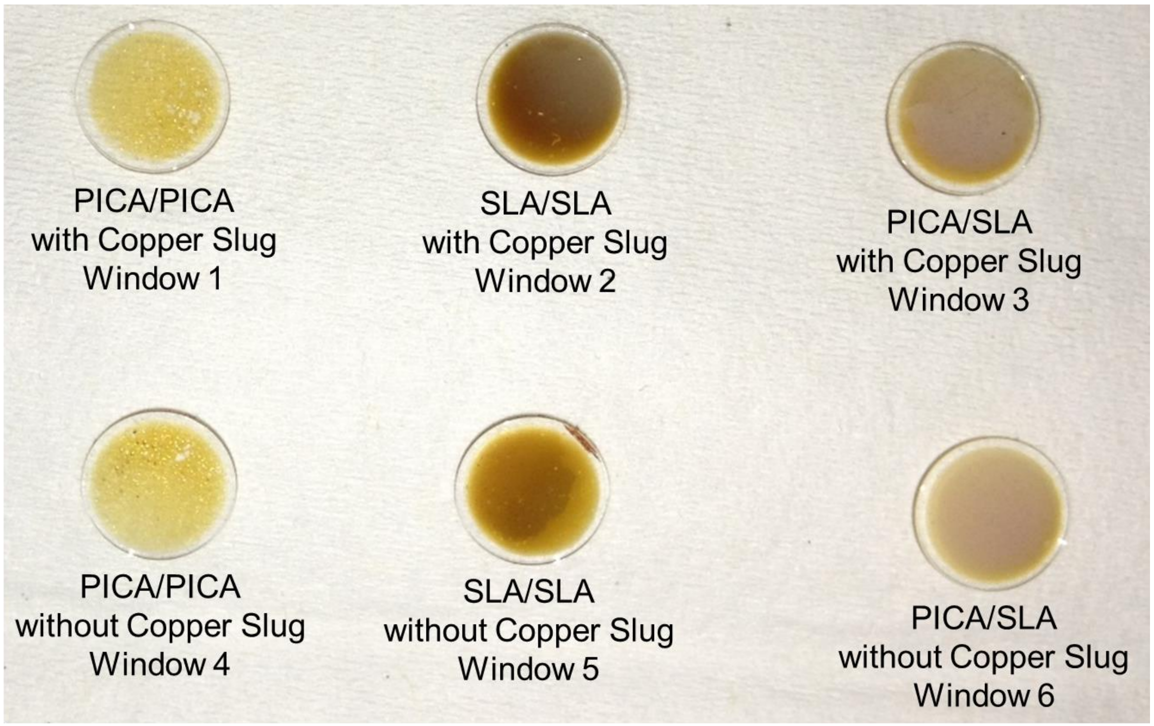


Test Conditions:

- 90% CO_2, 10% N_2 (by mass)
- Mass Flow Rate: 0.1 g/s
- Arc Current: 40 A
- Distance From Nozzle: 20 mm
- Model Inclination Angle: 45°

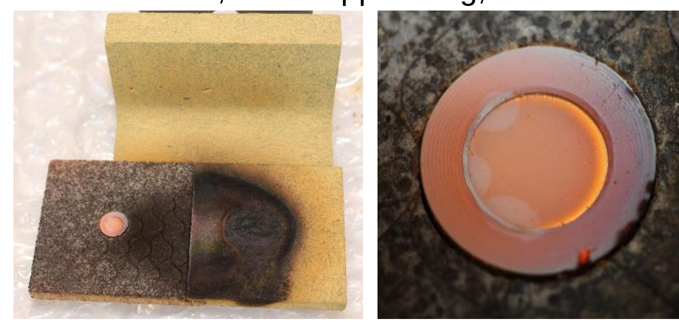
Run Number	Window Number	Duration (sec)	TPS #1/TPS #2	Copper Slug?
1	1	55	PICA/PICA	Yes
2	4	40	PICA/PICA	No
3	3	30	PICA/SLA	Yes
4	6	30	PICA/SLA	No
5	2	30	SLA/SLA	Yes
6	5	30	SLA/SLA	No

Radiometer Windows



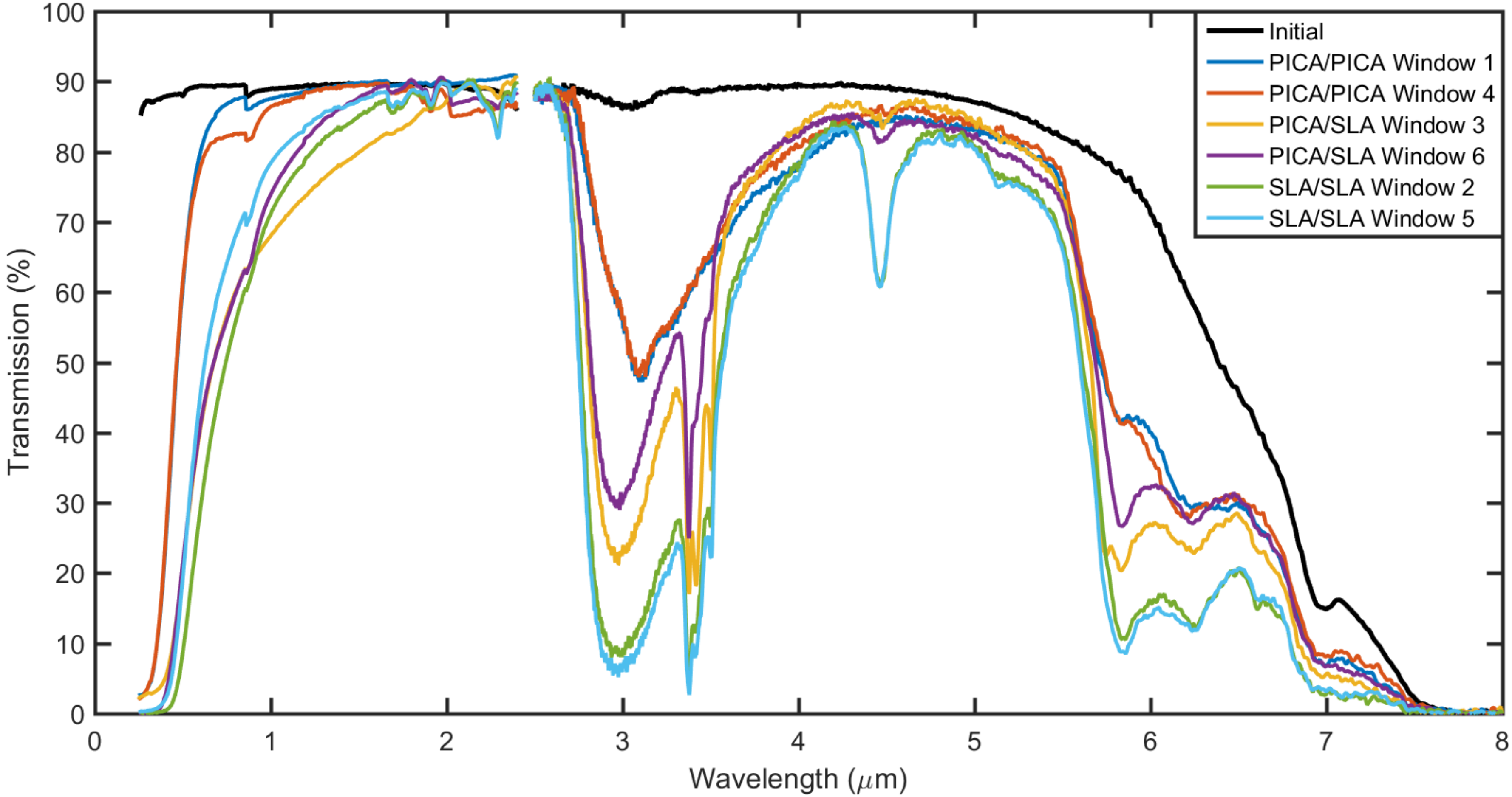
PICA/PICA, with Copper Slug, Window 1

PICA/SLA, with Copper Slug, Window 3

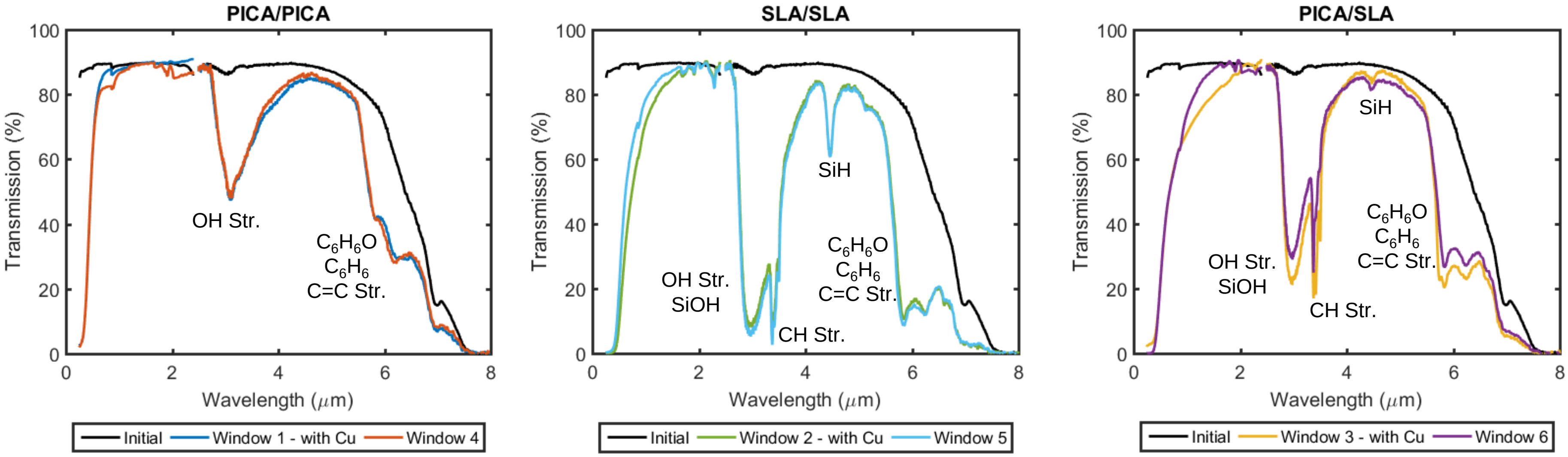


SLA/SLA, with Copper Slug, Window 2

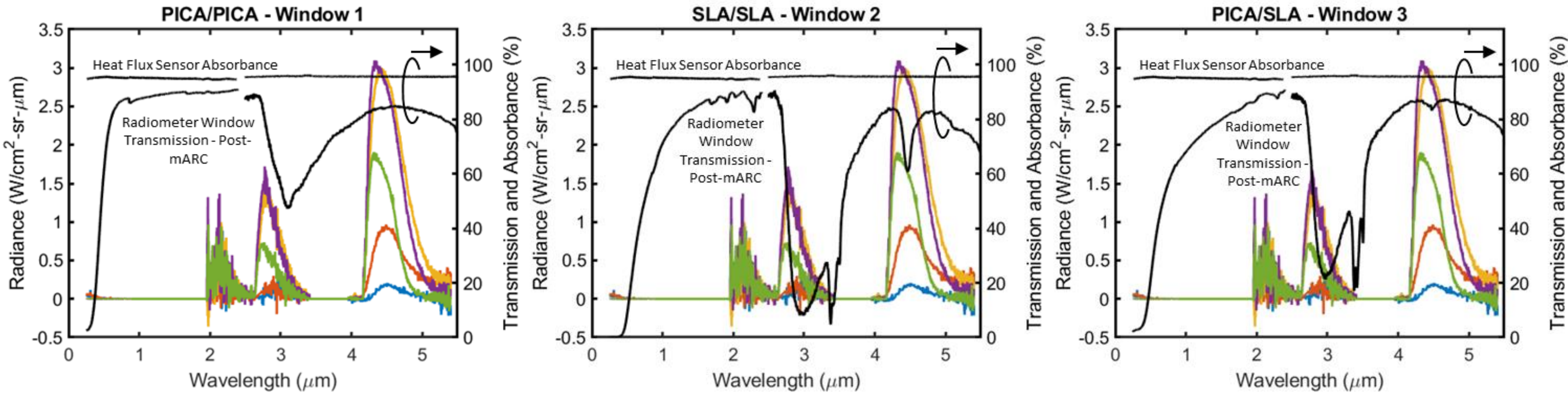
Radiometer Window Transmission Post-mARC Test



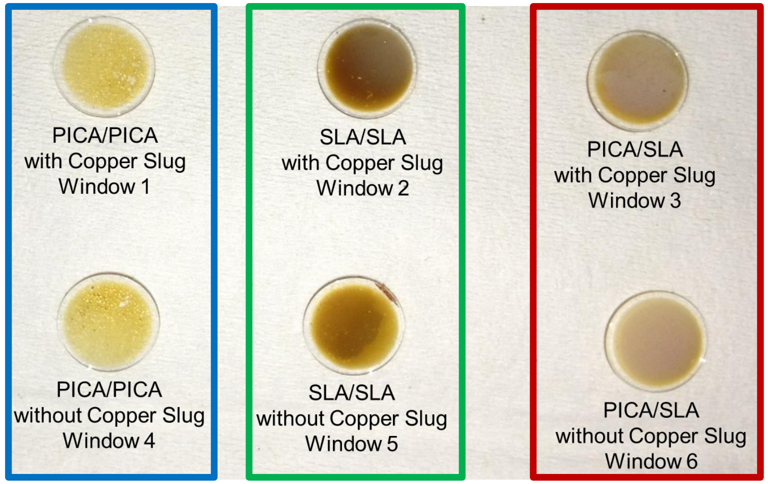
Radiometer Window Transmission Post-mARC Test



Comparison to EAST MSL Data



Percent Signal Loss



	Initial	PICA/PICA	PICA/PICA	SLA/SLA	SLA/SLA	PICA/SLA	PICA/SLA
Copper Slug?	---	Yes	No	Yes	No	Yes	No
Window Number	---	1	4	2	5	3	6
Max S_{loss} (%)	**1.8**	**12.2**	**13.1**	**27.9**	**29.0**	**19.7**	**19.1**

- 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	Not Flight Matched Conditions
Peak heatshield heat flux on TPS #1	Heat profile
Peak backshell heat flux at window location	Length scale
Heat load	

- 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?

Appendix

XPS Results – Atomic % (Average)

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

- 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