


# Aftbody Heating Short Course: Mars 2020

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# Bio

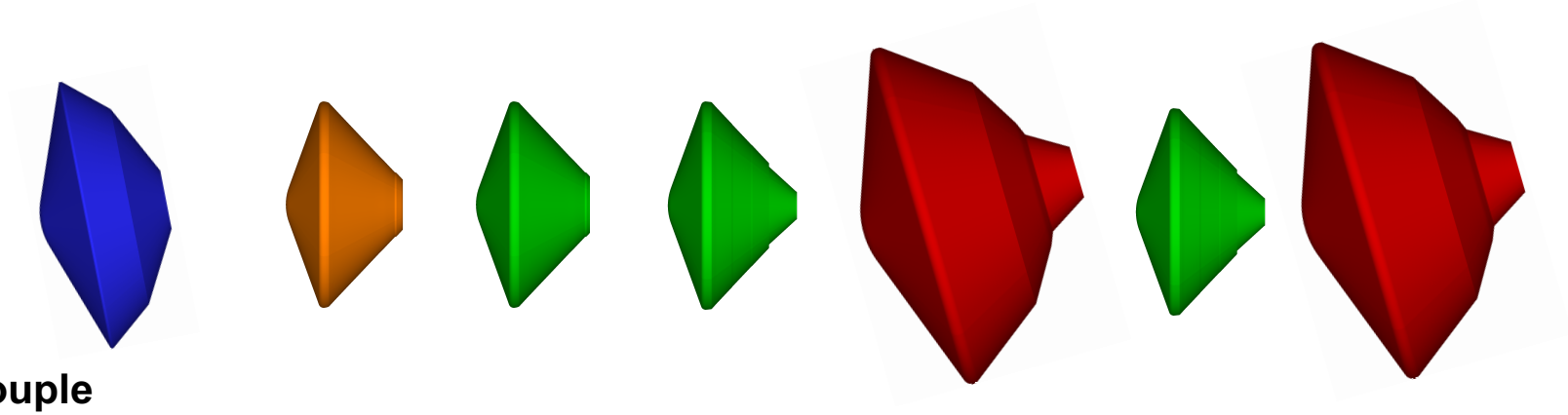
- At NASA Langley Research Center since 2000
- Bachelor's and Master's degrees in Aerospace Engineering from the University of Colorado and the University of Maryland, respectively
- Specialty: aerodynamic and aerothermodynamic analysis of planetary entry vehicles for NASA science missions and technology development projects
- Roles:
  - Mars Science Laboratory Aerothermal Lead
  - Mars 2020 Aerothermal Lead
  - Mars Phoenix Aerodynamics Lead
  - Propulsive Descent Technologies (STMD, Commercial)

# Outline

- Background
- Mars Science Laboratory
- Mars 2020
- ExoMars Flight Data

# Successful U. S. Mars Landers

| Viking 1 & 2 | Pathfinder | MER A/B | Phoenix | MSL | InSight | Mars 2020 |
|---|---|---|---|---|---|---|
| 1976 | 1997 | 2004 | 2008 | 2012 | 2018 | 2021 |



**TC = thermocouple**

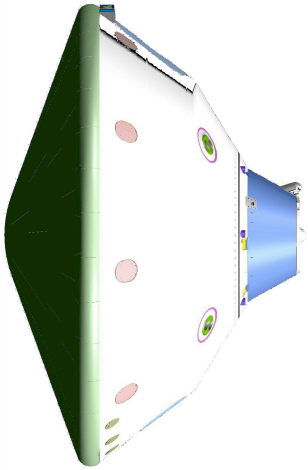
| | Viking 1 & 2 1976 | Pathfinder 1997 | MER A/B 2004 | Phoenix 2008 | MSL 2012 | InSight 2018 | Mars 2020 2021 |
|---|---|---|---|---|---|---|---|
| **Diameter, m** | 3.5 | 2.65 | 2.65 | 2.65 | 4.5 | 2.65 | 4.5 |
| **Entry Mass, kg** | 930 | 585 | 840 | 602 | 3300 | 615 | 3300 |
| **Entry Vel., km/s** | 4.5/4.42 | 7.6 | 5.5 | 5.9 | 5.6 | 5.9 | 5.6 |
| **Hypersonic AoA, deg** | -11 | 0 | 0 | 0 | -16 | 0 | -16 |
| **Hypersonic L/D** | 0.18 | 0 | 0 | 0 | 0.24 | 0 | 0.24 |
| **Control** | RCS | Spinning | Spinning | None | RCS | None | RCS |
| **Aftbody Aerothermal Instrumentation** | 2 TCs | 3 TCs (2 failed?) | None | None | None | None | 6 TCs<br>3 heat flux sensors |

**Mars 2020 will be the first Mars entry vehicle since Pathfinder to have aerothermal instrumentation on the aftbody**

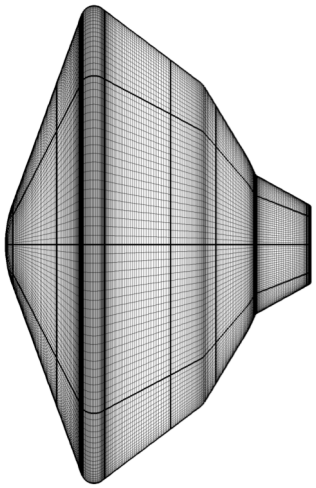
# CFD for Mars Aeroheating

- Starting with the Mars Pathfinder mission, computational fluid dynamics (CFD) has been the sole source of Mars aeroheating predictions
  - CFD cases are run on one or more “design” trajectories
  - No facility can duplicate the Mars atmosphere (mostly $CO_2$, some $N_2$), flight Mach numbers (~25 at peak heating) and enthalpies (temperatures)
- Ground testing is done (usually in air) on sub-scale Mars EDL models to explore basic physics (e. g. RCS interference, special geometric features, turbulence)
  - Ground tests typically focus on forebody heating

**Vehicle Geometry**



**CFD Mesh**



**Navier-Stokes Equations**

*Continuity equation*

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0$$

*x Momentum*

$$\rho \frac{Du}{Dt} = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z}$$

*y Momentum*

$$\rho \frac{Dv}{Dt} = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z}$$

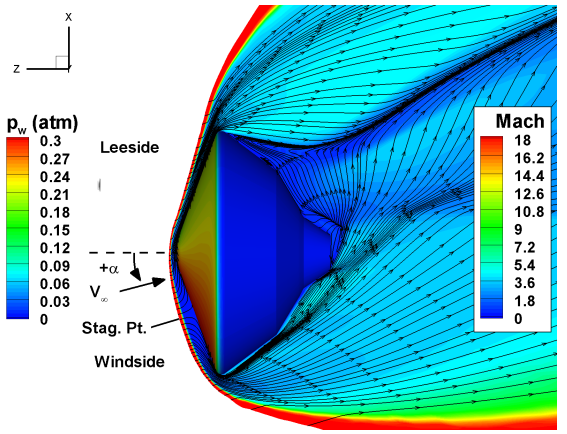
*z Momentum*

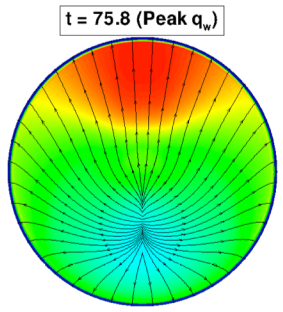
$$\rho \frac{Dw}{Dt} = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}$$

*Energy*

$$\rho \frac{D(e + V^2/2)}{Dt} = \rho \dot{q} + \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k \frac{\partial T}{\partial z}\right) - \nabla \cdot p\mathbf{V}$$
$$+ \frac{\partial (u\tau_{xx})}{\partial x} + \frac{\partial (u\tau_{yx})}{\partial y} + \frac{\partial (u\tau_{zx})}{\partial z} + \frac{\partial (v\tau_{xy})}{\partial x} + \frac{\partial (v\tau_{yy})}{\partial y}$$
$$+ \frac{\partial (v\tau_{zy})}{\partial z} + \frac{\partial (w\tau_{xz})}{\partial x} + \frac{\partial (w\tau_{yz})}{\partial y} + \frac{\partial (w\tau_{zz})}{\partial z}$$

**CFD Output**

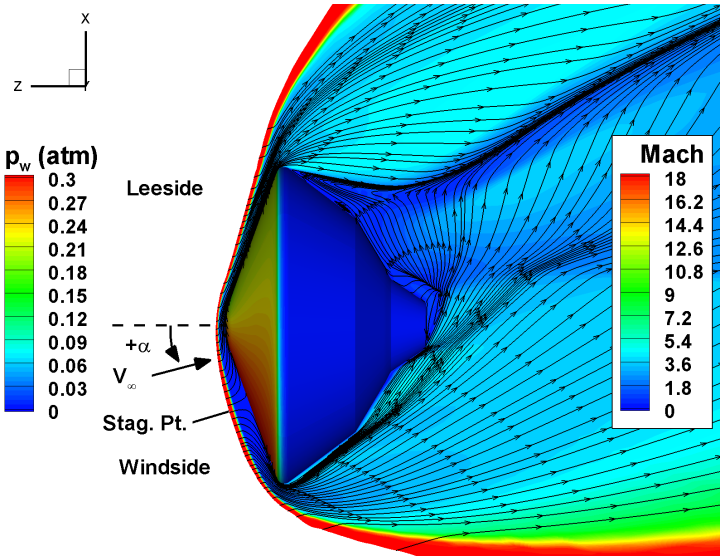


# Recent Mars Aerothermal Approach

- The LAURA Reynolds Averaged Navier-Stokes CFD code has been used as the primary tool for convective heating predictions on the last 2 U. S. Mars missions (MSL, InSight), and was used for the upcoming Mars 2020 mission
  - Code was started at Langley in the 1980s by P. Gnoffo and has been used on numerous Earth and Mars entry vehicles (aerodynamics and aeroheating)
- The DPLR code developed at NASA Ames has been used for independent verification of LAURA results
  - Typically excellent agreement with LAURA for attached flow
- Up to and including the Mars Science Laboratory mission, only convective heating was included in the aeroheating design environments

**Sample LAURA Flowfield**

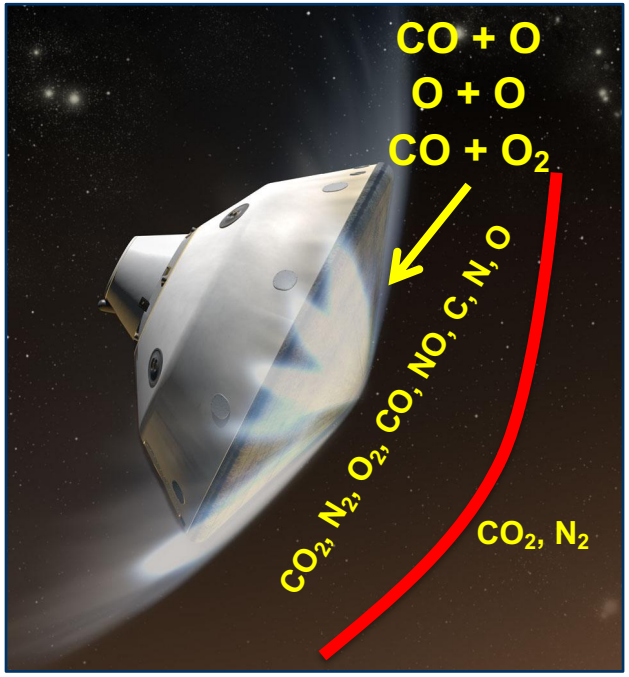


# Recent Mars Aerothermal Approach (cont.)

Convection Radiation

$$q_w = q_{cond} + q_{cat} + \cancel{q_{rad}}$$

**Temperature gradient at surface = conduction**
**Chemical reactions at surface = catalytic heating**




- CFD modeling assumptions:
  - Finite-rate, chemically-reacting 8-specie gas mixture ($CO_2$, $N_2$, etc.)
  - Two-temperature model (translational and vibrational)
  - "Super-catalytic" wall: forces recombination of molecules back to freestream mass fractions of $CO_2$ and $N_2$, maximizes catalytic heating

# Recent Mars Aerothermal Approach (cont.)

- How do we estimate the uncertainty in convective heat flux for TPS design?
- Answer: through CFD and engineering judgement based on allowable mission risk

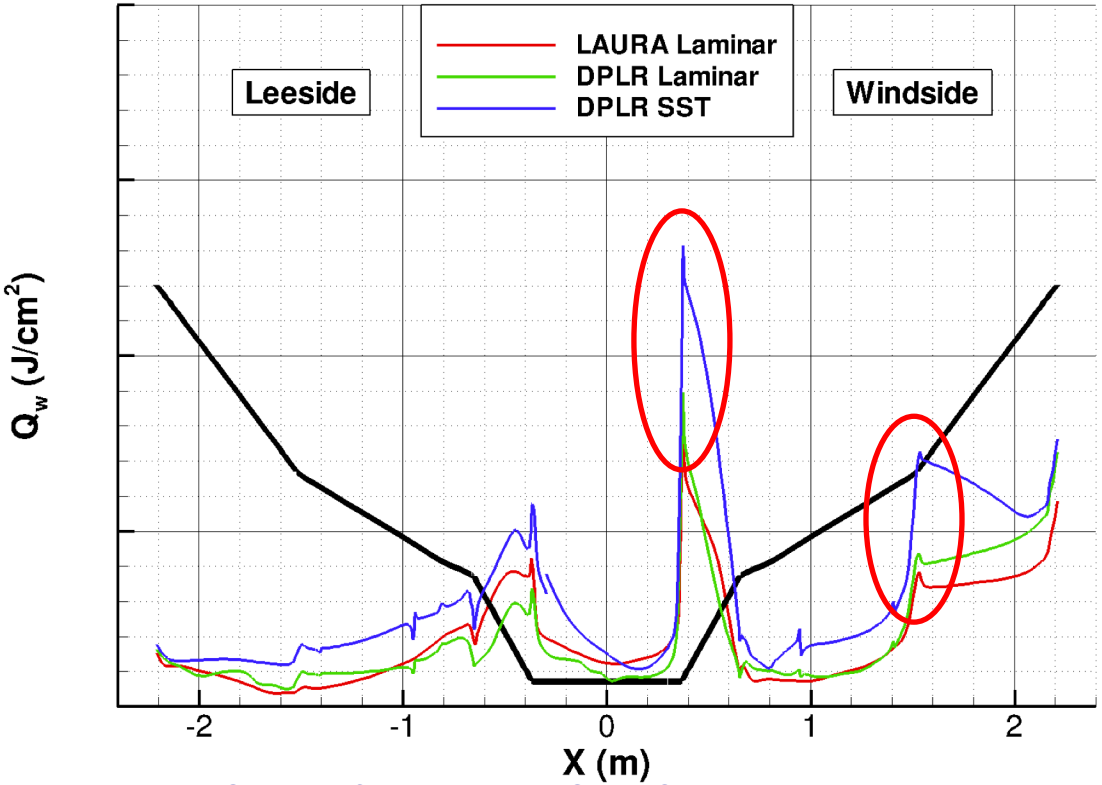
- We have so few in-flight measurements of Mars aftbody aeroheating and we have lower confidence in our turbulence models for wake flowfields, that we have no choice but to use what we consider to be a "large" uncertainty on laminar convective heat flux
- Aftbody design convective heat flux for MSL and Mars 2020:

$$q_{conv,design} = 3 \times q_{conv,laminar,LAURA}$$

  - Uncertainty factor 3x covers possible turbulent augmentation, angle of attack uncertainties, and atmospheric uncertainties

# Flight Calculations

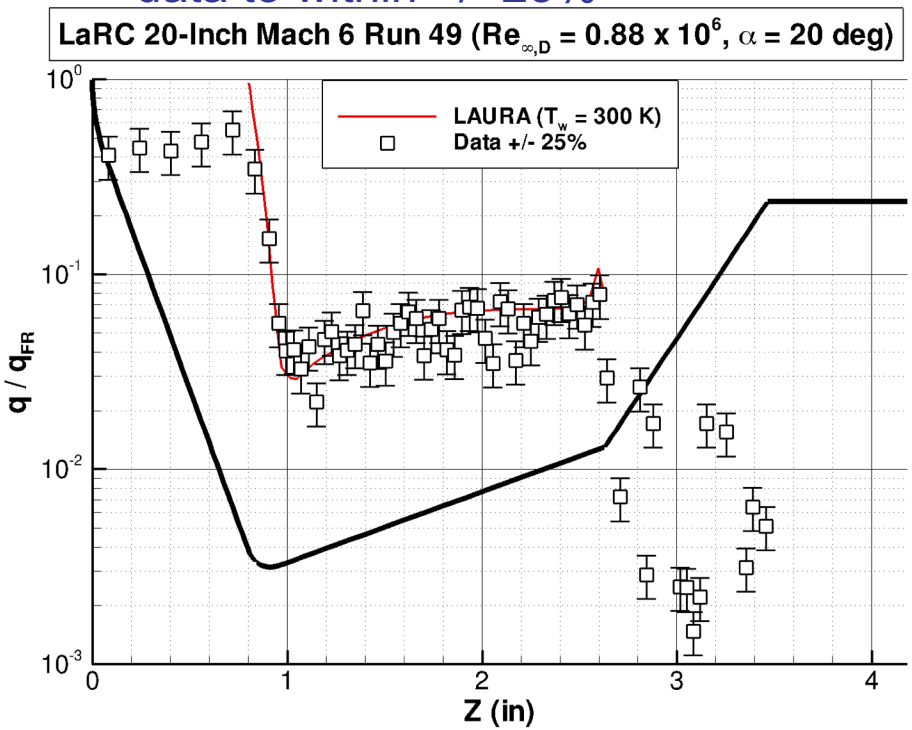
- Where does the 3X uncertainty factor from?
- CFD calculations for MSL showed that the available turbulence models predicted up to a ~2X increase over laminar heating in attached flow on the windside aftbody
- Design heating = laminar heating x 2 (for turbulent augmentation) x 1.5 (estimated uncertainty on attached flow turbulent heating)

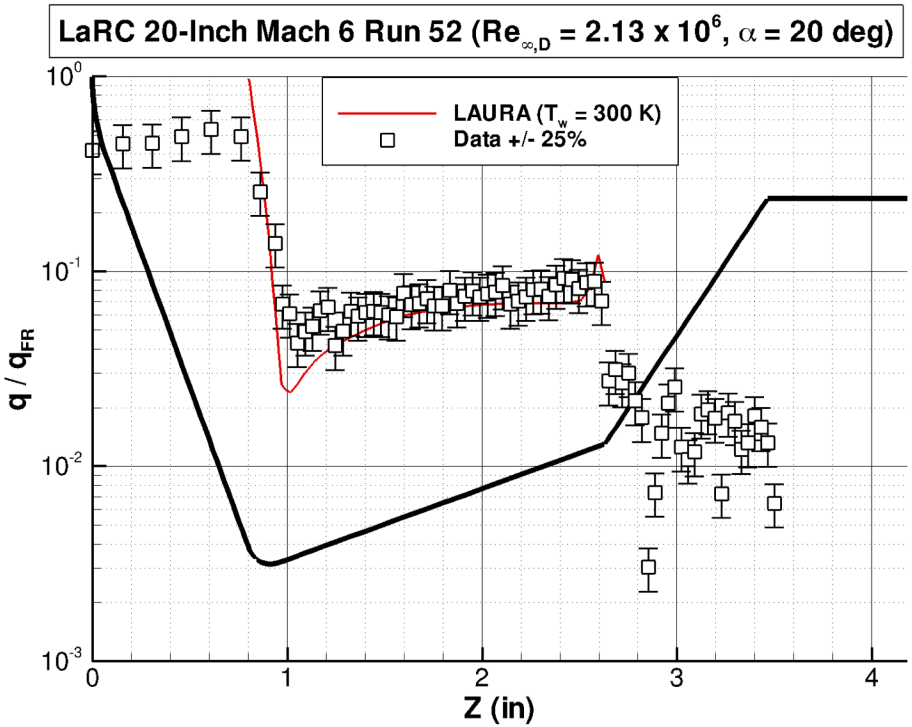


# MSL Aftbody Testing

- Limited testing was completed in the LaRC 20-Inch Mach 6 Tunnel (air)
  - Sting-mounted ceramic models are coated in phosphor to view surface temperature, which is turned into a heat flux
  - Flow on forebody is laminar
  - No catalytic heating, no radiative heating
- Across different Reynolds numbers, LAURA matches data to within +/- 25%

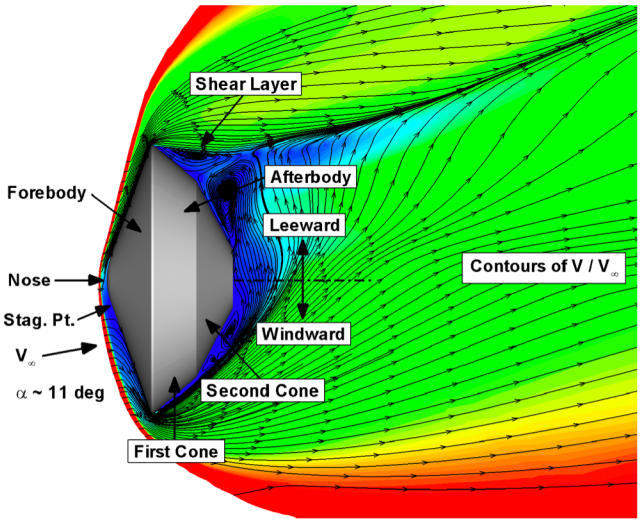


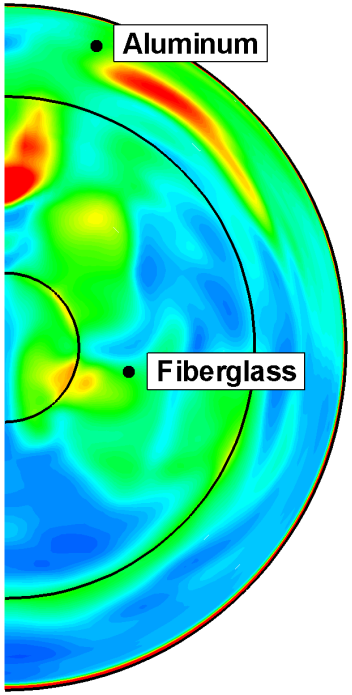


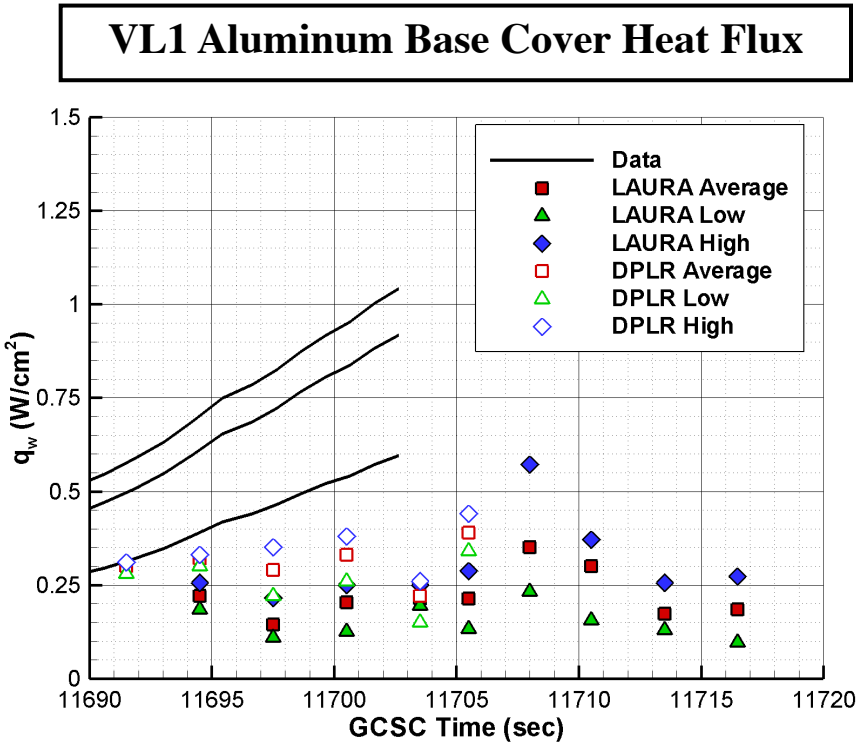



# CFD Compared to Viking Flight Data (AIAA-2006-0386)

- Viking had two surface thermocouples on the aftbody
  - Surface heat flux was reconstructed from the temperature data
- CFD convective heat fluxes are well below the reconstructed heat fluxes
  - At the time, this difference was attributed to possible turbulence, improper surface catalysis modeling, inadequate grids, etc.
  - What else could it be?



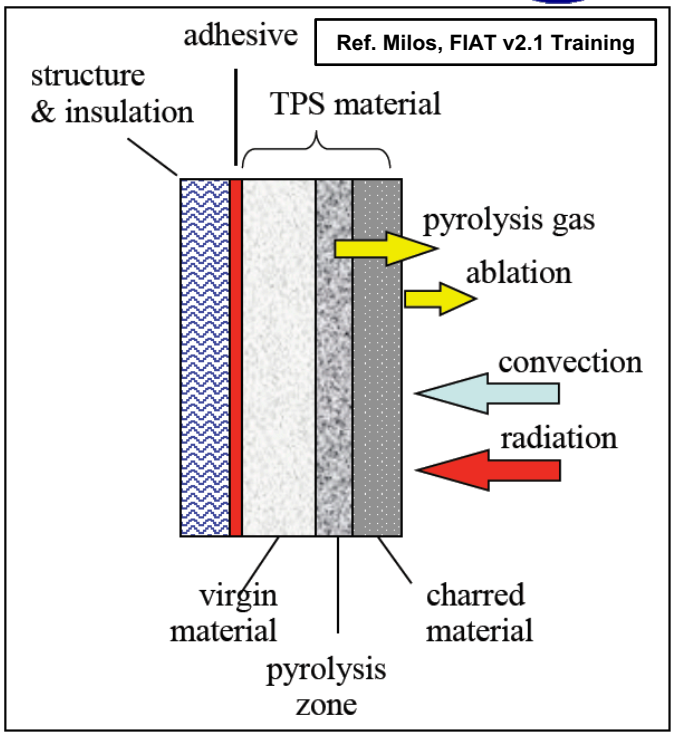



# Mars Radiative Heat Transfer

- Shock layer radiation for MSL and all previous missions was incorrectly assumed to be negligible
  - Legacy radiation codes assumed thermo-chemical equilibrium flowfields…and very little $CO_2$ in the shock layer
  - $CO_2$ infrared (IR) emissions dominate radiation below 6 km/sec at Mars, but with negligible $CO_2$ predicted, radiation was negligible
- Fortunately, TPS margins were sufficient on past Mars missions to survive the as-flown convective plus radiative heating environments
- Studies in support of ExoMars starting in ~2011 identified $CO_2$ IR radiation as being non-negligible (AIAA 2011-0135)
  - IR bands were added to radiation codes and ground testing was conducted in the U.S. to confirm $CO_2$ IR bands
- Lesson learned: All future Mars EDL missions must include radiative heat transfer
  - Convective heating dominates radiative on the forebody, but the reverse often is predicted to be true for blunt vehicle aftbodies, especially when the flow is detached

# TPS Material Response

- CFD-based heat transfer is fed into a material response code to predict the TPS response
  - Amount of recession
  - Blowing
  - Char layer depth
  - In-depth temperature
  - Bondline temperature
- For Mars missions, the primary requirement is that maximum bondline temperature (at the interface between the TPS material and structure) does not exceed a value that depends on the TPS material and structural loads




**TPS Response (FIAT)**

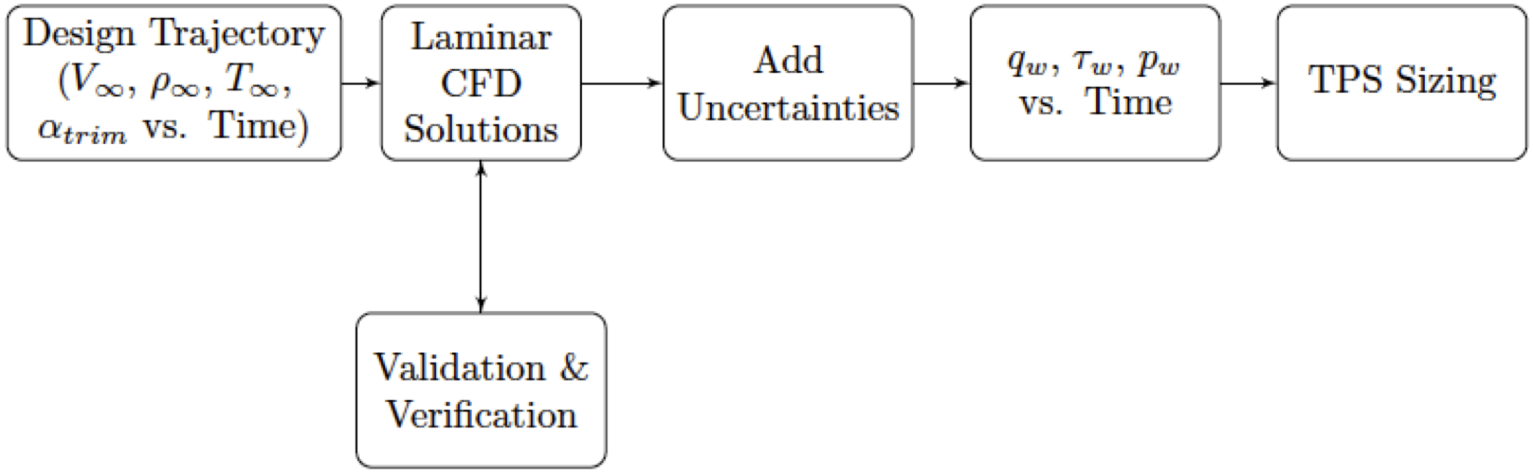
$$C_H(H_r - h_w) + \alpha_w q_{rad} + \dot{m}_g h_g + \dot{m}_c h_c - (\dot{m}_g + \dot{m}_c) h_w = \sigma\epsilon(T_w^4 - T_\infty^4) + q_{cond}$$

**Convective Heating (LAURA)**

**Radiative Heating**

# CFD Analysis Approach

1. Choose one or more aerothermal design trajectories for the mission
   - Typically we use engineering-level estimates for heat transfer as an initial guess
2. Run CFD at several time points that span the heat pulse, using established modeling assumptions
3. Add uncertainties to heat transfer results
4. Provide the necessary inputs (convective and radiative heating) to the TPS material response code
   - Results: TPS material thickness needed to keep the maximum bondline temperature below the allowable limit
5. Repeat the process as needed based on changes to the mission (e. g. entry vehicle mass, entry vehicle flight path angle, launch date, etc.)



# Why is Mars Aftbody Heating so Challenging?

- Wake flowfield is massively separated, unsteady and turbulent, stretching our standard CFD tools past their limits
- Predicting turbulent heating on the aftbody is even more difficult than it is on the forebody
- Ablation products from the heatshield TPS can be deposited onto the aftbody, how does that affect heating?
- We have so few missions, and even fewer flight data sets to gage how well we predict heating



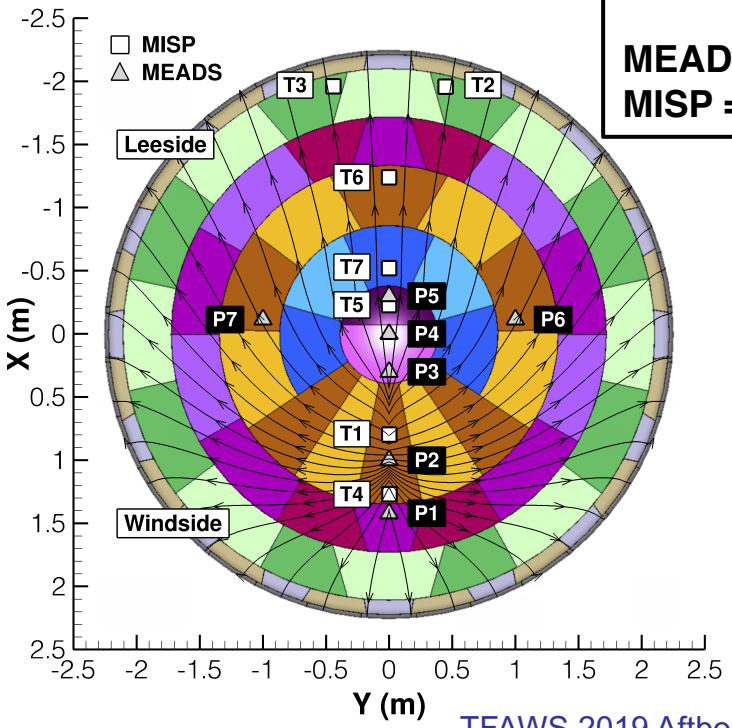




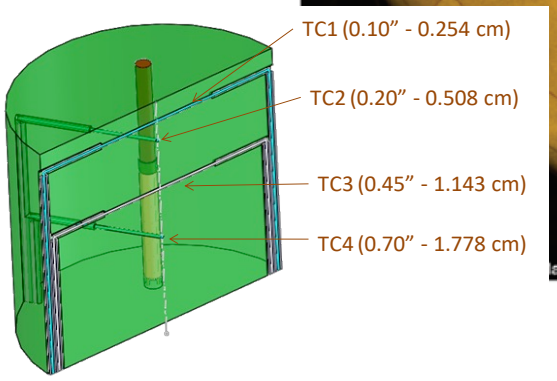
# Mars Science Laboratory

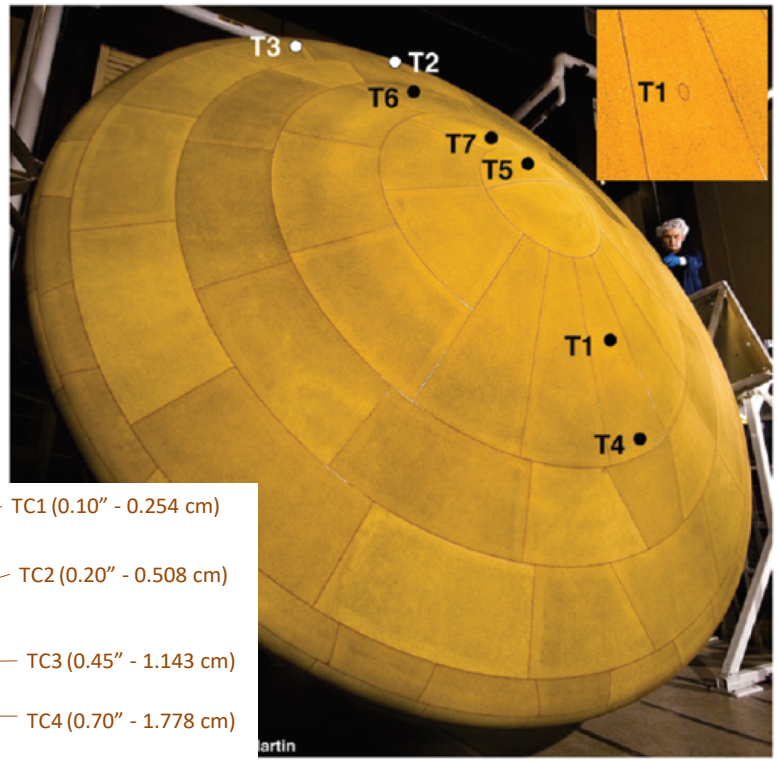
# Mars Science Laboratory

- MSL was the largest & heaviest Mars capsule, flew the highest angle-of-attack, and was the first to use RCS thrusters for guided bank angle maneuvers
- MSL had the "first" instrumented heatshield (no instrumentation on aftbody)
  - Viking and MPF had some instrumentation, but of unknown or questionable efficacy
- Aeroheating challenges:
  - Heatshield boundary layer transition
  - RCS thruster plume interference



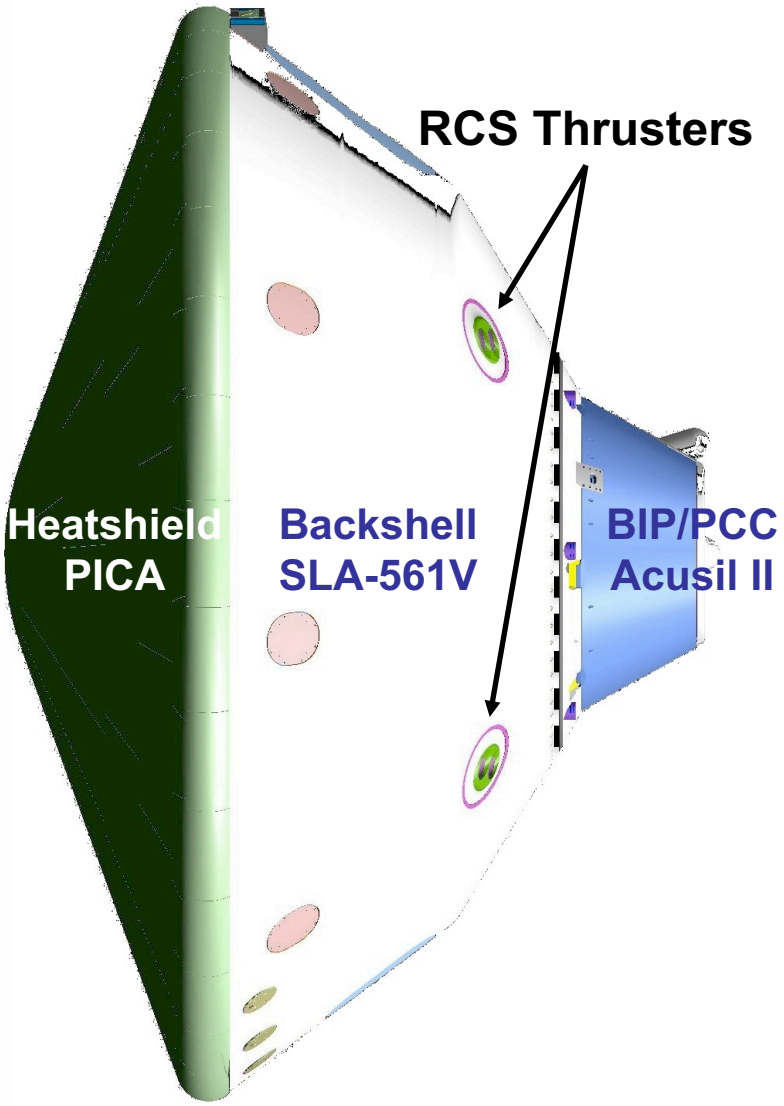

**MEDLI**
**MEADS = Pressure**
**MISP = Thermocouples**



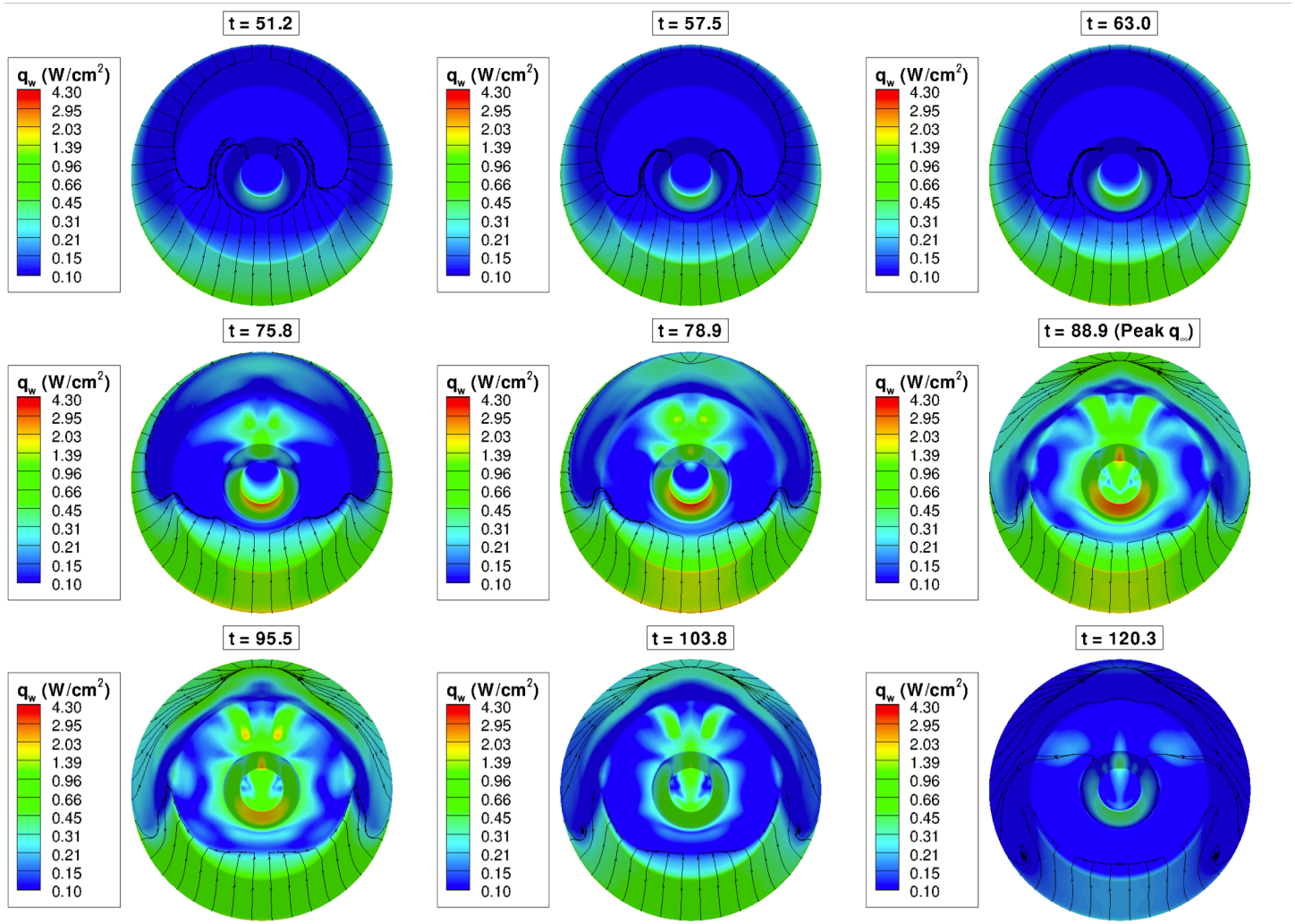
# MSL Thermal Protection System

- Heatshield: PICA, 1.25 in. uniform thickness
  - MSL design required 0.94 in.
  - Thickness chosen based on mass constraints
- Backshell: SLA-561V, 0.5 in. uniform thickness
  - MSL design required 0.32 in.
  - Thickness originally chosen to address RCS plume interference, which eventually was reduced
- BIP/PCC: Acusil II, variable thickness
- Problem Statement: Predict the margined convective heat transfer to the aftbody (Backshell, BIP, PCC)
  - Include the effects of RCS thruster plume interference and local protuberances



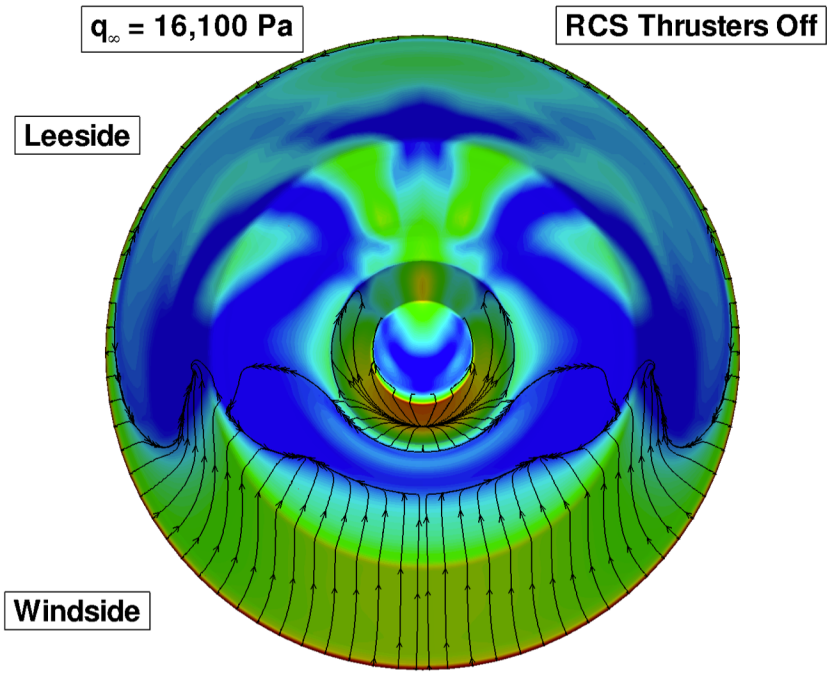
# LAURA Laminar Solutions

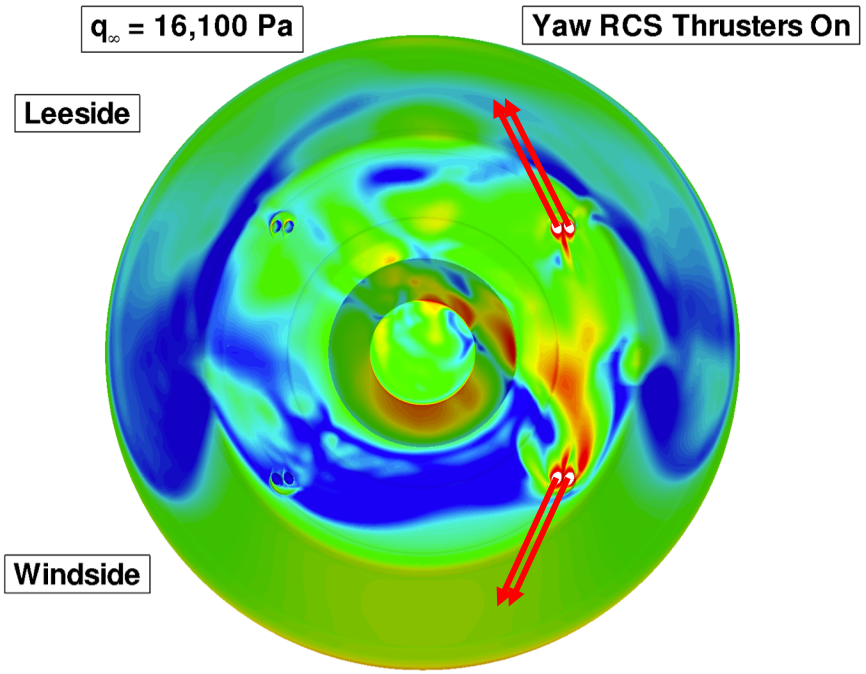
- At 16-deg angle of attack, part of the windward side of the backshell was predicted to have attached flow and higher heating, as was the parachute cover



# RCS Thruster Plume Interference

- Four pairs of RCS thrusters were used to change the capsule's bank angle (lift direction) during entry
- The RCS thruster plumes obstruct the wake flowfield and can augment the convective heat transfer
- The effects of RCS thruster plume interference on convective heating were estimated using steady-state LAURA and DPLR CFD simulations

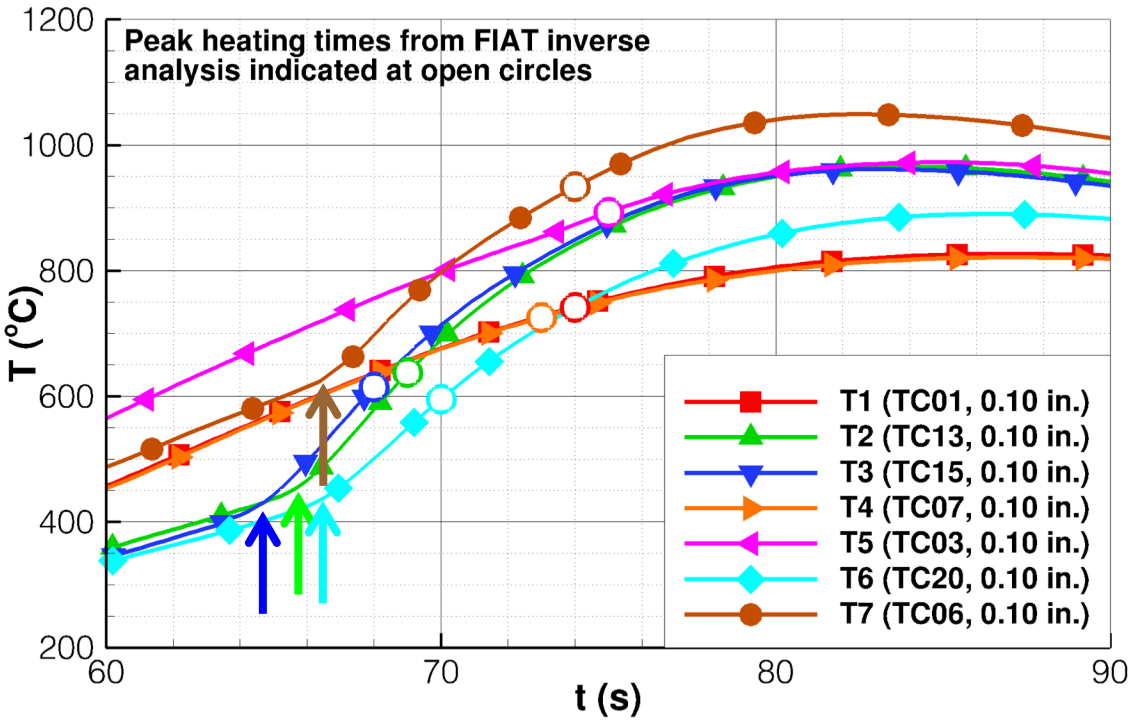


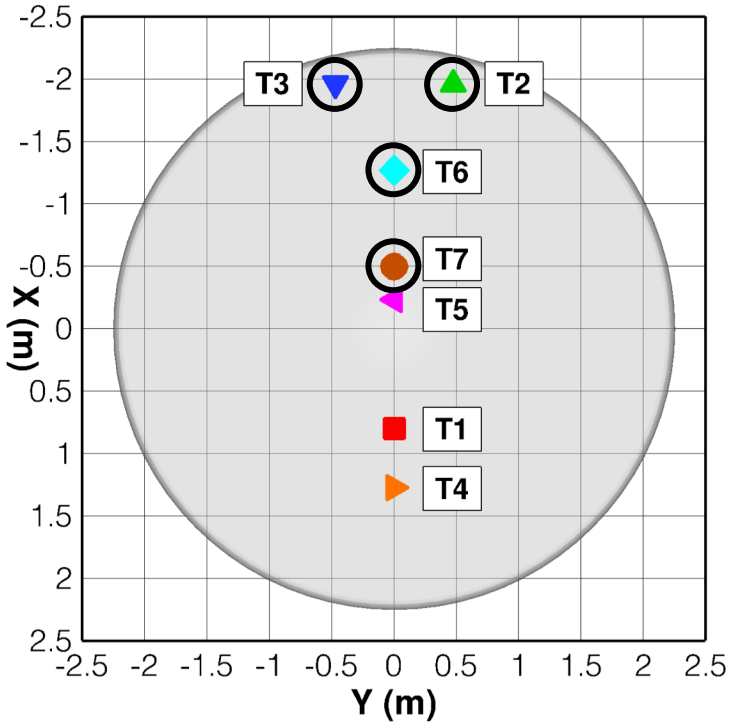



# MSL Heatshield Flight Data (MEDLI)

- No data dropouts → recession < 0.1”, less than expected
- Boundary Layer Transition detected by abrupt change in temperature slope vs. time
- MISP T2, T3, T6, and T7 experienced BLT before peak heating
- Estimate peak bondline temperature of ~0 °C was well below the design limit of 250 °C

**Measured Temperature at MISP 0.1” Thermocouples**

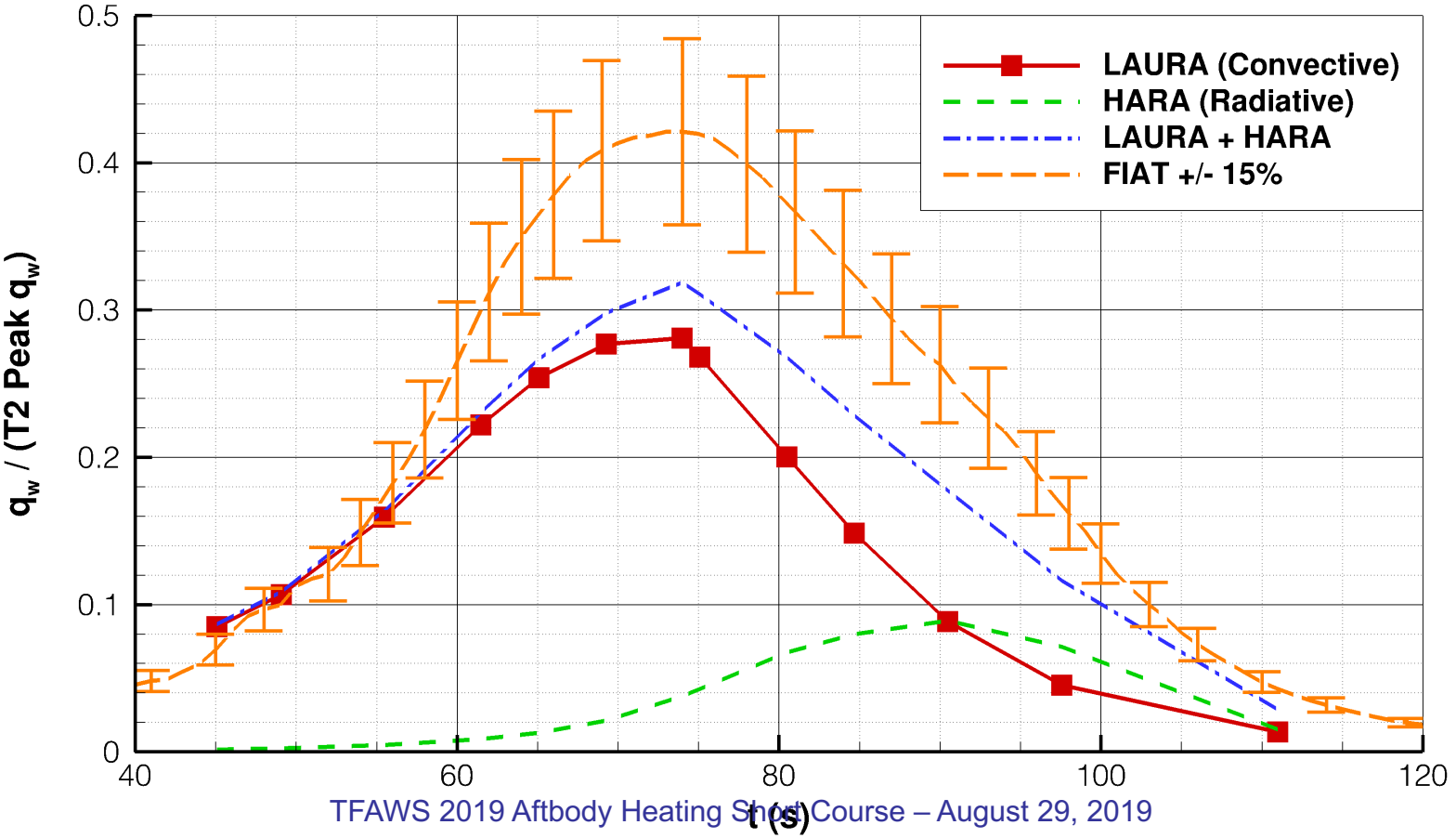


# MSL Stagnation Point Heating

- Q: Was high heating at T1 (and T4) due to shock layer radiation?
- A: Probably, but HARA radiation results don't fully explain differences between convective and reconstructed heating

**Convective & Radiative Heating at MISP T1 vs. Reconstructed Heating**



# MSL Aerothermal Lessons Learned

- Heating reconstruction is very difficult without an accurate in-flight recession measurement (or recession model)
- Heatshield stagnation point heating was under-predicted, mostly due to unaccounted for radiative heating
- Heatshield bondline temperature remained well below the design limit i. e. design heating was conservative (convective heating only)
- Heatshield experienced turbulent flow prior to peak heating, as expected

- Put instrumentation on the aftbody!



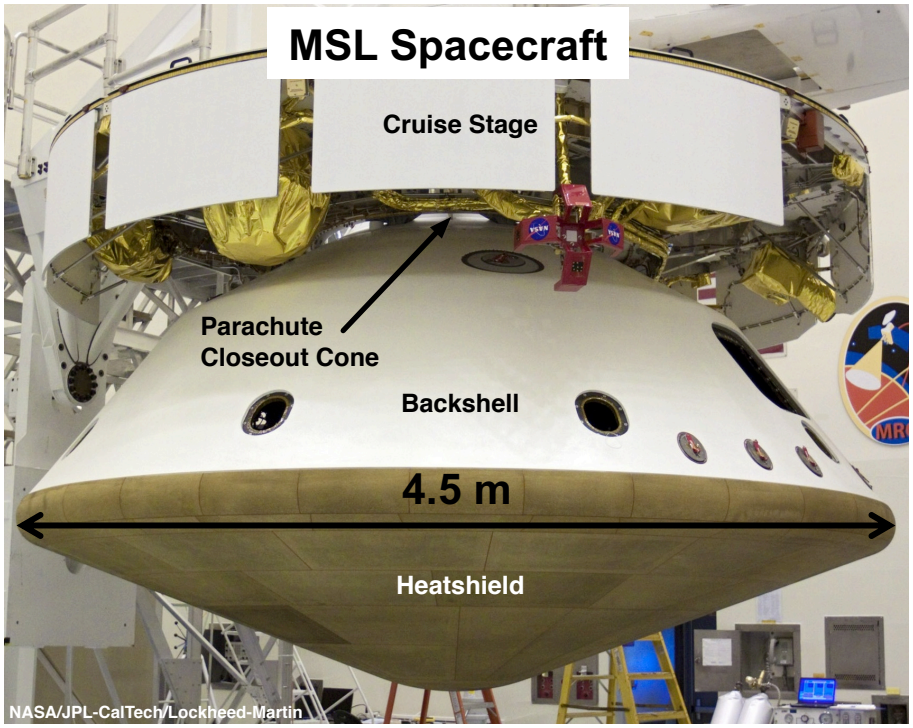




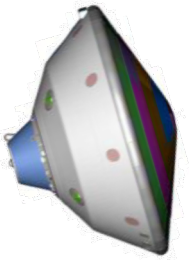
# Mars 2020

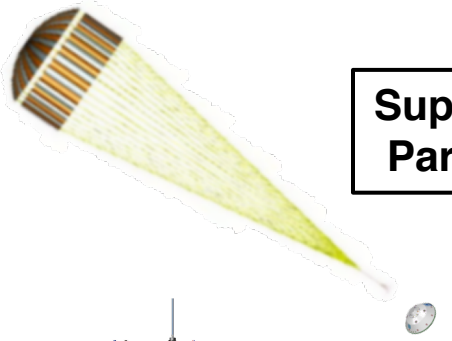
# Mars 2020

- The Mars 2020 entry system is a rebuild of MSL, which successfully landed Curiosity on Aug. 5th, 2012
- Aerothermal problem statement: Will the MSL-designed TPS provide sufficient margin for the Mars 2020 mission after radiative heat transfer is added?

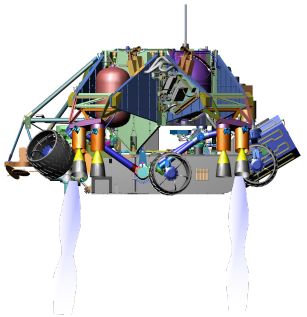



**Rigid Aeroshell Guided Entry L/D = 0.24**

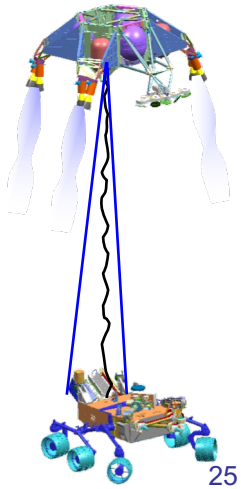




**Supersonic Parachute**



**Powered Descent**



**Sky Crane**

# Changes for Mars 2020 Aerothermal

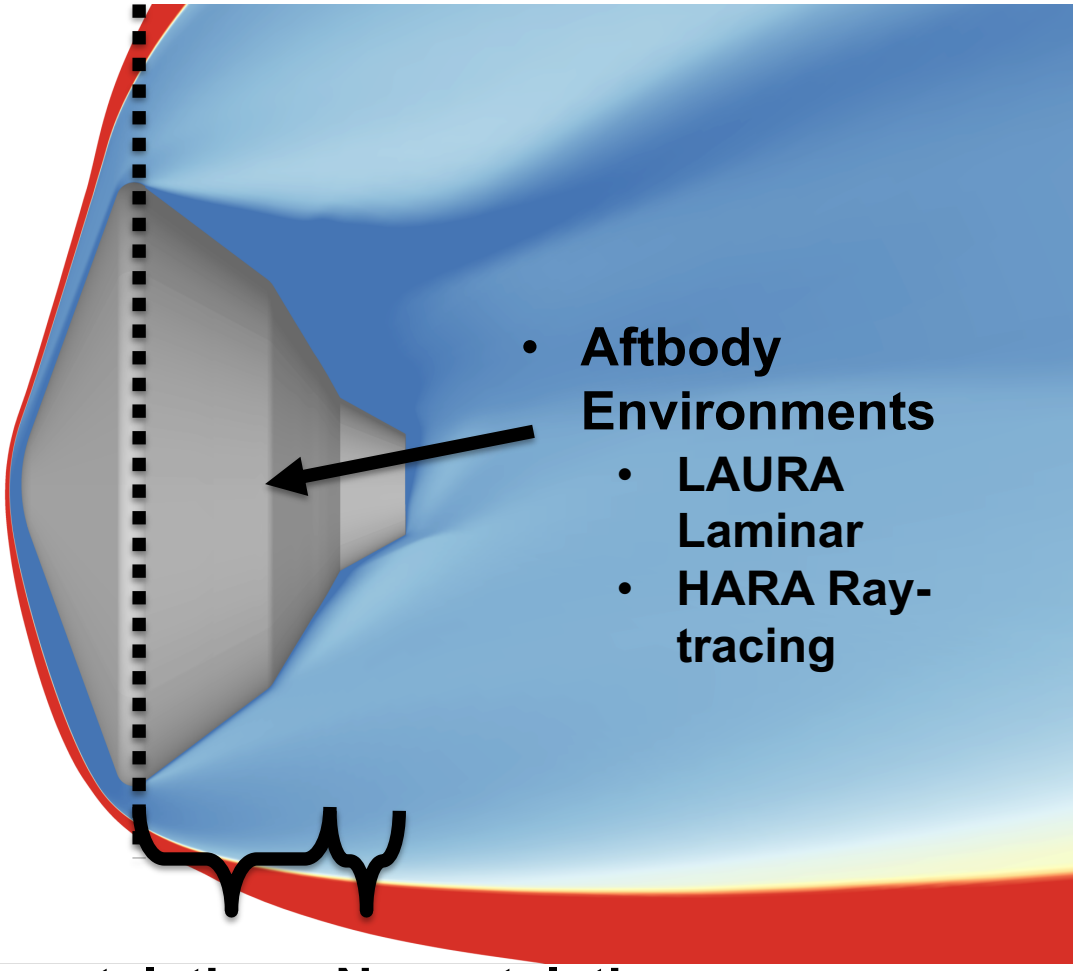
- Switch to LAURA 5 for convective heating
  - Legacy LAURA 4 re-written in modern Fortran, integrated with HARA radiative heat transfer code
- Add radiative heat transfer using HARA
- Switch from super-catalytic to non-catalytic surface for the parachute cover (Acusil II)
  - Non-catalytic convective heating < super-catalytic convective heating
- Complete more detailed analysis of parachute cover, due to relative magnitude of radiative heat flux and small TPS margins

# Computational Tools

- **Navier-Stokes Solvers**
  - *LAURA 5*
    - Fortran 95 update to version 4 (MSL version)
      - Retaining same numerics and gas-physics
    - Updated $CO_2$ kinetics necessary for shock-layer radiation calculations
  - *DPLR version 4.04*
    - Like LAURA, a finite-volume, viscous, thermochemical nonequilibrium flow solver for structured grids
- **Shock-Layer Radiation Codes** – use species number densities and temperature from LAURA and DPLR flow solvers
  - *HARA* – works with LAURA
    - line-by-line and a new multiband opacity-binning
    - Tangent-slab approach
      - Ray-tracing
  - *NEQAIR* – works with DPLR
    - Similar results to HARA

# Aftbody Solution Methodology

1. Run LAURA laminar steady-state solutions until attached-flow convective heating converges
2. Switch to time-accurate time-stepping
3. Take an average of several unsteady solutions to get time-averaged convective heating in detached flow regions, until the averaged heating converges
4. Run HARA using the final LAURA flowfield solution

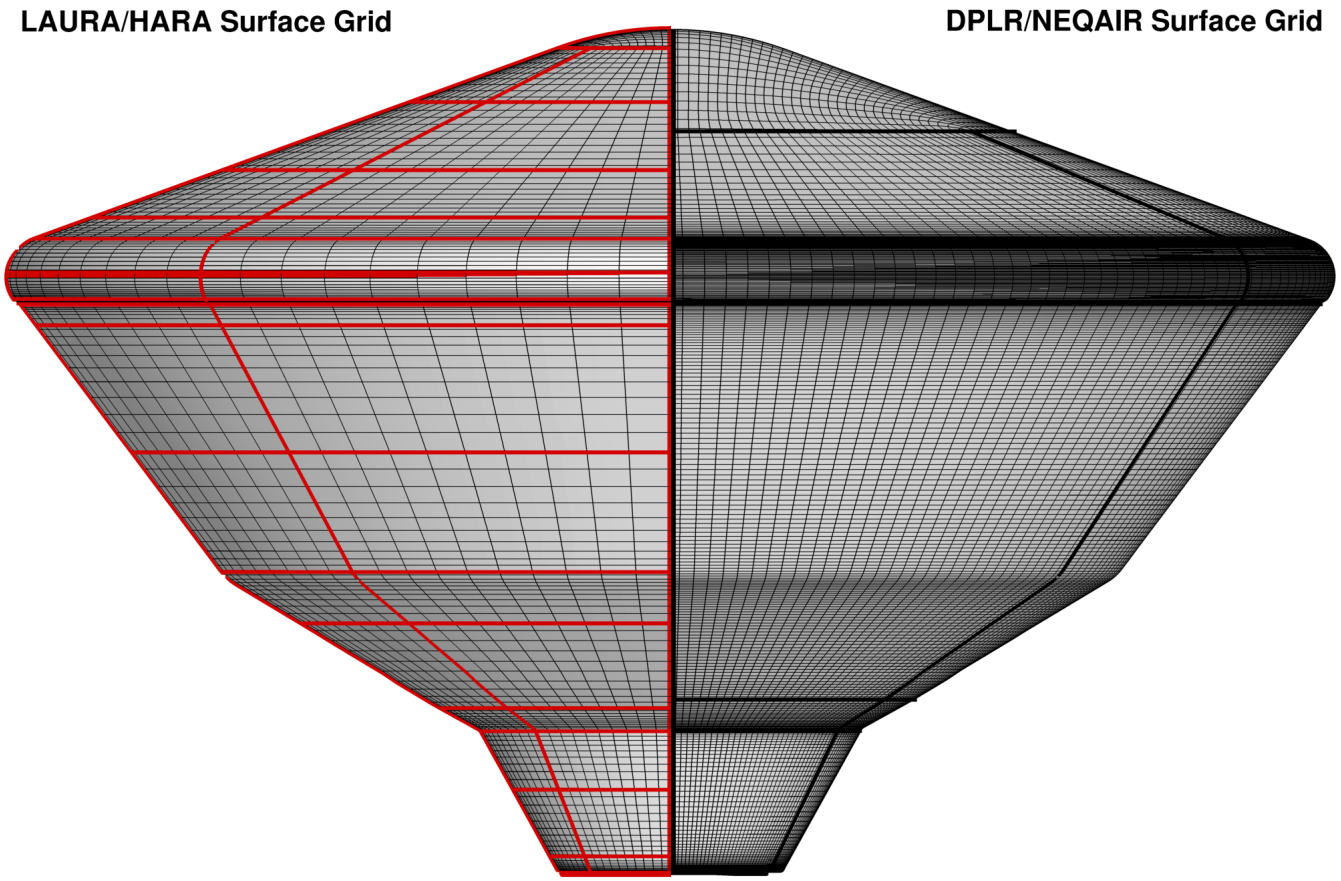



**Supercatalytic surface recombination**

**Noncatalytic on BIP and PCC**

# Grids

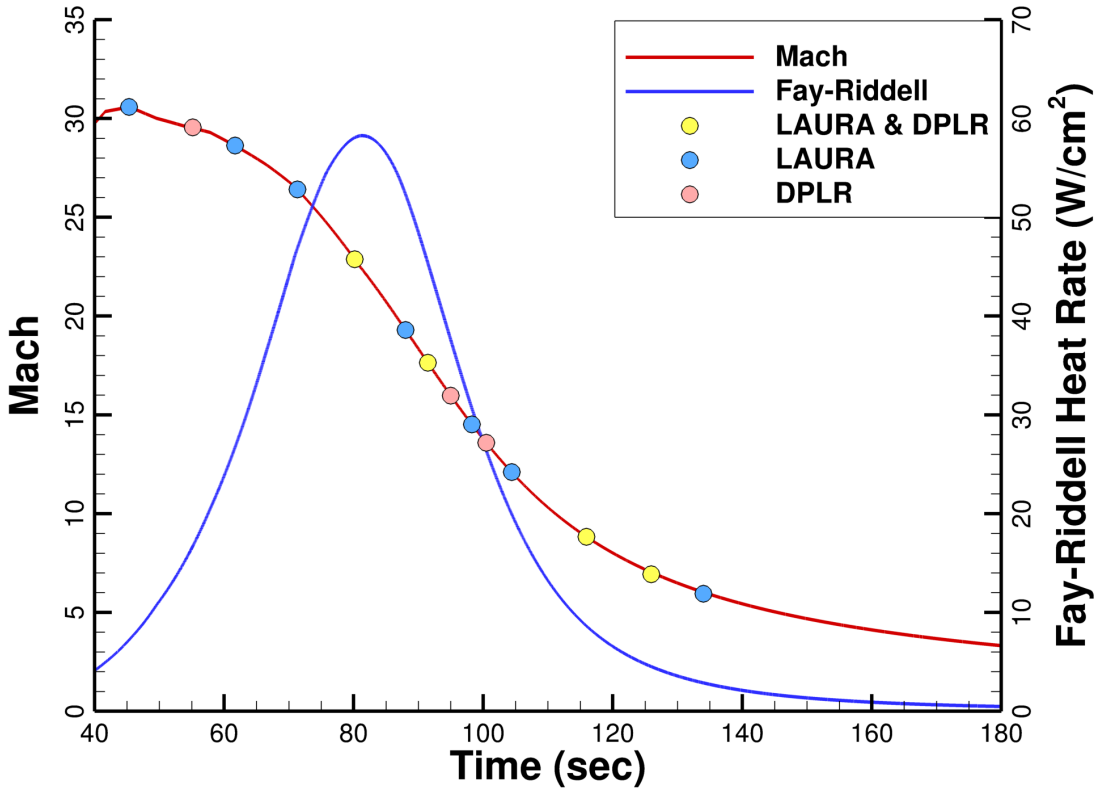
- Two independent grid systems
- Both grids include 129 wall-normal points
- Shock tailoring performed by LAURA and DPLR
- Half body
  - Full body for time-averaged cases




- **LAURA Surface Grid**
  - Axial points = 211
  - Azimuthal points = 41
- **DPLR Surface Grid**
  - Axial points = 407
  - Azimuthal points = 97

# CFD Points

- Trajectory points were chosen to bookend the Mars 2020 heat pulse
  - Capture the peak heat rates
  - Have enough resolution to accurately integrate the heat load
- Common points used for code-to-code verification




| Case# | Time s | Vel. m.s$^{-1}$ | Dens. kg.m$^{-3}$ |
|---|---|---|---|
| 1 | 45 | 5552 | 5.6E-06 |
| 2 | 55 | 5546 | 3.0E-05 |
| 3 | 62 | 5456 | 8.4E-05 |
| 5 | 71 | 5270 | 3.2E-04 |
| 7 | 80 | 4857 | 8.0E-04 |
| 9 | 88 | 4227 | 1.5E-03 |
| 10 | 91 | 3895 | 1.8E-03 |
| 11 | 95 | 3551 | 2.2E-03 |
| 12 | 98 | 3246 | 2.5E-03 |
| 13 | 100 | 3046 | 2.7E-03 |
| 14 | 104 | 2722 | 3.1E-03 |
| 16 | 116 | 2000 | 3.6E-03 |
| 17 | 126 | 1592 | 3.9E-03 |
| 18 | 134 | 1367 | 3.9E-03 |





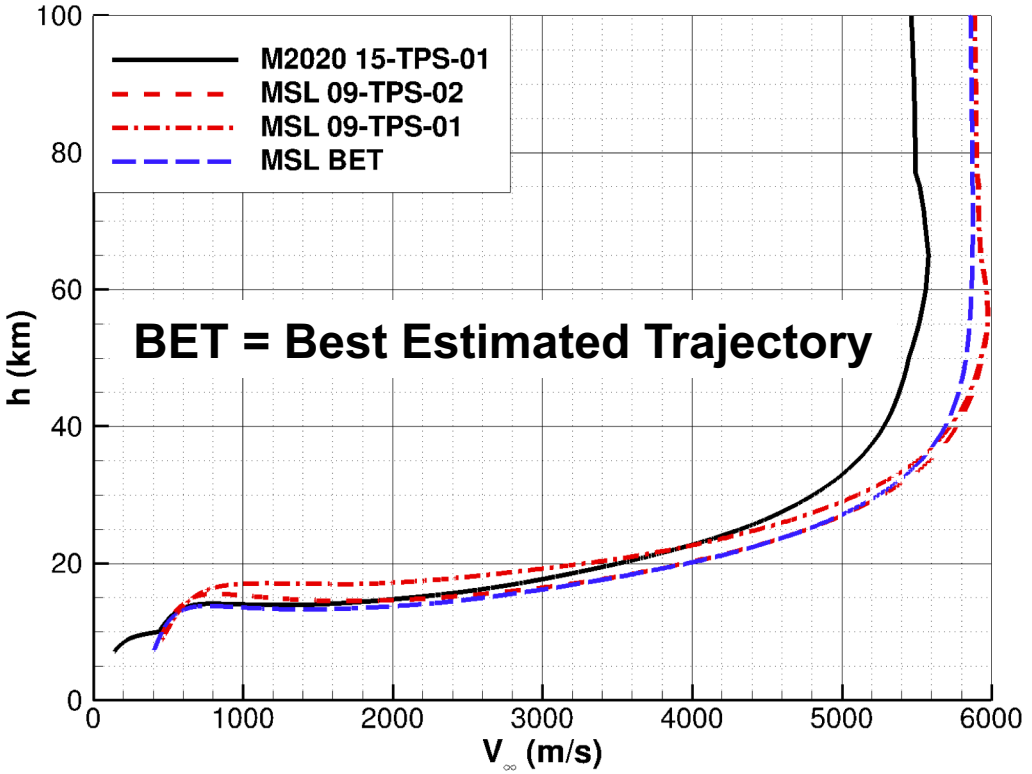


# Mars 2020 Design Compared to MSL Design

# Trajectory Comparison

- MSL 09-TPS-XX were the aerothermal design trajectories
- Mars 2020 is heavier than MSL was, but has a lower entry speed
- Will the slower entry speed for Mars 2020 offset the heavier mass and addition of radiative heat transfer to the aftbody?

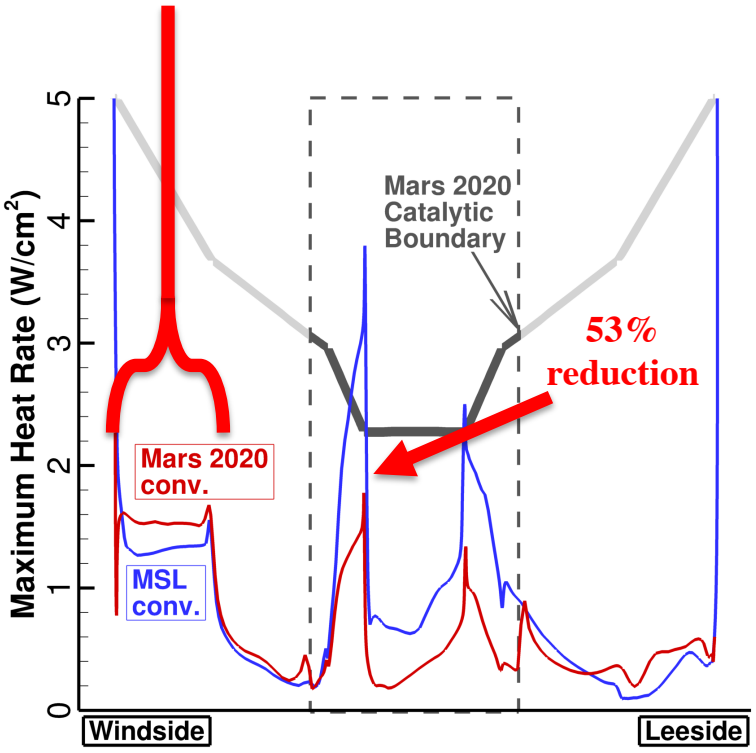
| Parameter | Mars 2020 15-TPS-01 | MSL 09-TPS-02/01 | MSL BET |
|---|---|---|---|
| Relative Entry $V_\infty$ $(km/s)$ | 5.45 | 5.87 | 5.85 |
| Inertial Entry $\gamma$ $(deg)$ | -15.2 | -15.5/-14 | -15.5 |
| Entry Mass $(kg)$ | 3353 | 3348 | 3158 |



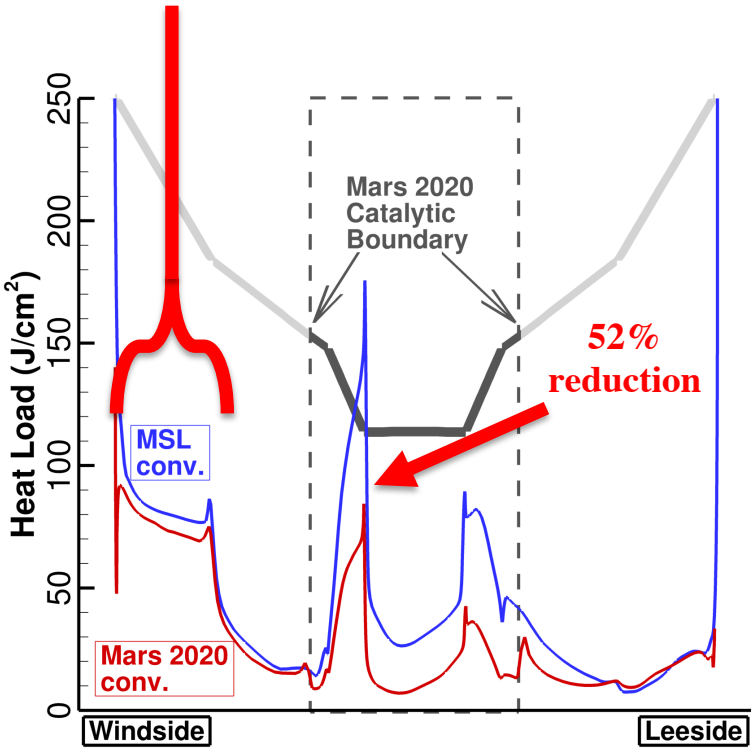
# Aftbody Peak Convective Heat Flux

- **Aftbody, *convective (unmargined)*, laminar**

**Maximum Heat Rate:**
**Mars 2020 heat rate higher on the 1st backshell cone by 10-16%**



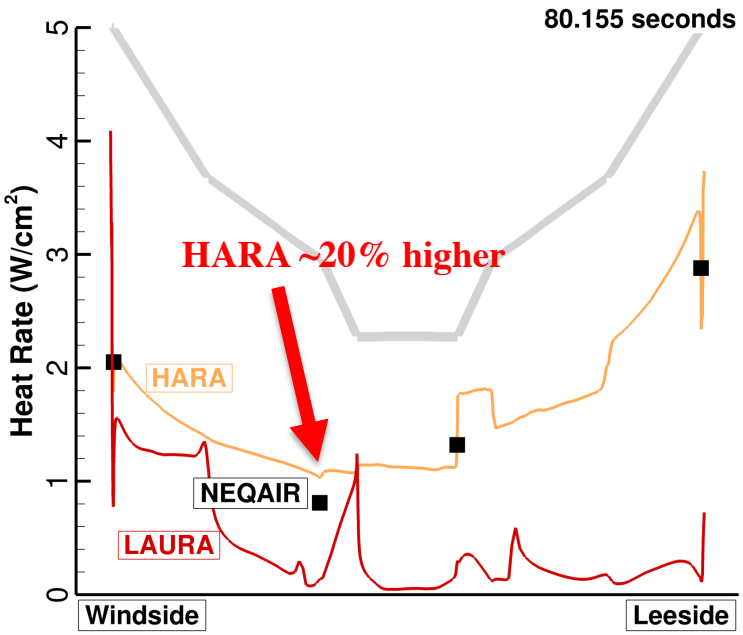

**Heat Load:**
**MSL heat load higher on the 1st windside backshell cone by 10-12%**



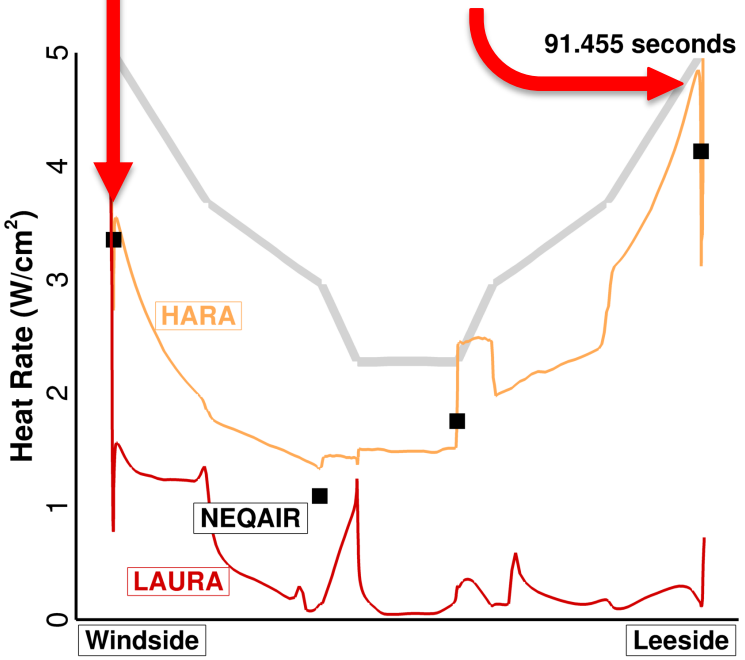
# HARA/NEQAIR Aftbody Comparison

- **Code-to-code verification check (Aftbody, radiative *(unmargined)*)**
  - **HARA and NEQAIR compare well**
  - **Radiative higher on the leeside**
- **Radiative heating dominates the heat load levels for most of the backshell**

**Radiative heating can be more than two times higher than convective**



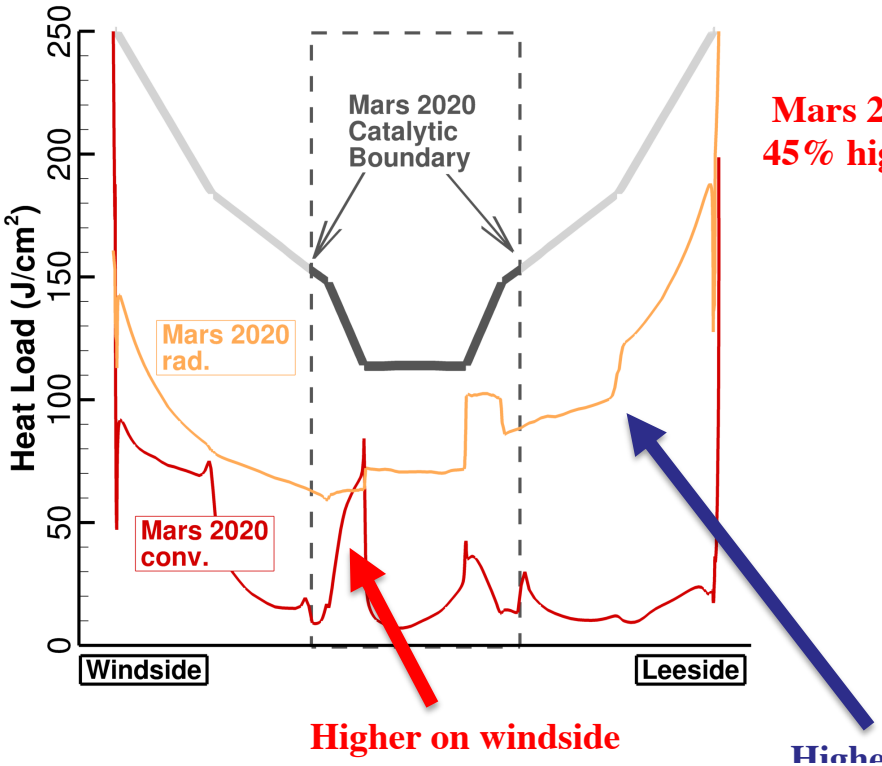

**Radiative heating up to order of magnitude higher than convective**



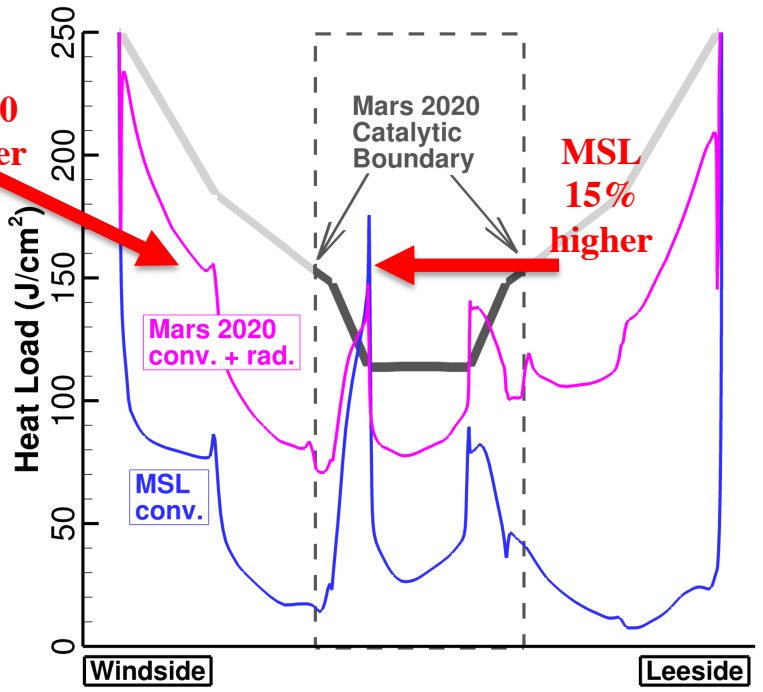
# Add Radiation – Aftbody

- **Aftbody, *convective and radiative (unmargined)*, laminar**
  - **Radiative heat load data integrated using trapezoidal rule**
- **Environments for TPS verification use curve fits based on trajectory**

**Mars 2020 convective and radiative**




**Mars 2020 total and MSL convective**




**The reduction in Mars 2020 entry velocity *does not* offset the addition of radiative heating estimates on the backshell**

# Heating Uncertainty Factors

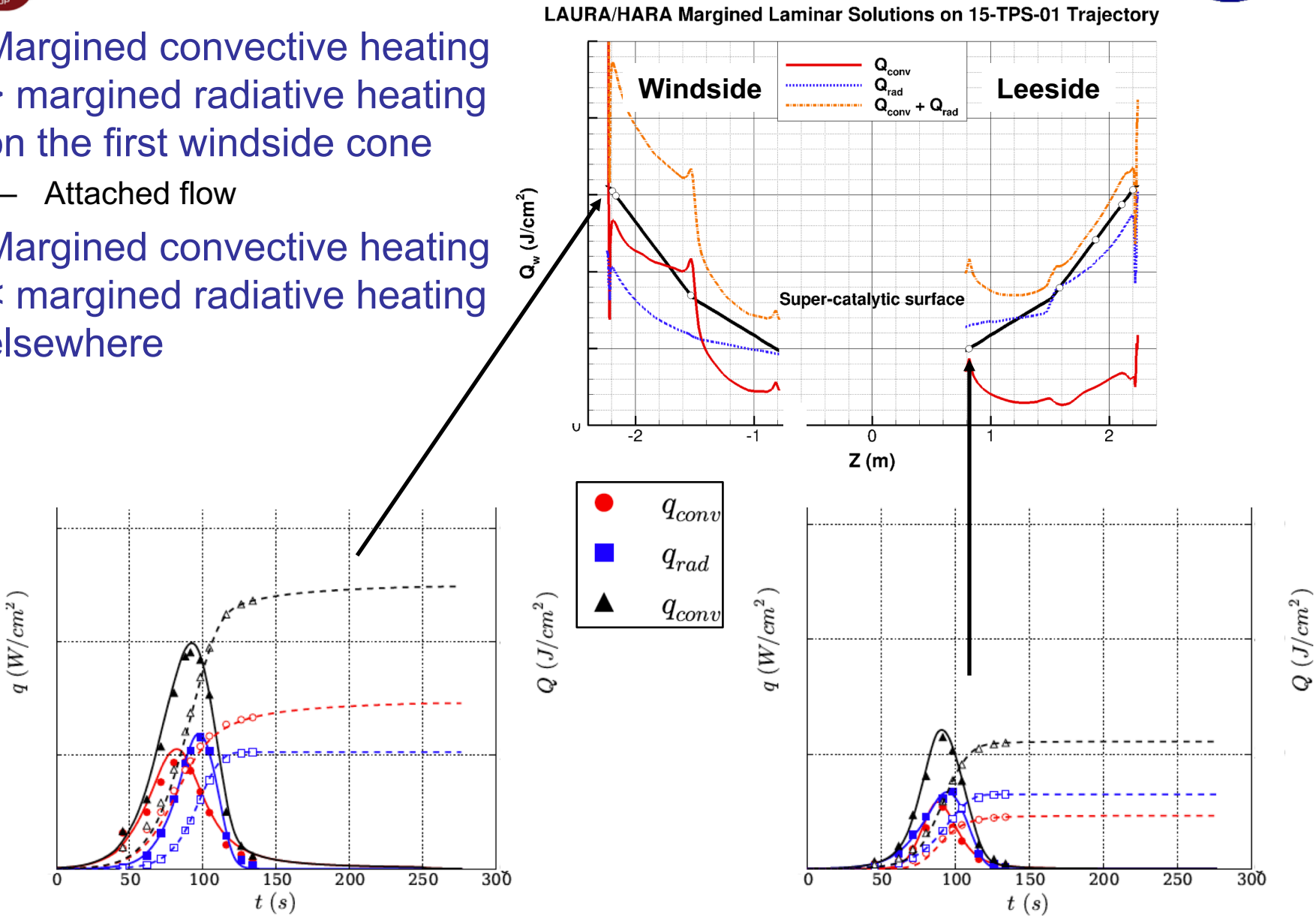
- Unmargined CFD environments were calculated as laminar on the backshell, BIP, and PCC
- Margined heat flux, $q_{design} = (q_{conv,LAURA} \times \Delta q_{conv}) + (q_{rad,HARA} \times \Delta q_{rad})$

***Convective & Radiative Heating Uncertainty Factors (Δq)***

| | Backshell/BIP/PCC |
|---|---|
| Convective (MSL values, AIAA 2009-4075) | 3 |
| Radiative | 1.47 (parametric analysis) |

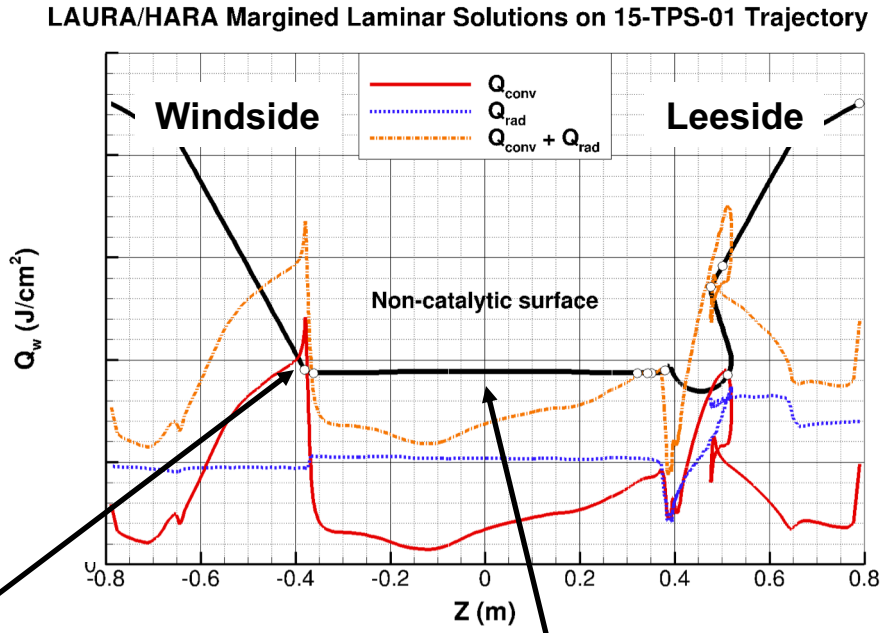
# Backshell Design Heating

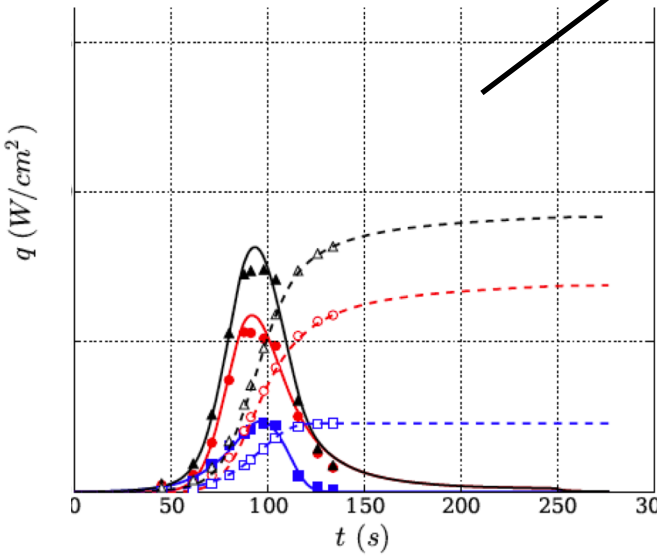
- Margined convective heating > margined radiative heating on the first windside cone
  - Attached flow
- Margined convective heating < margined radiative heating elsewhere

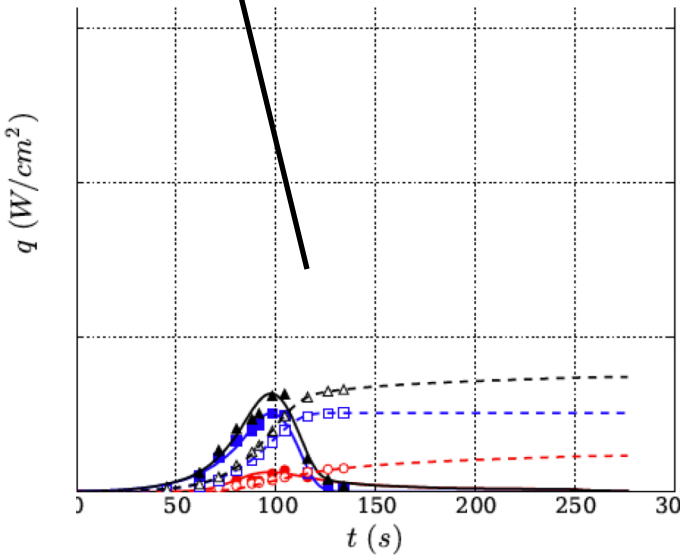


# PCC Design Heating

- Margined convective heating > margined radiative heating on the windside cone
- Margined convective heating < margined radiative heating on lid, radome, and leeside cone



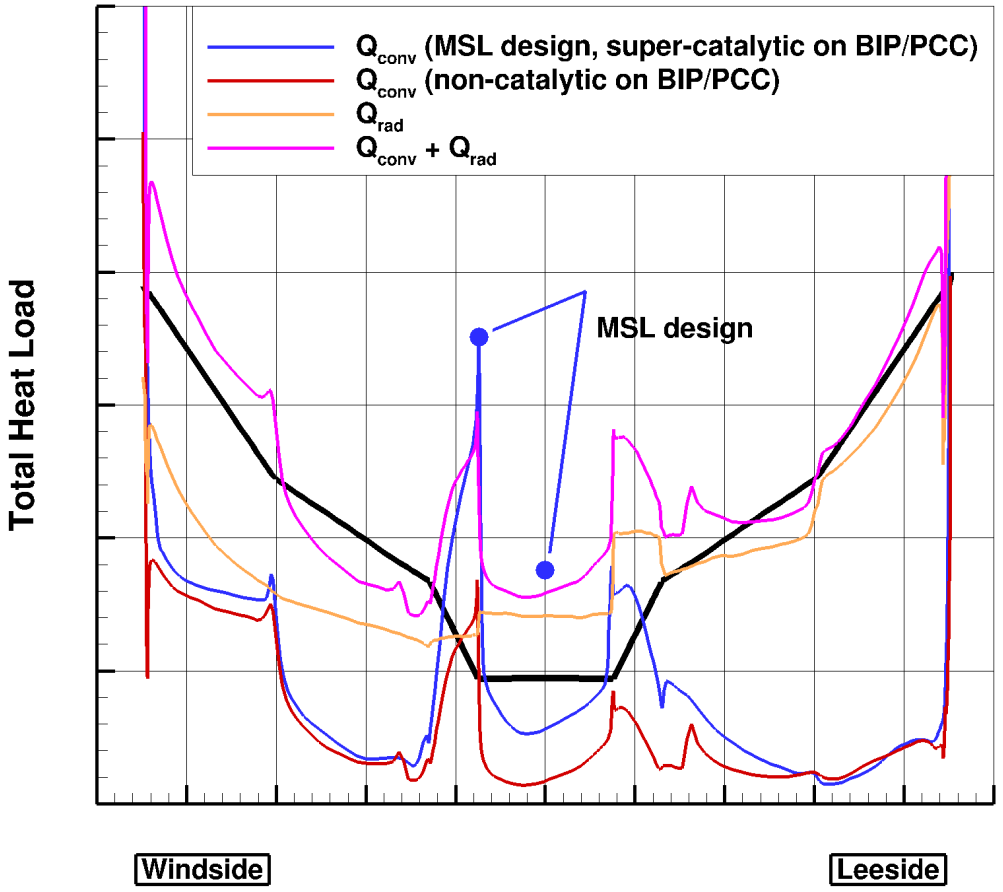



# Mars 2020 Aftbody Heating Compared to MSL

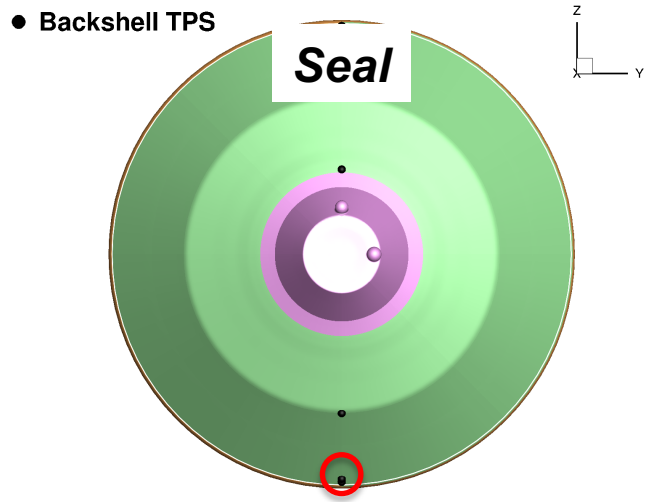
- The Mars 2020 convective heat load is lower than the MSL convective heat load, due to a lower entry speed
- Backshell:
  - Mars 2020 radiative heat load is higher on the leeside than the windside
  - Adding radiation makes the Mars 2020 combined heat load higher than MSL design
- PCC:
  - Mars 2020 combined heat load is higher than MSL heat load, due to radiation, except at the windside corner
  - Fortunately, a convective heating bump factor (50%) was used for the MSL lid design

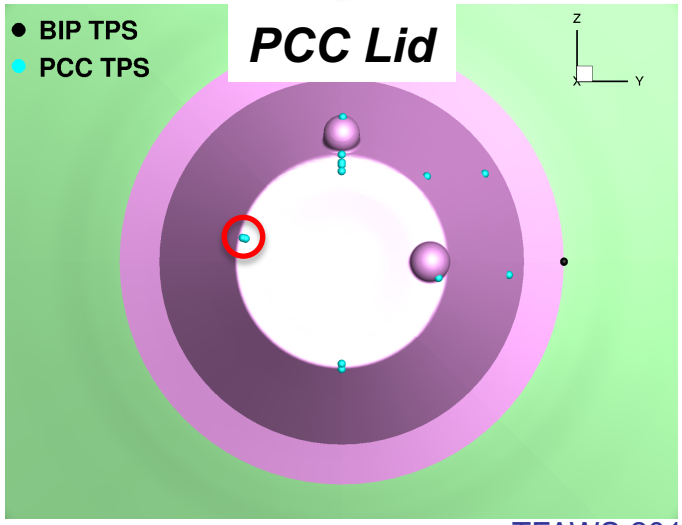
***Design Heat Load for MSL (Convective) and Mars 2020 (Convective + Radiative)***
***Trim angle-of-attack = ~16 deg***

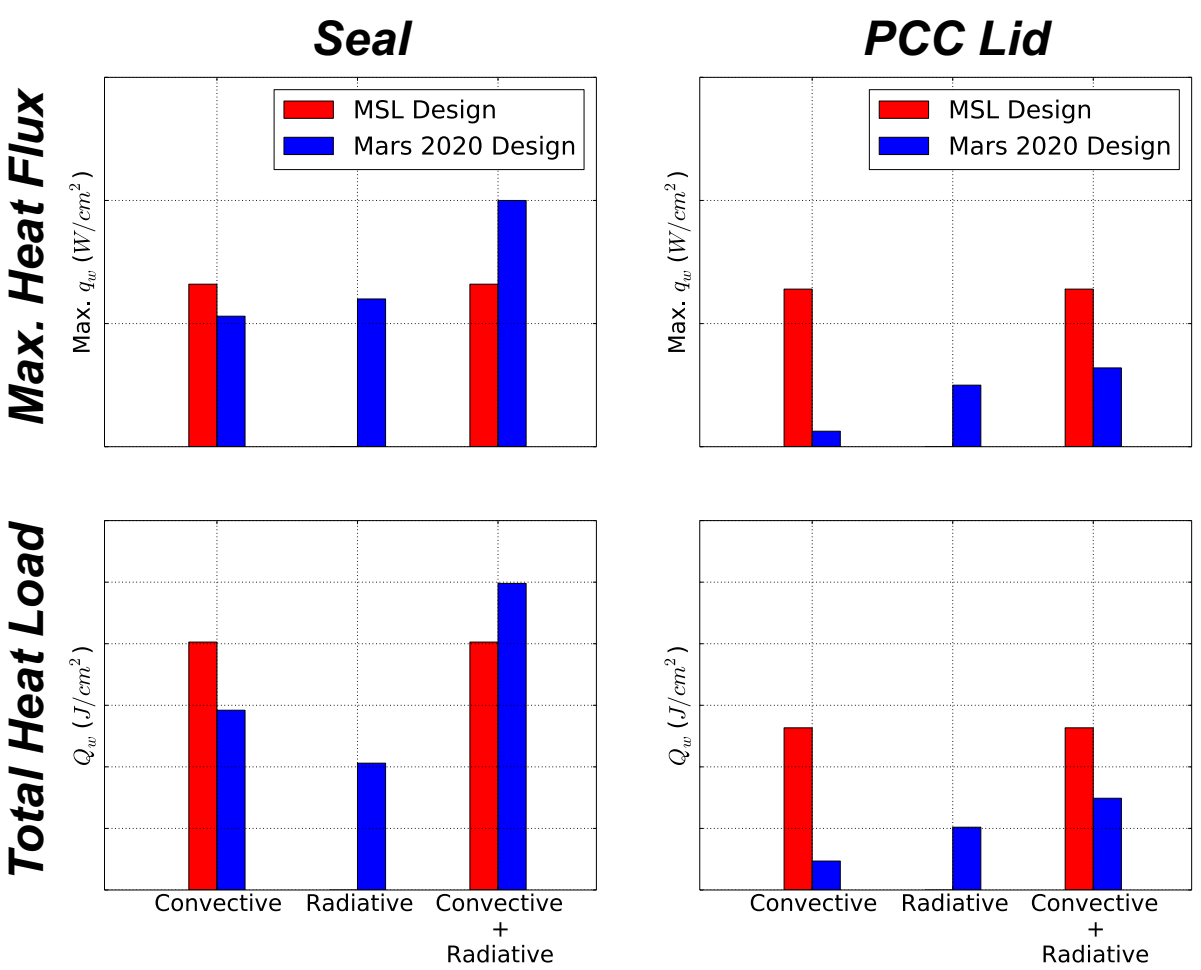


# Mars 2020 Compared to MSL: Design Heating

- Seal: total heating increases due to addition of radiation
- PCC Lid: total heating decreases due to use of actual environments vs. bump factors

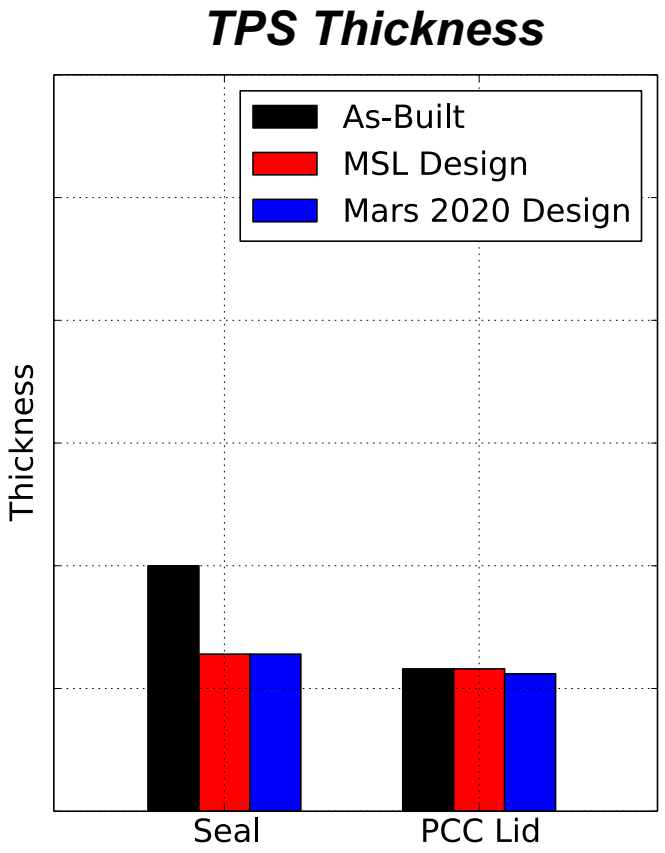


# Mars 2020 Compared to MSL: Required TPS Thickness

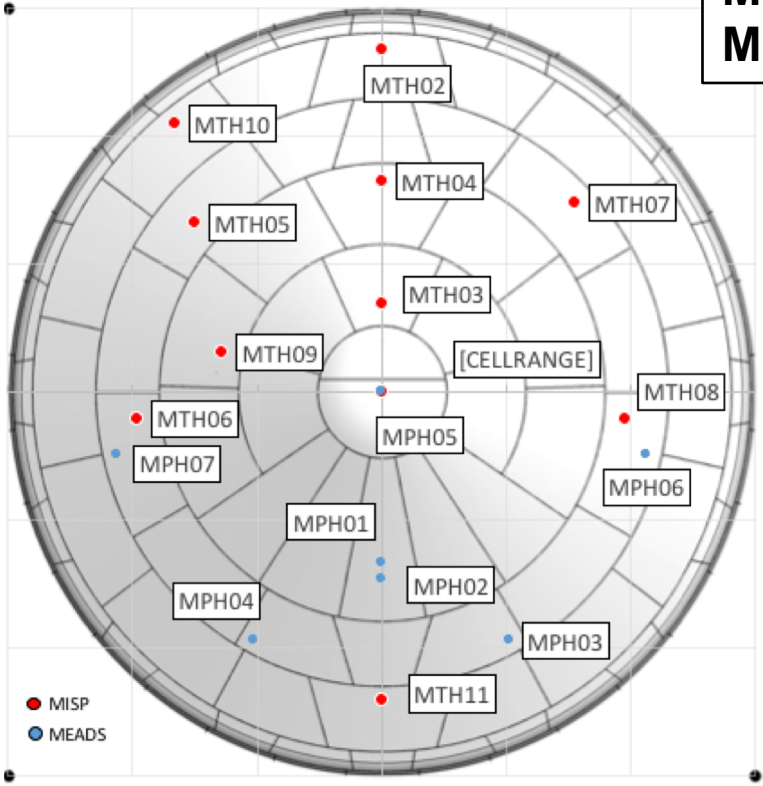
- **Seal: Mars 2020 required thickness is the same as MSL, even though heating is higher**
  - **Why? Because initial pre-entry temperature is lower for Mars 2020**
- **PCC Lid: Mars 2020 required thickness is 0.01-in less than it was for MSL**
  - **Why? Because MSL (fortunately) used 50% of convective heating from the PCC windside corner, where convective heating was high**

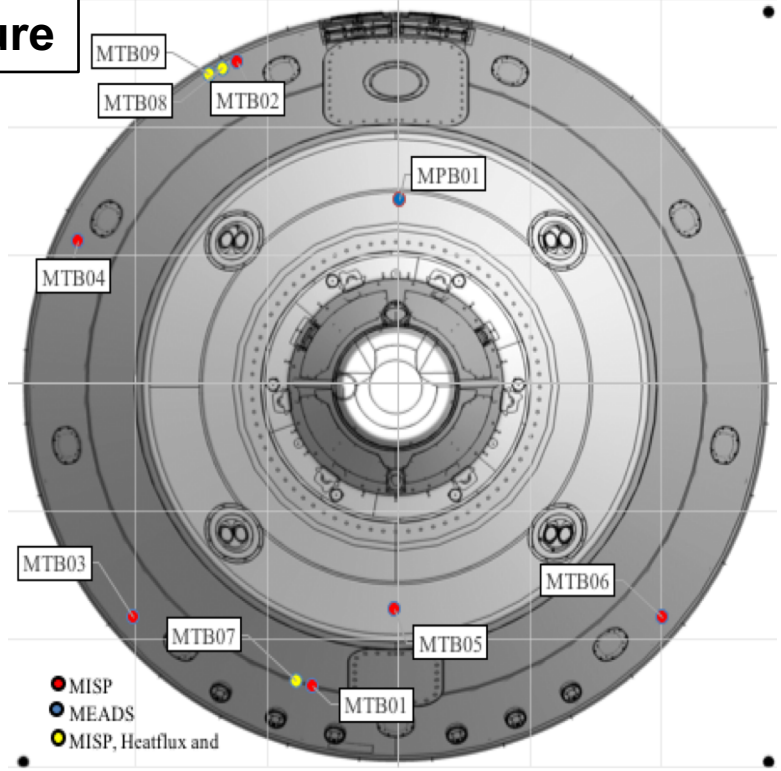


# Mars 2020 Instrumentation

- Similar heatshield pressure and temperature measurements to MSL, but different locations
- Added one aftbody measurement of pressure
- Added several aftbody measurements of temperature, a direct heat flux measurement, and a radiometer

**MTH = Thermal**
**MPH = Pressure**

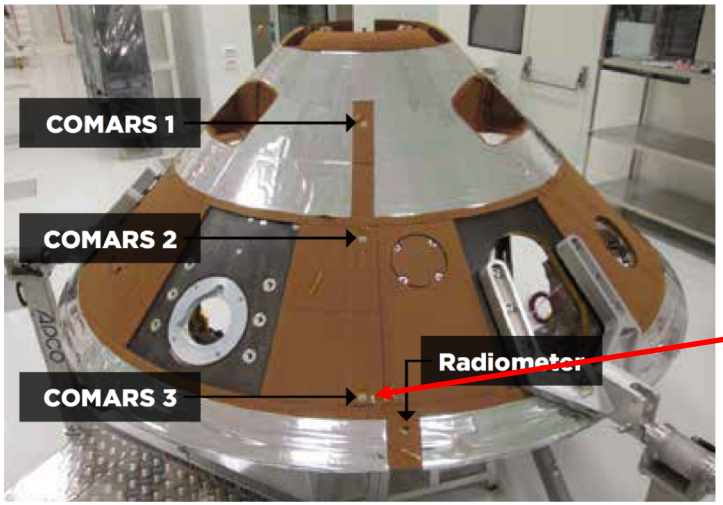


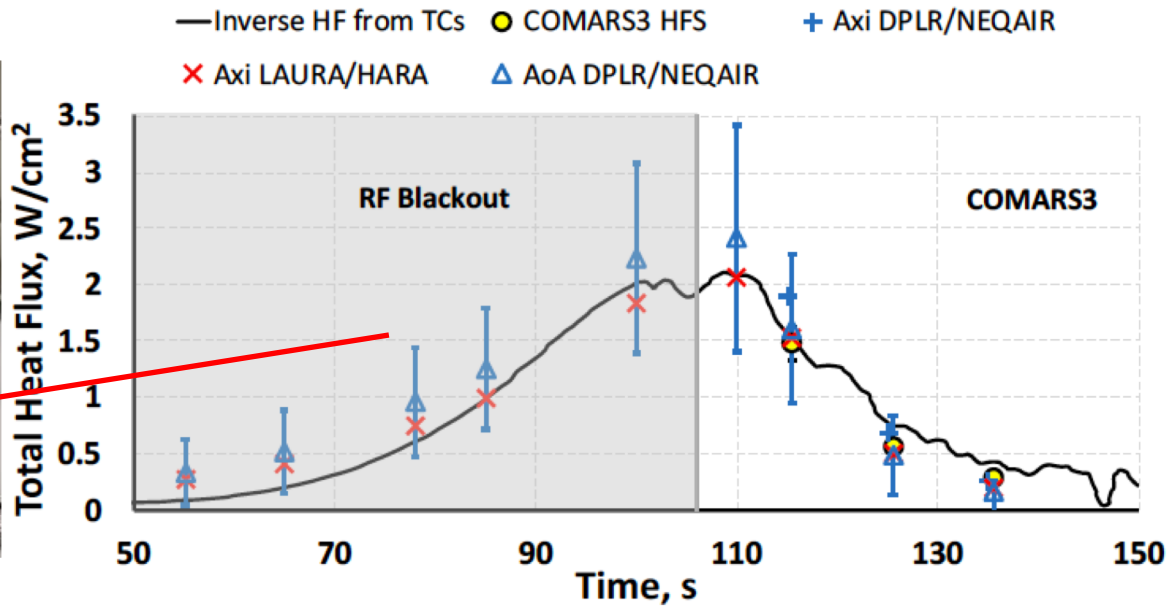



# ExoMars Flight Data and CFD

- The ExoMars Schiaparelli entry capsule (2016) was instrumented with aerothermal measurements on the backshell
- The entry capsule crash landed, but limited data were returned
- Laminar CFD results using DPLR and LAURA are encouraging when compared to reconstructed total heating at 3 aftbody locations
  - Total heating is predicted to have been ~70% radiative due to separated flow

**Ref. Brandis, AIAA 2019-3260**









# Questions?

# References


1. Karl T. Edquist, Brian R. Hollis, Chris O. Johnston, Deepak Bose, Todd R. White, and Milad Mahzari, “Mars Science Laboratory Heat Shield Aerothermodynamics: Design and Reconstruction,” Journal of Spacecraft and Rockets (2014), Vol. 51, No. 4, pp. 1106-1124, doi: 10.2514/1.A32749
   - http://arc.aiaa.org/doi/abs/10.2514/1.A32749
2. Karl Edquist, Artem Dyakonov, Michael Wright, and Chun Tang, “Aerothermodynamic Design of the Mars Science Laboratory Backshell and Parachute Cone,” AIAA Paper 2009-4078, 41st AIAA Thermophysics Conference, 22 June 2009 - 25 June 2009, San Antonio, Texas
   - http://arc.aiaa.org/doi/abs/10.2514/6.2009-4078
3. Adam Wise, Dinesh Prabhu, David Saunders, Chris Johnston, and Karl Edquist, "Computational Aerothermodynamic Environments for the Mars 2020 Entry Capsule," AIAA Paper 2018-3116, 2018 Joint Thermophysics and Heat Transfer Conference, June 25-29, 2018, Atlanta, Georgia
   - https://arc.aiaa.org/doi/abs/10.2514/6.2018-3116
4. Karl Edquist, Adam Wise, Chris Johnston, "Aerothermodynamic Design of the Mars 2020 Entry Capsule," 2018 Joint Thermophysics and Heat Transfer Conference, June 25-29, 2018, Atlanta, Georgia
5. Karl Edquist, Michael Wright, and Gary Allen, “Viking Aftbody Heating Computations and Comparisons to Flight Data,” 44th AIAA Aerospace Sciences Meeting and Exhibit, 2006, doi: 10.2514/6.2006-386.
   - http://arc.aiaa.org/doi/abs/10.2514/6.2006-386