MSR
SAMPLE RETRIEVAL
LANDER

Aerothermal Analysis and Environment Predictions for the Mars Sample Retrieval Lander (SRL)

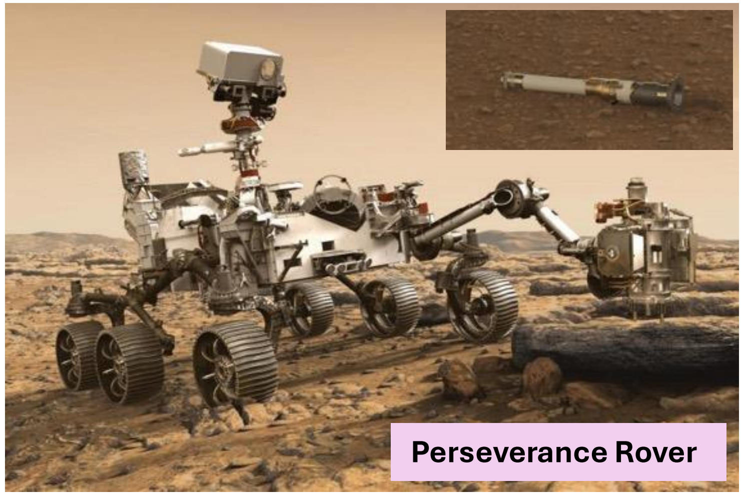
Suman Muppidi	NASA Ames Research Center
Dinesh Prabhu	AMA Inc., NASA Ames Research Center
David Saunders	AMA Inc., NASA Ames Research Center
Ryan McDaniel	NASA Ames Research Center
Rathakrishnan Bhaskaran	AMA Inc., NASA Ames Research Center
David Kinney	NASA Ames Research Center
Kaelan Hansson	AMA Inc., NASA Ames Research Center
Alireza Mazahari	NASA Langley Research Center
Karl Edquist	NASA Langley Research Center

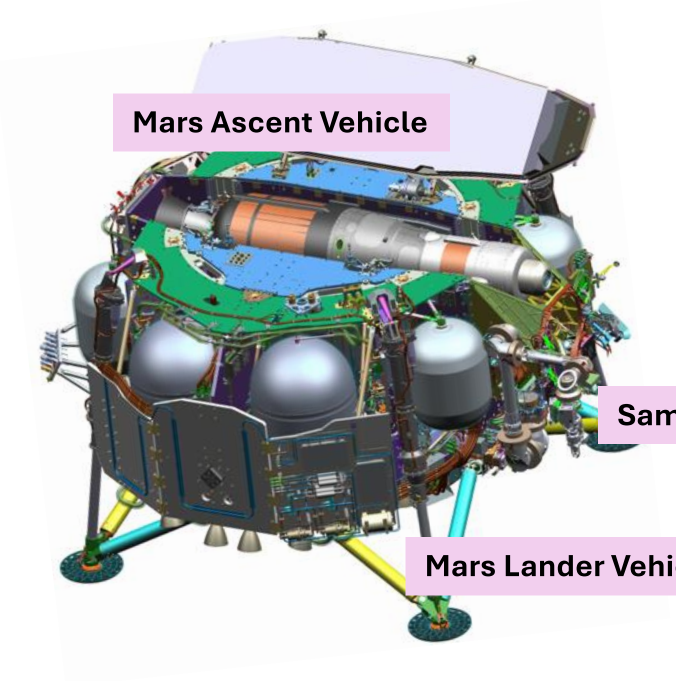
AIAA AVIATION FORUM

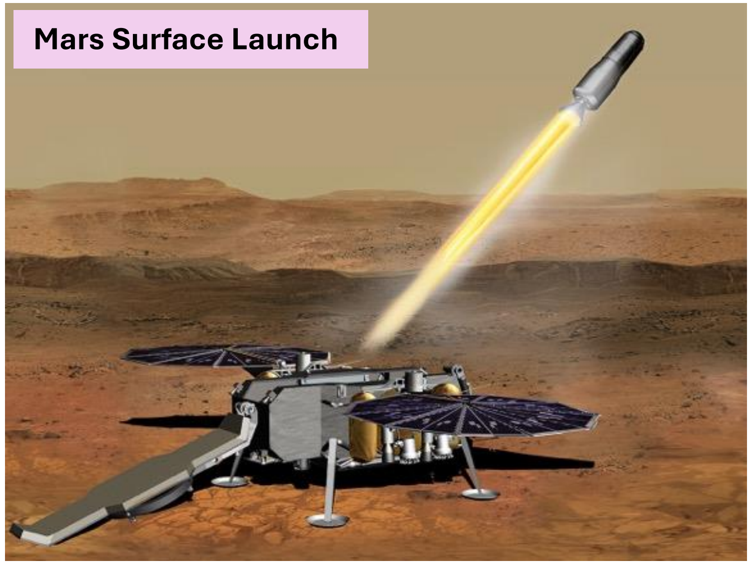
29th July 2024, Las Vegas, NV

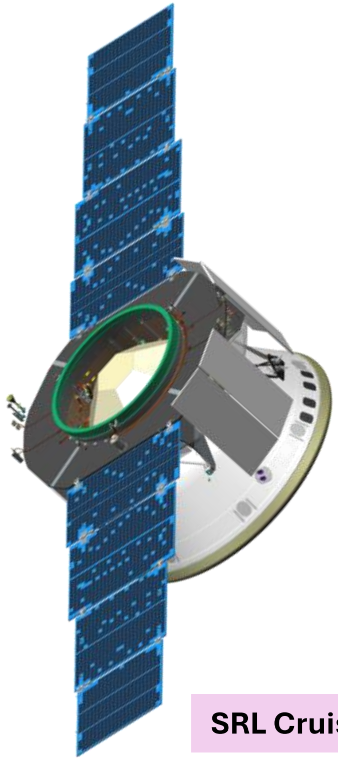
Sample Retrieval Lander (SRL)

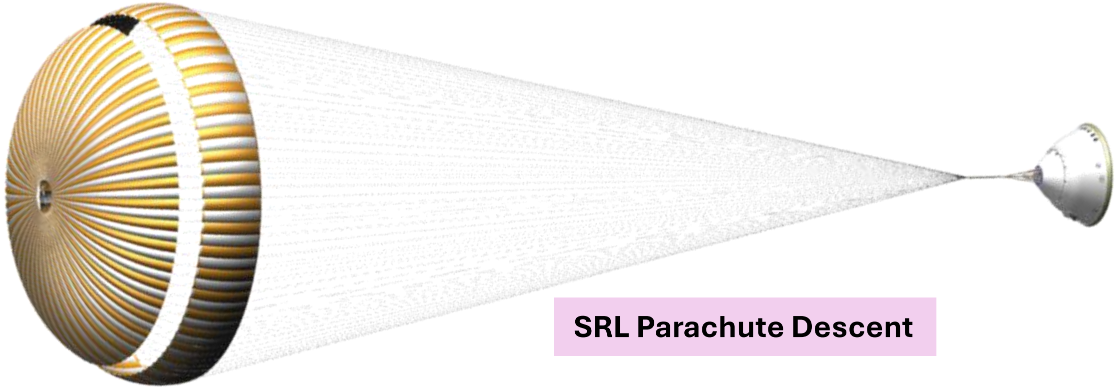
NASA
MSR
SAMPLE RETRIEVAL
LANDER

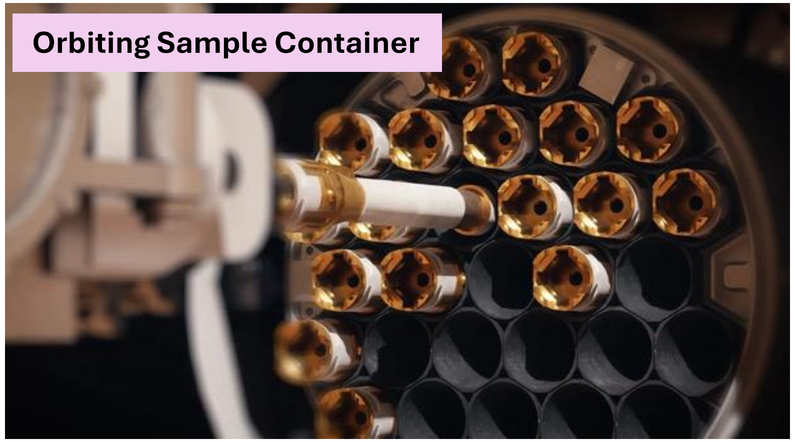






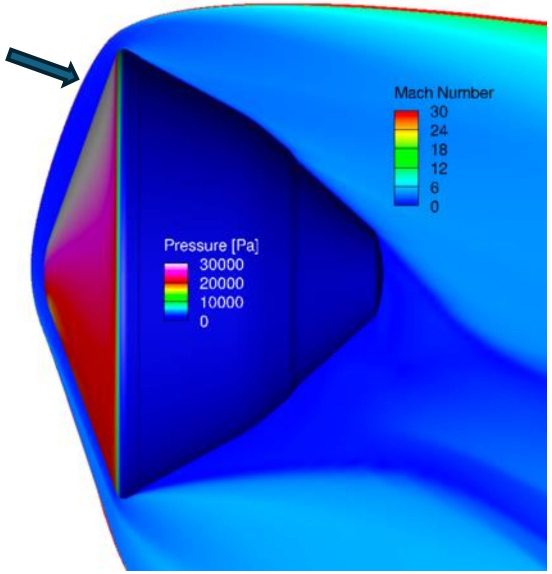


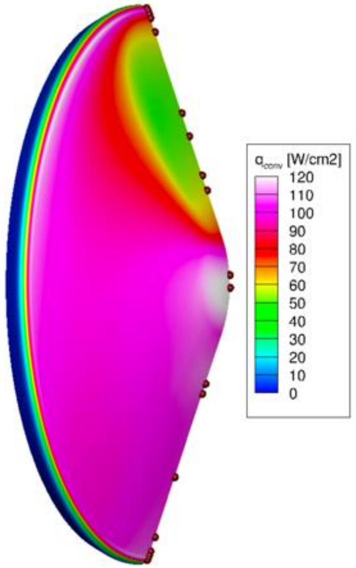


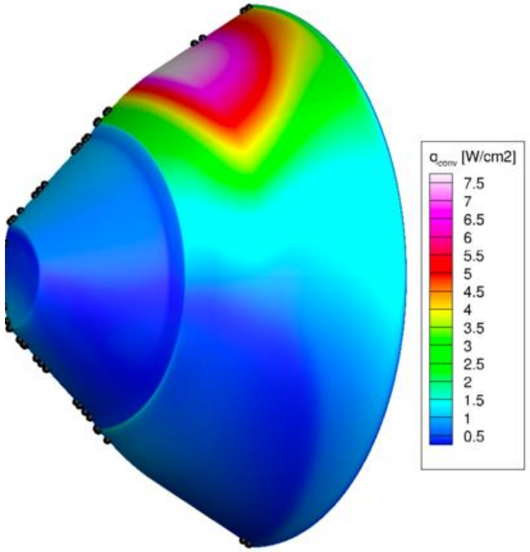


Aerothermal Analysis

MSR SAMPLE RETRIEVAL LANDER







- Environment prediction towards design of Thermal Protection System (TPS)
- Planetary protection assessment
- Inputs to thermal analyses, stress analyses
- Design of specific features (gaps, protrusions, RCS thrusters)

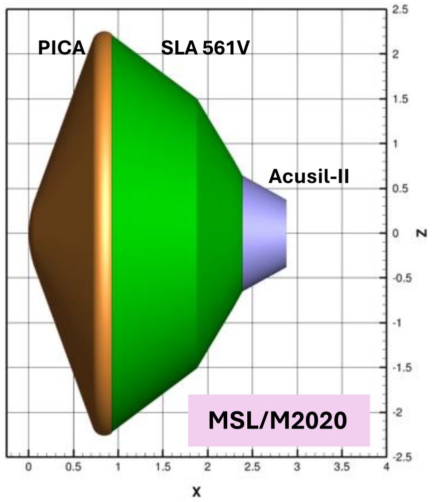
SRL Analysis leans strongly on MSL and Mars2020 experience, and the flight data provided by MEDLI/MEDLI2

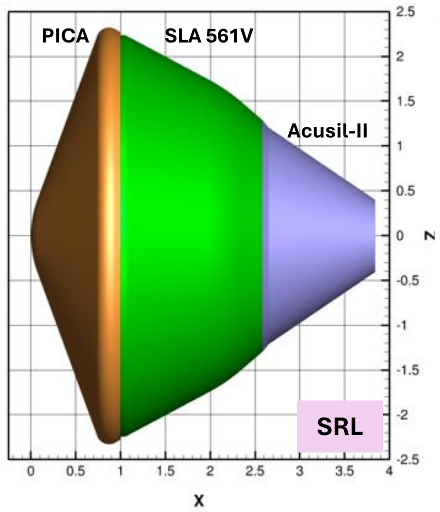
While also considering:

- Changes to geometry and trajectory space
- Improvements in predictive capabilities
- An emphasis on reducing conservatism where appropriate

MSL/Mars 2020 vs SRL

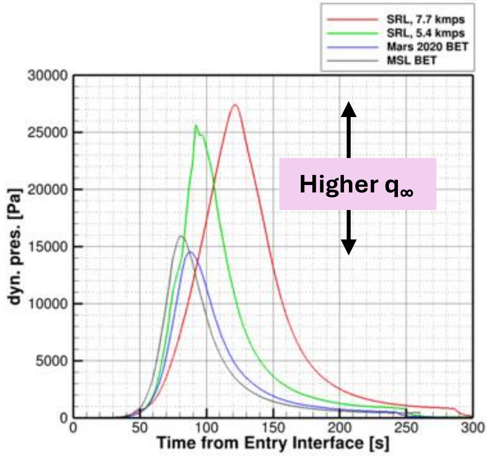
MSR SAMPLE RETRIEVAL LANDER

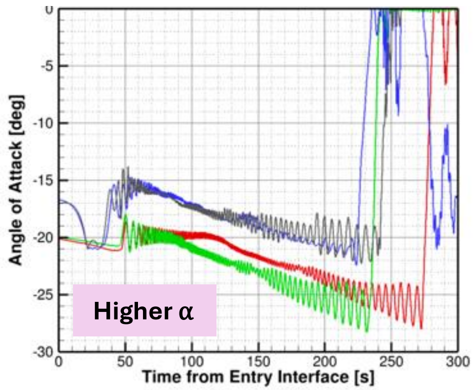


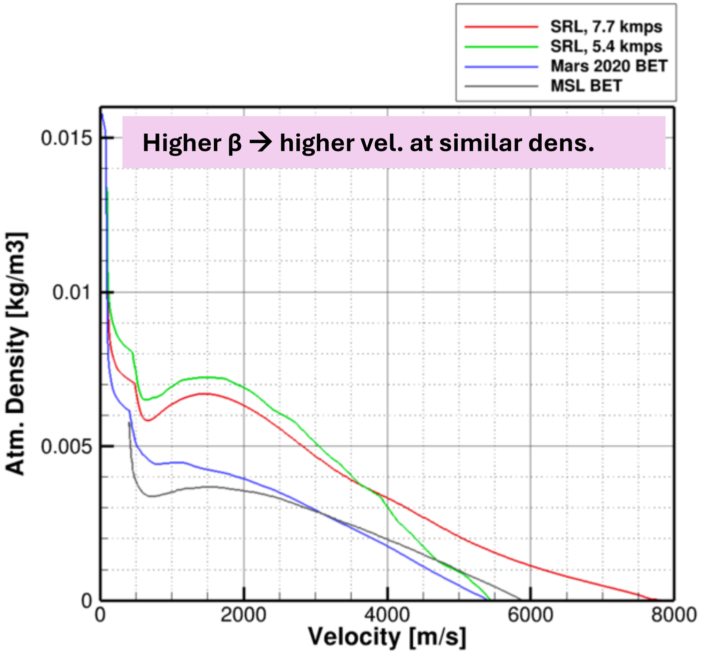


- Same TPS materials: PICA, SLA-561V and Acusil-II
- Very similar heatshields in shape and diameter (4.5 → 4.65/4.72 m)
- SRL aft body is longer and has a smaller backshell angle (more visible to the flow)

	MSL	M2020	SRL
Diameter [m]	4.5	4.5	**4.65 - 4.72**
Entry Mass [kg]	3153	3369	**5700 - 5900**
ballistic coefficient [kg/m2s]	146	156	**245**
Hypersonic L/D	0.24	0.24	**0.29**







- SRL pursuing 2030 and 2031 launches with different entry velocities
  2030: 5.6 km/s (similar to Mars2020)
  2031: (up to) 8 km/s

- SRL has a higher entry mass and ballistic coefficient (β)
  - Higher freestream dynamic pressure → higher surface pressure
  - Flies at a higher angle of attack (-20° vs -16°)
  - Higher velocity at comparable density → higher heating

Learning from MEDLI and MEDLI2

MSR SAMPLE RETRIEVAL LANDER

- MEDLI/MEDLI2 data used to continuously improve tools and models, and gain confidence in predictions

- MEDLI/MEDLI2 indicated transition to turbulence on the heatshield
→ SRL designed to fully turbulent flow

- MEDLI2 measured aft body radiation, validated our predictive capability
→ radiation heating is part of the SRL analysis and predictions

- MEDLI2 data used to update thermal response model for backshell TPS
→ included in SRL baseline

- MEDLI/MEDLI2 indicate over-prediction of recession, attributed to coating
→ appropriate modifications

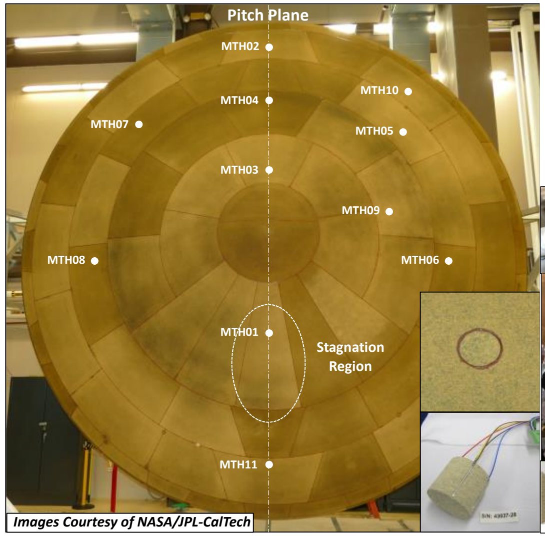
- <u>Substantiation of SRL Aerothermal Process</u>

  SRL Analysis tools (models, assumptions)and processes

  + Mars2020 Geometry and Trajectory

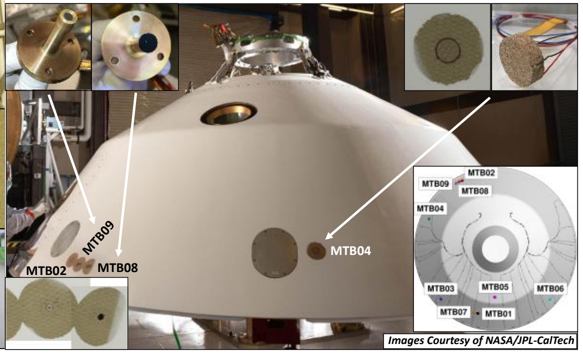
  → Prediction of in-depth temperatures

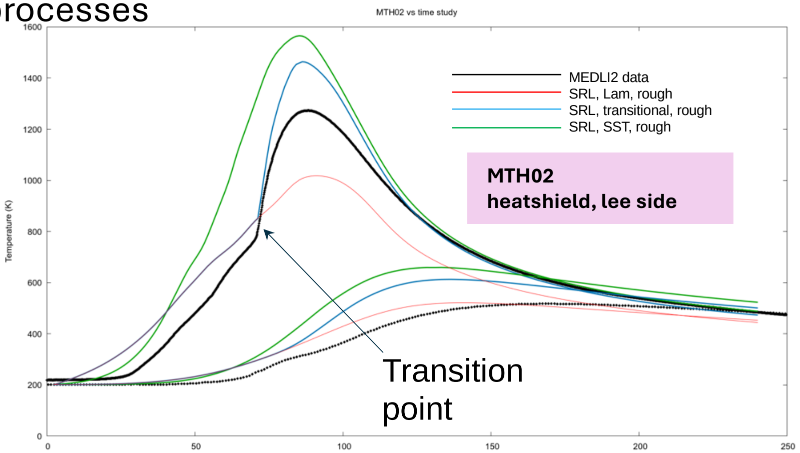
  → comparisons to MEDLI2

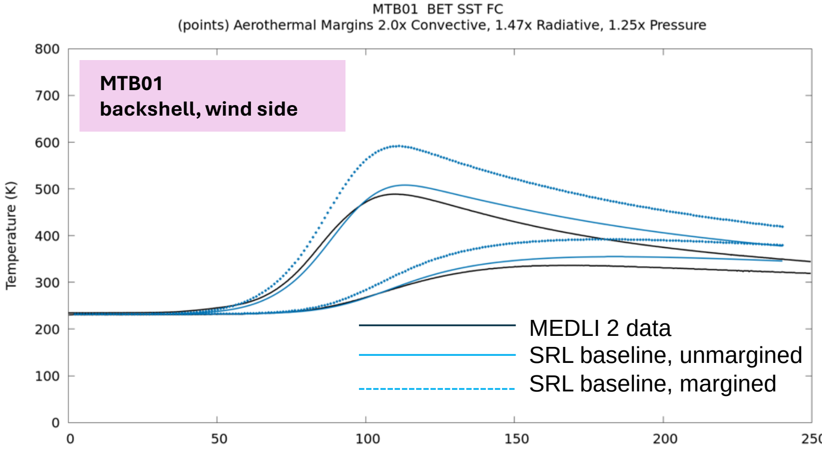


Mars2020 MEDLI2

White et al., AIAA Paper 2022-0011







Turbulence Modeling

MSR SAMPLE RETRIEVAL LANDER

Forebody/Heatshield

- MSL/Mars2020 designed to turbulent environments, using RANS and Baldwin-Lomax turbulence model.
- MEDLI & MEDLI2 confirm flow started out laminar, then transitioned (prior to peak heating) *Tang et al., AIAA Paper 2022-0552*
- SRL *also* designed for turbulent environments; expect transition to occur earlier

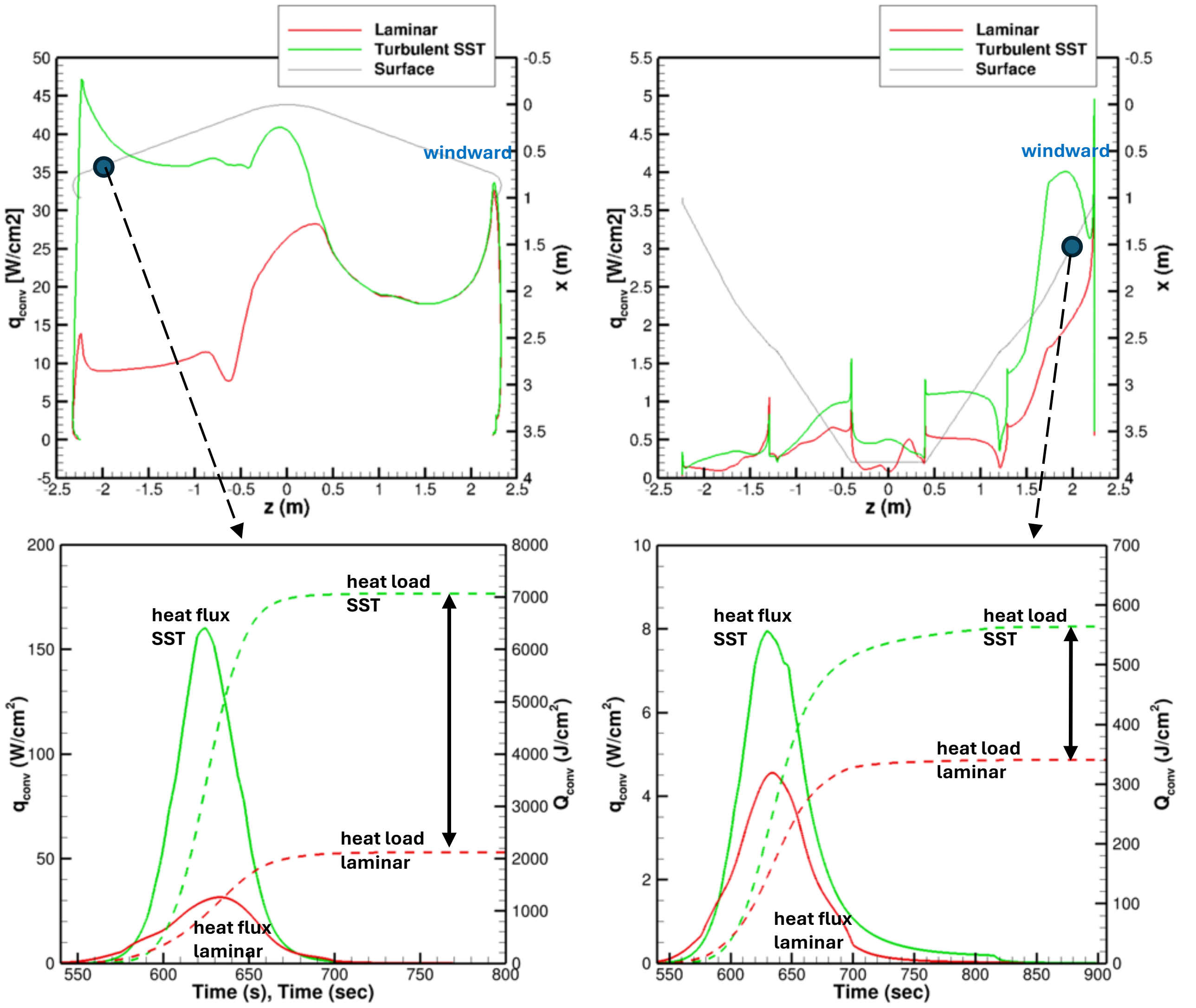
Aftbody

- MSL and Mars2020 were designed for laminar flow on the aft body. MEDLI2 data does not indicate if the flow transitioned
- SRL aft body has a longer run length → expect flow transition → designed for turbulent flow (departure from MSL/M2020)

Modeling and Verification

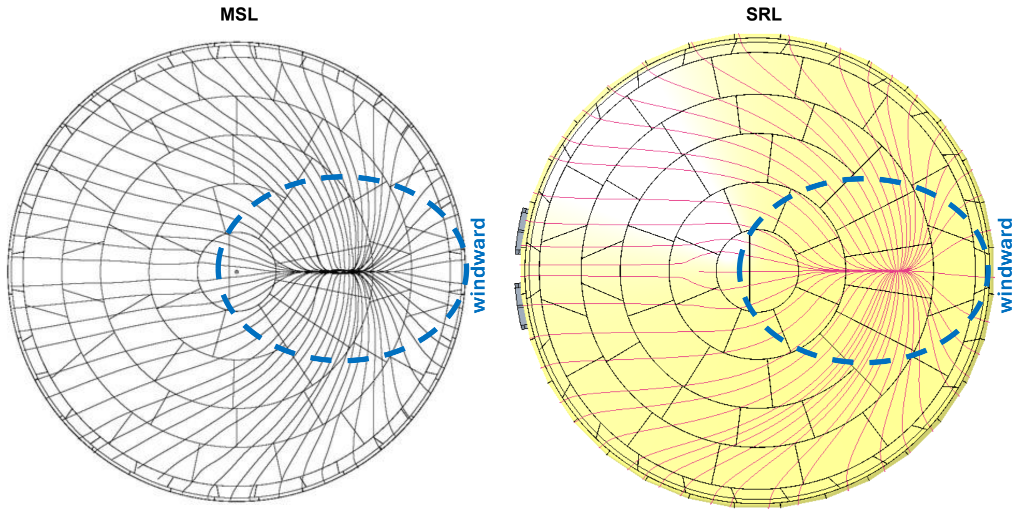
- Turbulent flow simulations use SST model (departure from MSL/M2020)
- Detailed validation against wind tunnel data

TP06: Dinesh Prabhu
An Assessment of Turbulence Models for MSR Sample Retrieval Lander Aerothermal Design

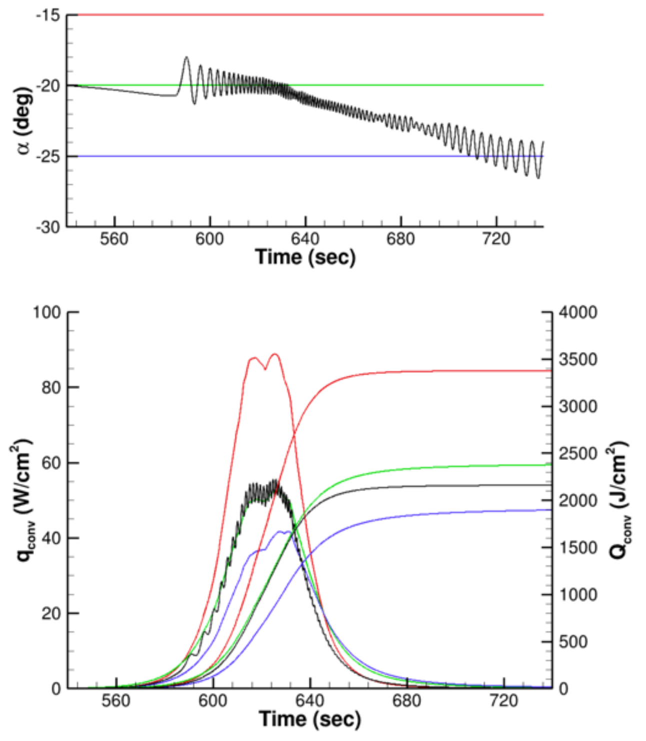


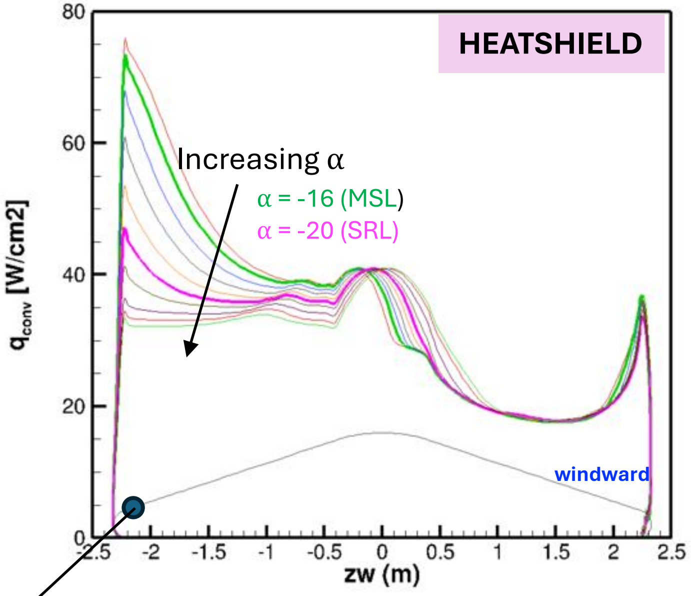
Impact of Angle of Attack

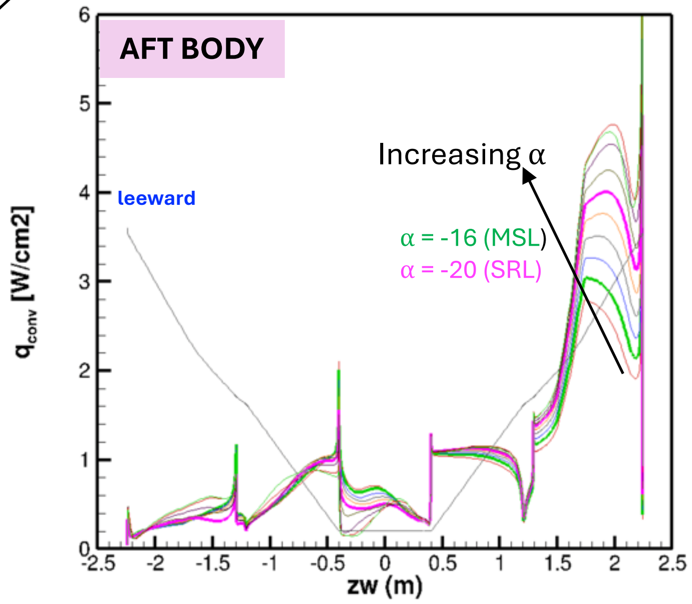
- SRL α = -20° compared to MSL/M2020 α = -16°
  (higher α → higher lift/drag)
- Convective heating (peak, distribution) sensitive to angle of attack
  - Heatshield: Peak turbulent convective heat flux decreases with increasing α
  - Aft body: Peak turbulent convective heating *increases* with α
- Analysis accounts for the appropriate angle of attack, *including* variations in α along trajectory.
- Angle of attack → surface streamlines → TPS tile layout



Effect of α on predicted environments







Thermochemical Modeling

MSR SAMPLE RETRIEVAL LANDER

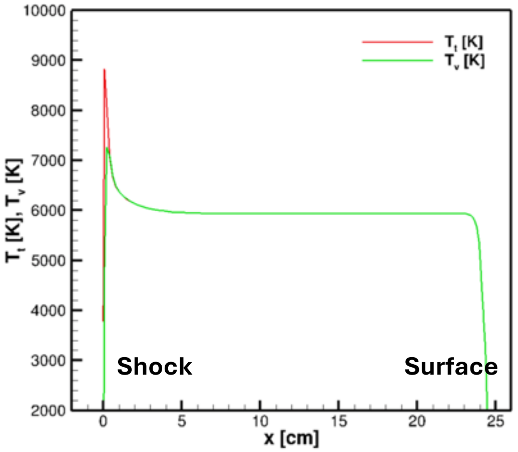
Mission	Mechanism	Species
MSL/Mars 2020	8-species*	CO_2, CO, N_2, O_2, NO, C, N, O
SRL (2030; 5.6 km/s)	10-species#	CO_2, CO, N_2, O_2, NO, **C_2**, **CN**, C, N, O
SRL (2031; 7.8 km/s)	18-species #	CO_2, CO, **CO^+**, C_2, N2, O_2, **O_2^+**, NO, **NO^+**, CN, C, **C^+**, N, **N^+**, O, **O^+**, **Ar**, **e^-**

Ar absorbed into N_2

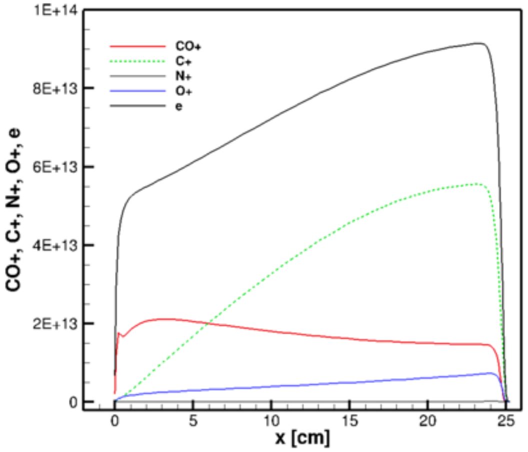
* *Mitcheltree et al. 1994, AIAA Paper 94-1958*

 # Johnston & Brandis, 2014, JQSRT

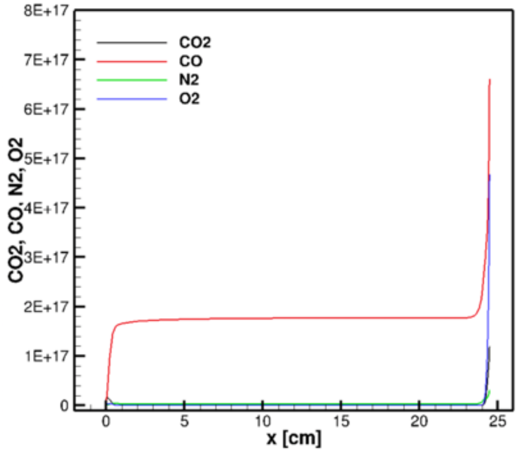
- Atmosphere of Mars is composed of CO_2 and N_2, with trace amounts of Ar
- SRL analysis utilizes updated chemistry models (departure from MSL/Mars 2020)
  - At higher entry velocities (2031 opportunity), ionization is important → chemistry model includies 18 species and 34 reaction



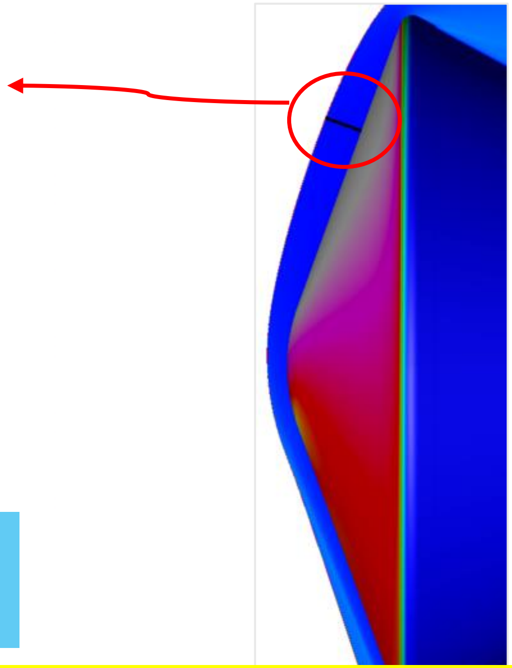
Largely in thermal equilibrium (other than at the shock)



Charged species continue to react along the stagnation line



Neutral species are in chemical Equilibrium for most of the stagnation line



Efforts underway to verify chemistry model through a detailed comparison against Electric Arc Shock Tube (EAST) data

Surface Catalycity

$$q_w = \left(k_c \frac{\partial T}{\partial \eta} + \rho \sum D_{ij} h_i \frac{\partial c_i}{\partial \eta} \right)_w$$

Conduction — Catalytic Heating

Surface heat flux includes a diffusive component (affected by *complex* chemical reactions at the surface)

MSL

- Heatshield: super-catalytic
- Backshell: super-catalytic
- Parachute cone and lid: super-catalytic

$Y_{w,CO_2} = Y_{\infty,CO_2}$; $Y_{w,N_2} = Y_{\infty,N_2}$
[all gases at the surface combine to freestream compositions]

Most conservative assumption (bounding)

Mars 2020

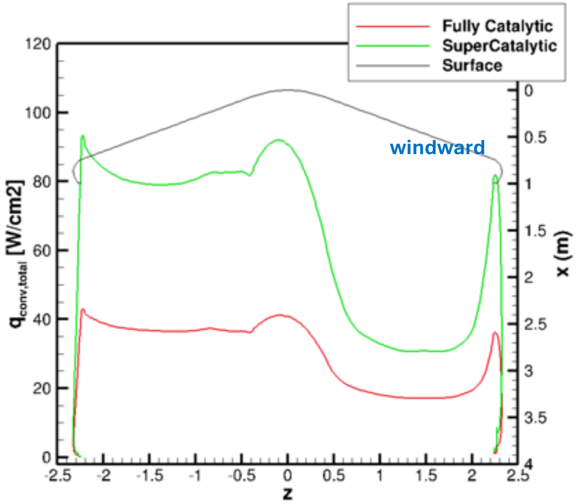
- Heatshield and backshell: super-catalytic
- Parachute cone and lid: non-catalytic → **Elimination of catalytic heating** ***Least conservative assumption***

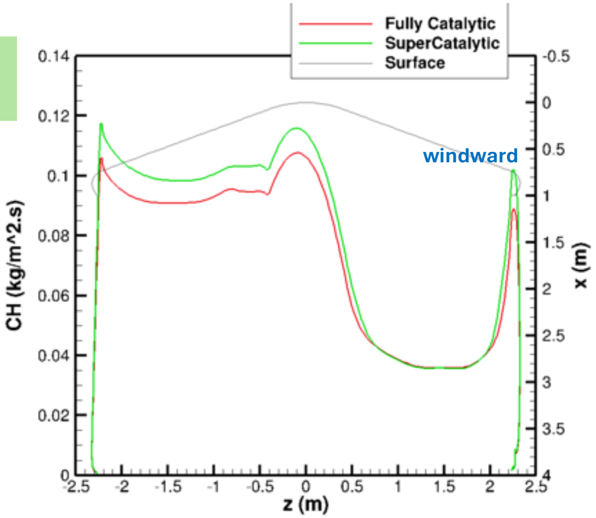
SRL

- Heatshield and backshell : *fully catalytic* to atom and ion recombination
- Parachute cone and lid: non-catalytic

Catalycity has a major impact on heat flux ; small impact on film coefficient C_H

Heatshield TPS sizing uses C_H
Backshell TPS sizing uses heat flux





Impact: From super-catalytic to fully catalytic treatment

- Heatshield: small effect on TPS Sizing (based on C_H), *but* significant impact on TPS test conditions/program.
- Backshell/SLA-561V: significant effect on TPS Sizing (based on heat flux) *and* on TPS test program

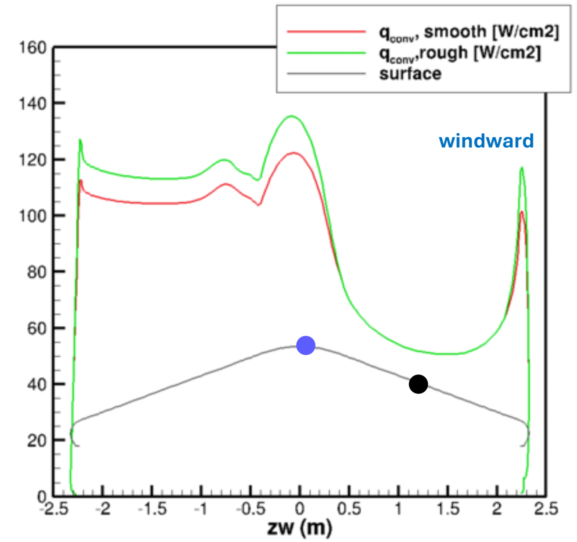
Efforts underway to justify the surface catalysis treatment assumptions, particularly at higher entry velocities

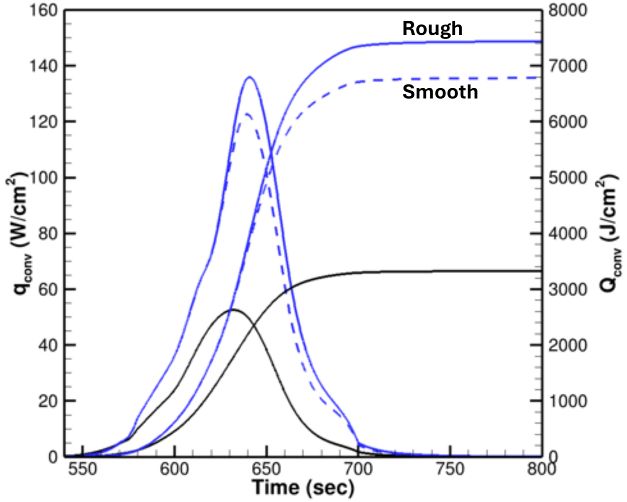
Roughness Augmentation

MSR
SAMPLE RETRIEVAL LANDER

Stardust (PICA) heatshield, post-entry

MSL (PICA) heatshield, pre-entry





- Ablation → roughness → augmented heating
- SRL likely to experience higher recession and more roughness ; analysis follows the MSL approach
  - Smooth wall CFD → rough wall heating (and shear)
  - Need a representative equivalent sandgrain roughness k_s (evaluated using test data)

$$U_\tau = \sqrt{\frac{\tau_w}{\rho_w}}$$

$$k^+ = \frac{\rho_w U_\tau k_s}{\mu_w}$$

$$\frac{\tau_{w,k}}{\tau_{w,0}} = 1 + 0.9\,(\log k^+ - 1)$$

$$\frac{q_{conv,k}}{q_{conv,0}} = 1 + 0.6\,(\frac{\tau_{w,k}}{\tau_{w,0}} - 1)$$

Dahm et al. 1976

- Aft body environments not expected to cause significant ablation, or for the TPS to develop roughness

Efforts underway to verify/modify the assumed roughness value (k_s), as well as the roughness augmentation

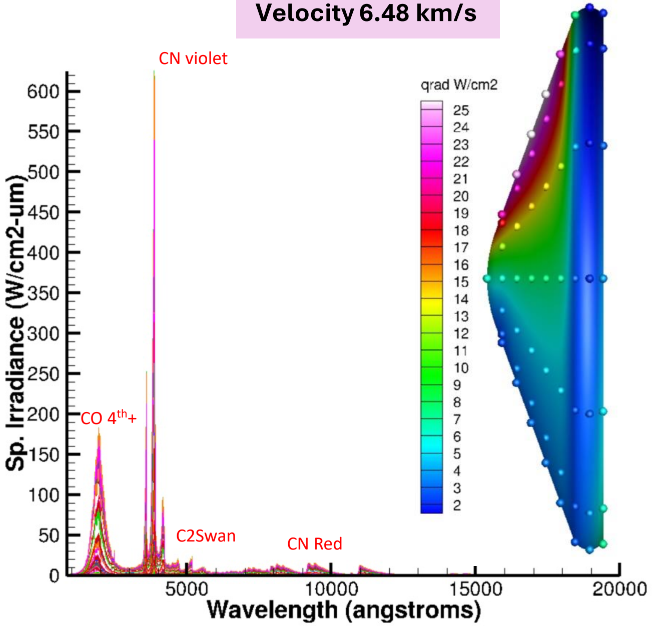
Radiative Heating

MSR
SAMPLE RETRIEVAL LANDER

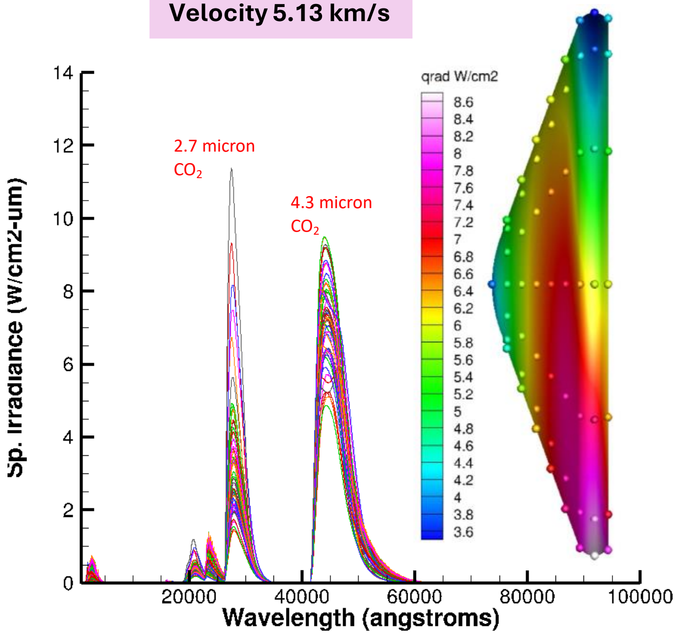
- MSL → radiation considered negligible
- Mars2020 → accounted for (fore and aft body) radiation *Brandis et al., 2020, JTHT*
- MEDLI2 → measured aft body radiation, justified Mars2020 analysis
- SRL largely follows the analysis methodology used for Mars2020
- Higher entry velocities → higher radiative heating, & different transitions (CO, CO_2, and CN)
  Brandis et al., 2013, JQSRT; Cruden et al., 2016, JTHT

Improved understanding of radiative heating at Mars over the last two decades

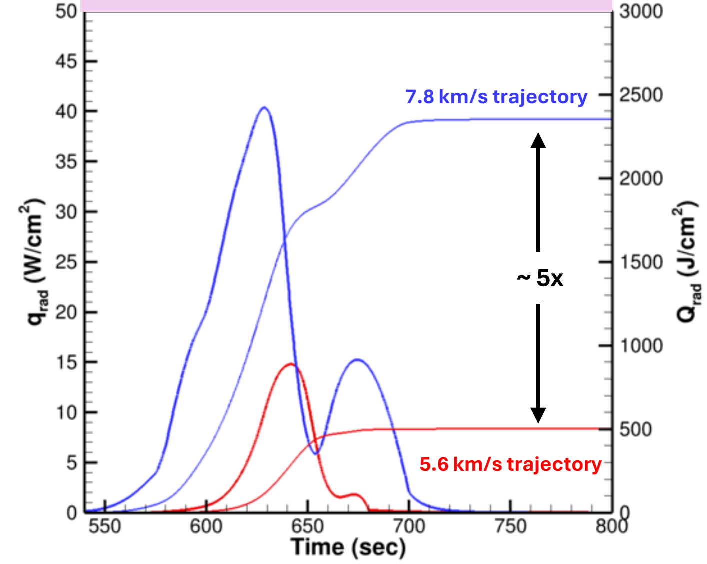
Velocity 6.48 km/s

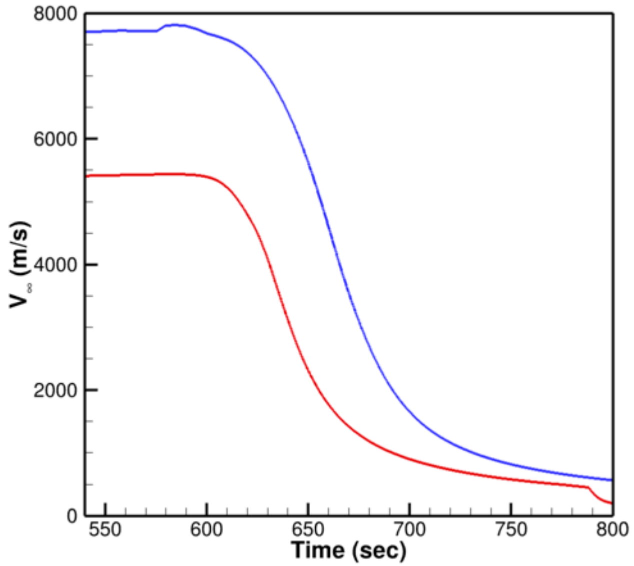


Velocity 5.13 km/s



Stagnation point radiative heating



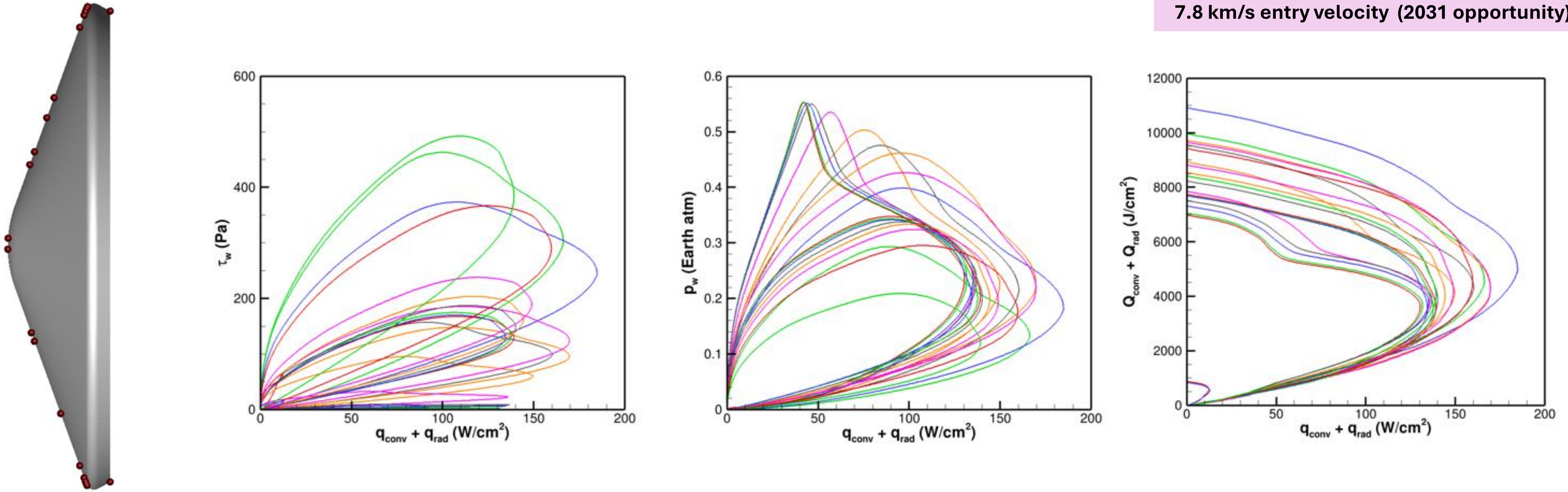


Efforts underway to justify radiation predictions through comparisons against Electric Arc Shock Tube data at relevant velocities

SRL Heatshield Design Environments

MSR SAMPLE RETRIEVAL LANDER

7.8 km/s entry velocity (2031 opportunity)



- Figures show rough wall, margined environments predicted at representative heatshield surface points.
    - Margin factors same as used for Mars 2020.
    - SRL-specific margin policy is being put together
      (comparisons against ground testing, MEDLI2 reconstruction, parameter sensitivity study)
- Predicted environments (pressure, heat flux, heat load) significantly higher than previous missions to Mars

Summary

- Mars Sample Retrieval Lander being designed to enter Mars atmosphere with almost *four times* kinetic energy compared to Mars 2020
    - SRL expected to experience the most stressing environments yet at Mars
- Aerothermal analysis largely based on Mars Science Laboratory (MSL) and Mars 2020 experience, lessons learned from MEDLI/MEDLI2, and general advances in predictive capabilities
- Changes from MSL/Mars2020
    - Less conservative surface catalycity treatment
    - Aft body designed for turbulent flow; incorporation of two-equation SST model
- Ongoing and Future Work
    - Establishment of SRL-specific uncertainties
    - Investigation of augmentation due to roughness (distributed, discrete/fence)
    - Validation of radiation predictions
    - Investigation of chemical kinetics
- SRL Analysis pathfinder for future (larger, higher-velocity, higher-ballistic coefficient) concepts to Mars, including potential human exploration missions