# Development and Sizing of the Mars 2020 Thermal Protection System

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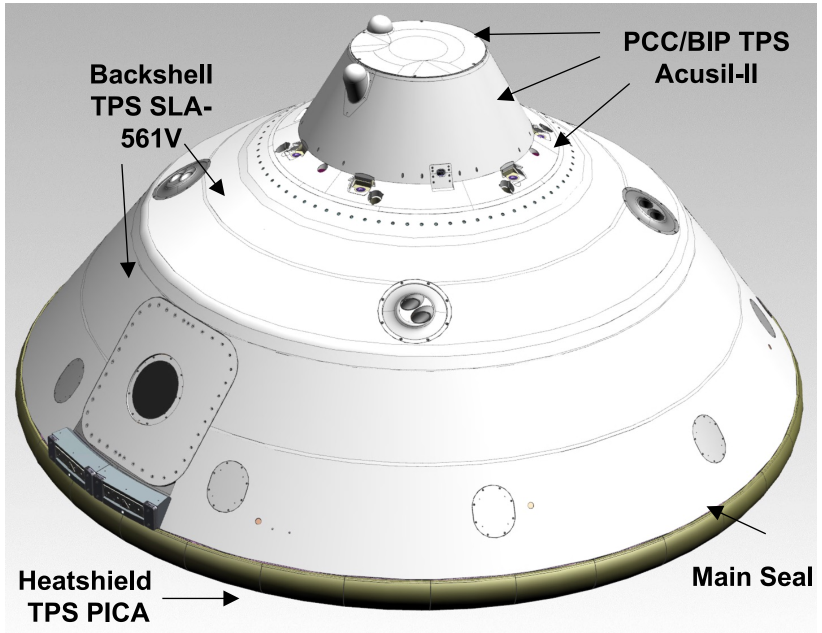
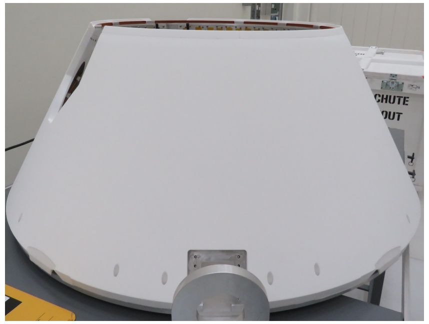
# Mars 2020 Entry Vehicle Overview

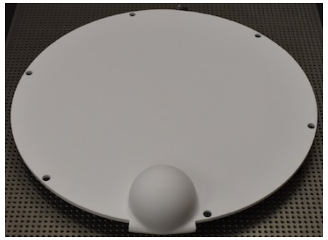
- Mars 2020 mission delivered the Perseverance rover to Jezero crater on Mars on February 18, 2021
- During Mars entry, the rover was housed in an aeroshell and shielded against aerodynamic heating with a Thermal Protection System (TPS)
  - The entry sequence and entry vehicle design were very similar to the previous Mars rover mission, Mars Science Laboratory (MSL)
- No major changes to the TPS materials and thicknesses compared to MSL
  - PICA tiles with RTV-560 gap fillers, coated with NuSil, on the heatshield
  - Painted SLA-561V on the backshell
  - Acusil-II on Parachute Closeout Cone (PCC), PCC lid, and Backshell Interface Plate (BIP)
- This paper reviews the the qualification of TPS design through thermal sizing and testing



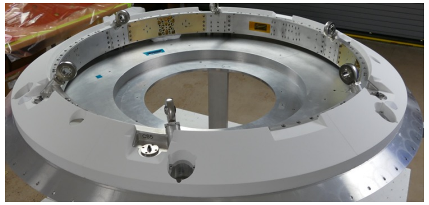

**PCC Cone**



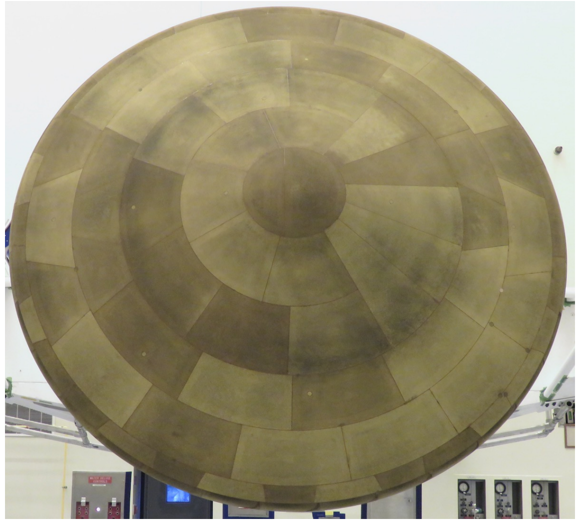
**PCC Lid**



**BIP**



**Heatshield**

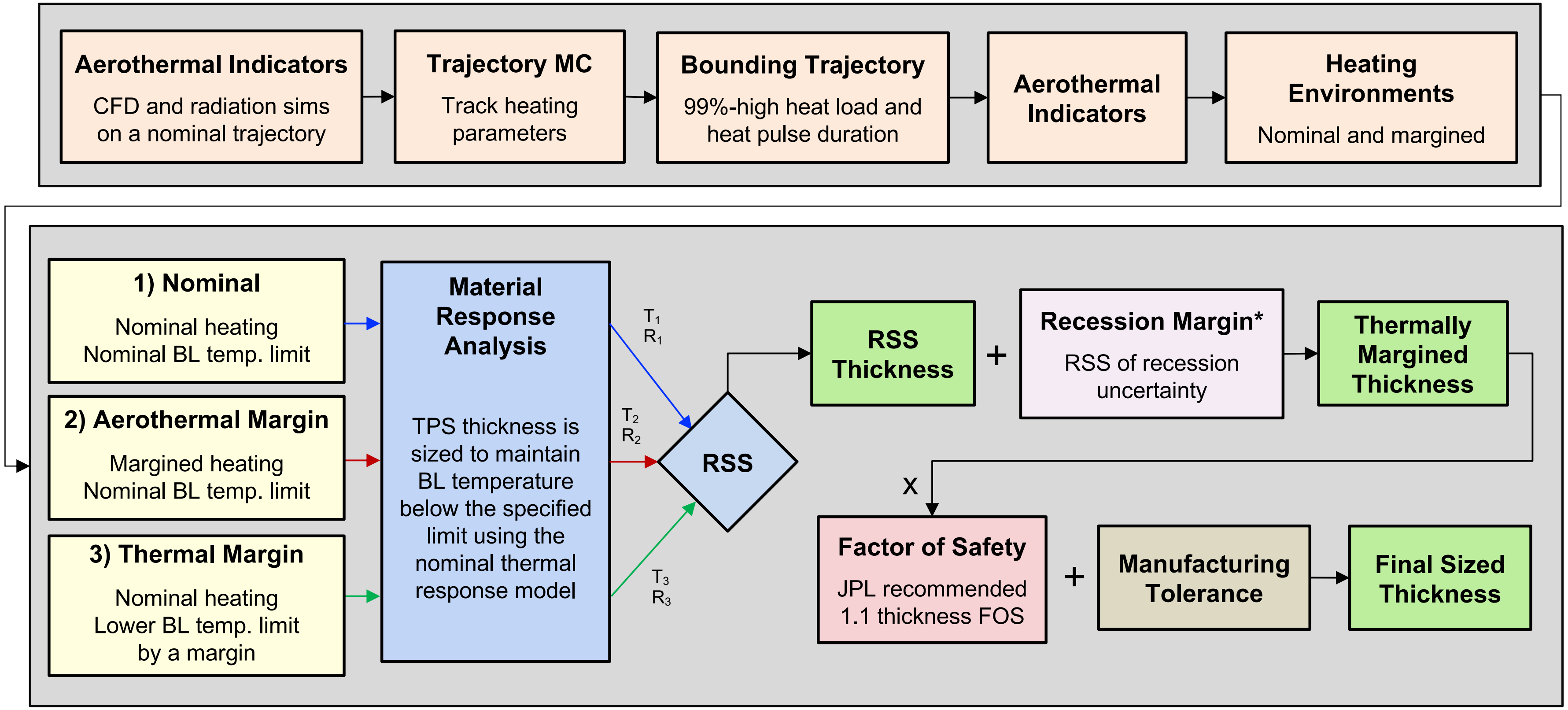


**Backshell**

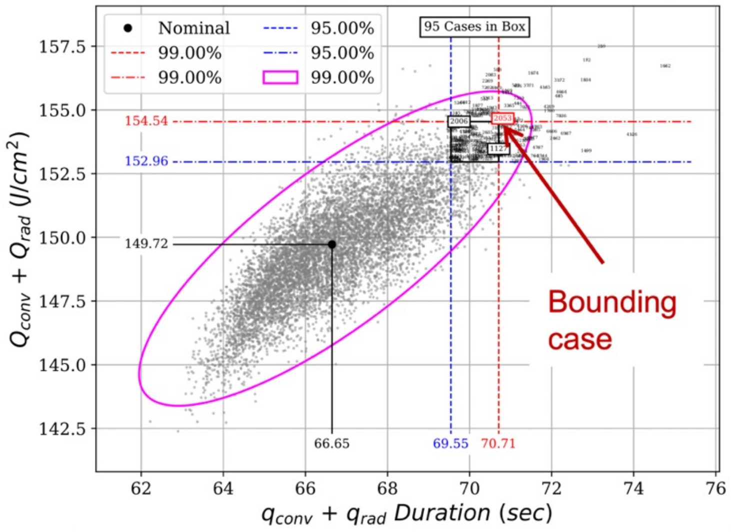
**Image Source: JPL**

# TPS Sizing Methodology

- Since TPS thicknesses were fixed to MSL design values, the goal of TPS sizing was to demonstrate that the design thicknesses were sufficient to maintain the TPS/structure bondline temperature below specified limits
- The TPS sizing approach, shown in the flow chart, accounts for various sources of uncertainty (trajectory, heating, material response)
  - These independent sources of uncertainty are RSS'ed to avoid stacked conservatism
  - Similar sizing methodology to the one used for MSL and Orion missions
- Final sized thickness is compared with the design thickness to show a sufficient factor of safety




## Identification of Bounding Trajectory




## Equation 1 – RSS'd Thickness

$$T_{RSS} = T_1 + \sqrt{(T_2 - T_1)^2 + (T_3 - T_1)^2}$$

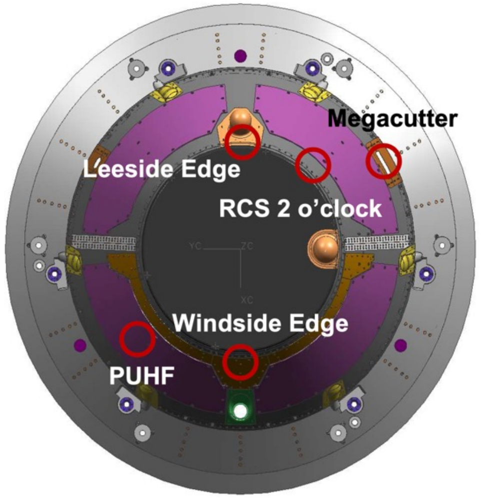
## Equation 2 – Design Factor of Safety

$$FOS_{Design} = \frac{T_{Design} - Man.Tol.}{T_{Margined}}$$

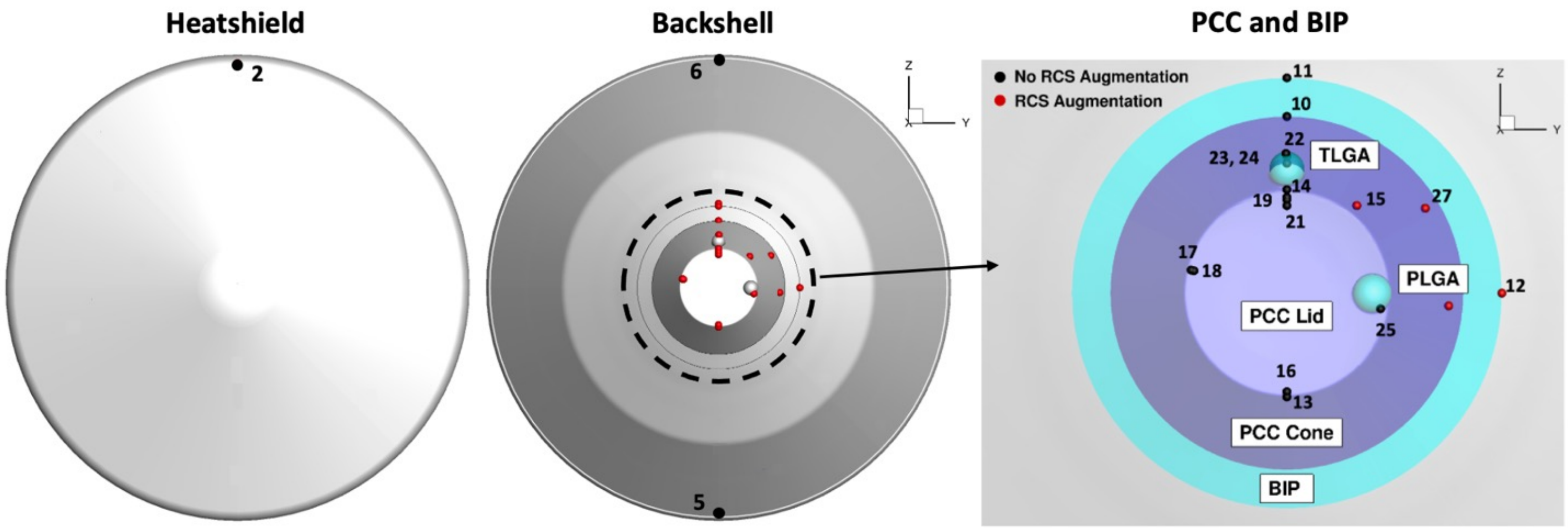
# TPS Sizing Locations

- Ablative TPS sizing is typically performed using 1D thermal response codes (NASA code FIAT used in this study)
- Many sizing locations had to be considered due to varying environments, substructure stack-up, TPS thicknesses, initial temperature and bondline temperature limits
  - 1 location on the heatshield, 2 locations in the backshell and 17 locations on the PCC/BIP
- The design thicknesses for PICA/SLA were suspected to have ample margin; therefore, worst on worst assumptions were used to reduce analysis effort
- On the PCC/BIP, more locations had to be considered because of the complex geometry, variations in structure and conditions, and suspected lower margins
  - Increases in Mars 2020 environments compared to MSL (inclusion of radiative heating)
- The paper provides a detailed discussion of the rationale and assumptions for each sizing location

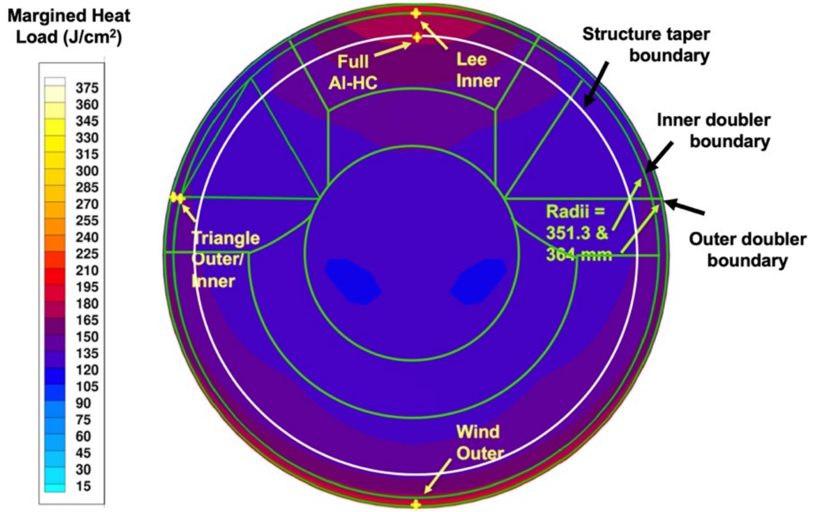
**Selection of Sizing Locations on PCC Cone**




**TPS Sizing Locations**




**Selection of Sizing Locations on PCC Lid**

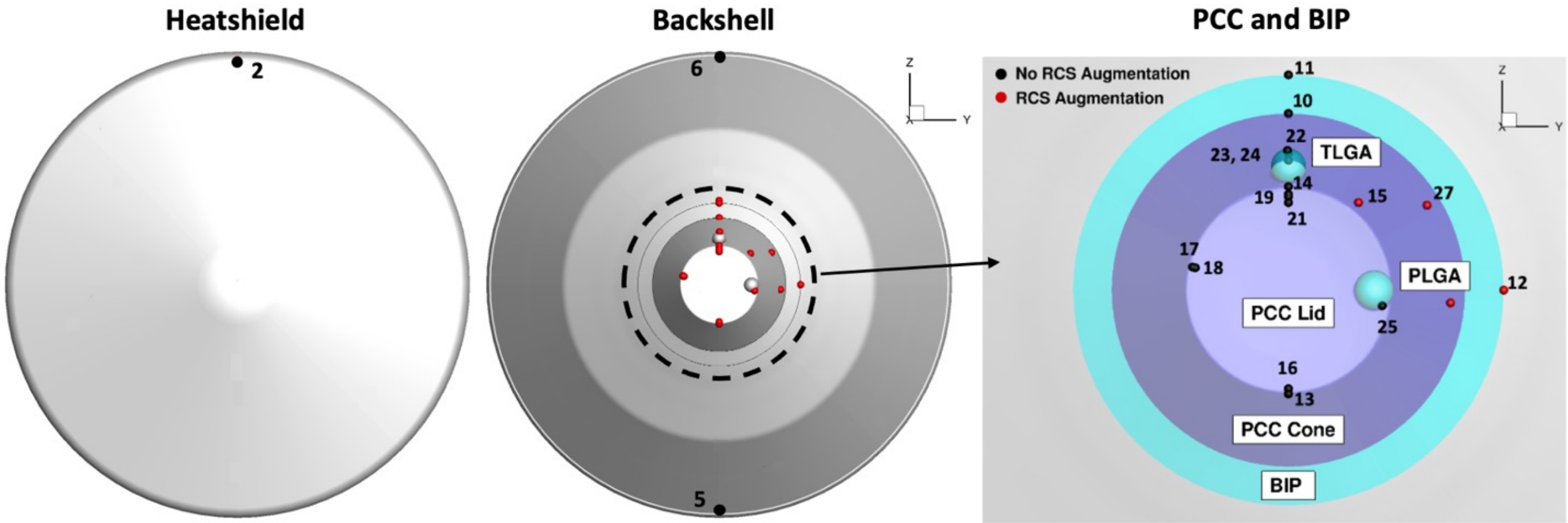


# TPS Sizing Results

- A summary of sizing results are shown here
  - Table shows the name of sizing location, its designated body point #, the design thickness, the sized thickness and the design factor of safety
- This study demonstrated that the design thickness was sufficient at all sizing locations except one
- Body point 18 (PCC Lid Trian. Inner) has a factor of safety of 1.07 (lower than 1.1 recommended by mission)
  - This was deemed acceptable given the maturity of the system and entry trajectory predictions
  - Also, this location is surrounded by regions with lower heating environments and thicker structure
  - Multi-dimensional analysis would have shown much lower temperatures due to in-plane conduction effects

**TPS Sizing Results**

| Sizing Case | Env. Body Point | Design Thick. (cm) | Sized Thick. (cm) | Design FOS |
|---|---|---|---|---|
| HS Max q | 2 | 3.05 | 2.02 | 1.52 |
| BS Seal (Wind) | 5 | 1.27 | 0.84 | 1.72 |
| BS Seal (Lee) | 6 | 1.27 | 0.80 | 1.83 |
| BIP Lee PCC | 10 | 2.45 | 2.25 | 1.20 |
| BIP Lee BS | 11 | 3.97 | 2.31 | 1.90 |
| BIP Side RCS* | 12 | 3.97 | 2.22 | 1.98 |
| PCC Windside Edge | 13 | 1.50 | 0.92 | 1.82 |
| PCC Leeside Edge | 14 | 1.74 | 1.63 | 1.18 |
| PCC RCS 2 o'clock* | 15 | 1.74 | 1.34 | 1.43 |
| PUHF Antenna | 13 | 1.29 | 0.75 | 1.93 |
| Megacutter* | 27 | 1.64 | 1.23 | 1.48 |
| TLGA | 22 | 2.50 | 2.06 | 1.34 |
| TLGA Base Lee | 23 | 1.59 | 0.61 | 2.96 |
| TLGA Base PCC | 24 | 1.59 | 0.83 | 2.14 |
| PLGA | 25 | 2.50 | 2.03 | 1.36 |
| PCC Lid Full Al-HC | 21 | 0.74 | 0.65 | 1.26 |
| PCC Lid Wind Outer | 16 | 0.96 | 0.61 | 1.76 |
| PCC Lid Lee Inner | 19 | 0.96 | 0.90 | 1.17 |
| PCC Lid Trian. Outer | 17 | 0.74 | 0.51 | 1.64 |
| PCC Lid Trian. Inner | 18 | 0.74 | 0.76 | 1.07 |

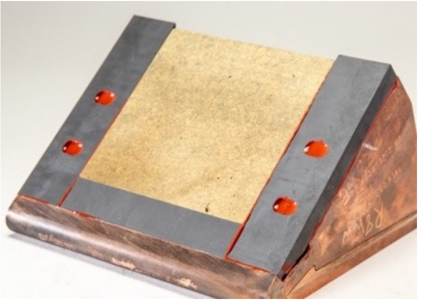


# Arc Jet Testing Overview

- A total of six arc jet test were conducted by the Mars 2020 project in the Panel Test Facility (PTF) and Interaction Heating Facility (IHF) at NASA Ames
  - Evaluate surface and in-depth discolorations that were observed during PICA manufacturing
  - Verify that the flight lot TPS materials performed as expected

| Test | TPS Material | Facility | Test Config. | Objective |
|---|---|---|---|---|
| IHF 348 | PICA | IHF 6” Nozzle | Wedge | Recession behavior of discolored PICA under peak heat flux and shear conditions |
| PTF 158 | PICA | PTF | Panel | In-depth response of discolored PICA under peak heat flux and pressure condition |
| IHF 358 | PICA | IHF 6” Nozzle | Wedge | Verification of the recession behavior of flight lot PICA under shear conditions |
| IHF 361 | PICA | IHF 13” Nozzle | Stagnation | Verification of the recession and in-depth response of flight lot PICA |
| PTF 163 | SLA-561V | PTF | Panel | Verification of the thermal response of flight lot SLA-561V and repair techniques |
| PTF 163 | Acusil-II | PTF | Panel | Verification of thermal response of flight lot Acusil-II |

**Discolored PICA Test in IHF Wedge and PTF**



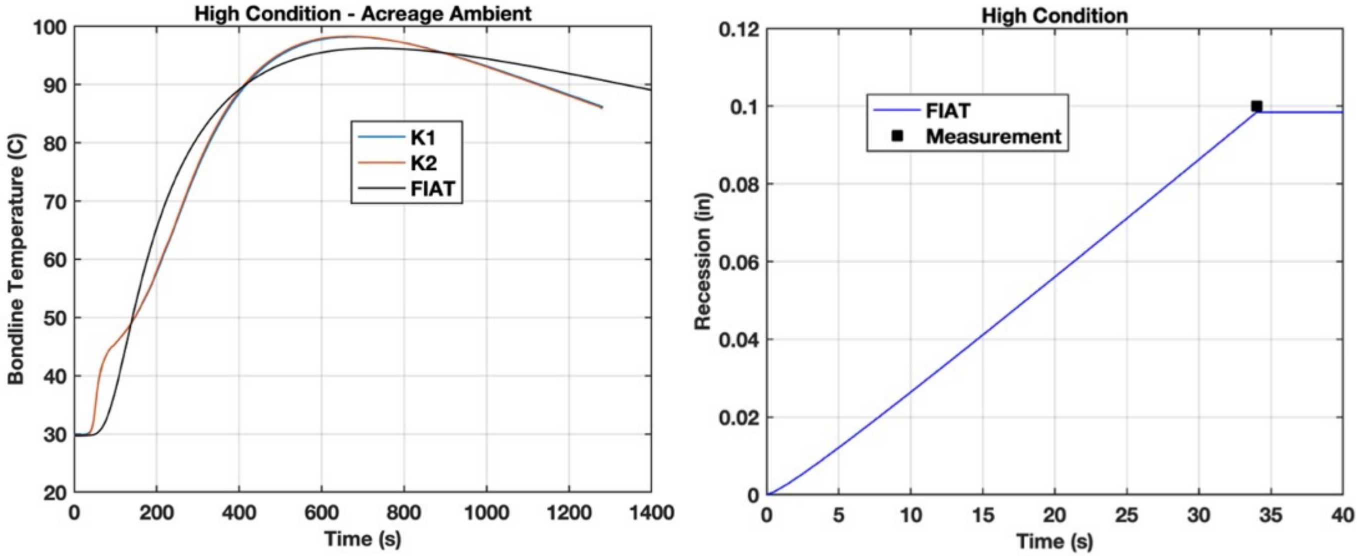
**PICA Flight Lot Test in IHF Wedge and Stagnation**

**SLA-561V and Acusil-II Flight Lot Test in PTF**

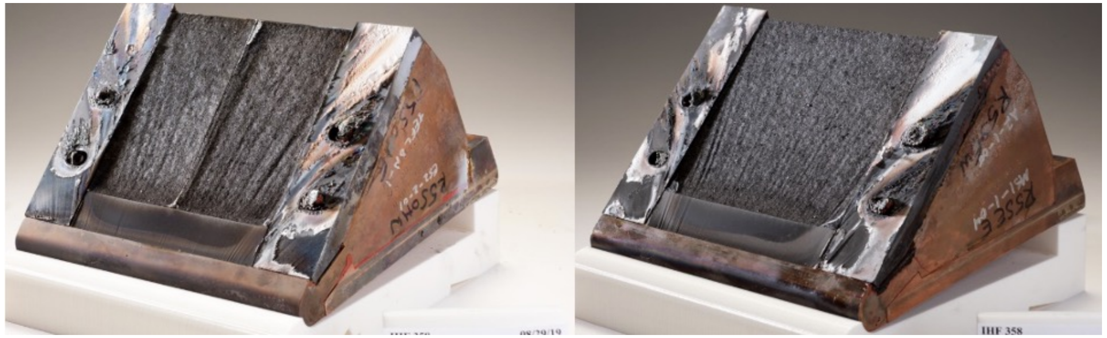
# PICA Flight Lot Testing

- Flight lot PICA material was tested in both wedge and stagnation configuration to verify the performance of the material
  - Acreage (only PICA) and Gap (RTV gap filer) models
  - Wedge testing targeted peak flight heat flux and shear
  - Stagnation testing included low and high conditions
  - All models tested successfully with no flaws/failures observed
- Verification of the FIAT thermal response model used in TPS sizing
  - PICA thermal response model predictions matched measured recession and bondline temperature data closely

**Comparison of Test Measurements with FIAT Response Model Predictions**

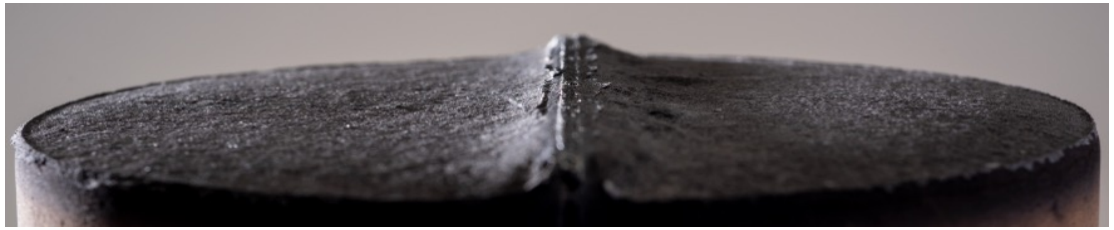



**Acreage and Gap Models in Wedge Configuration**



**Acreage and Gap Models in Stagnation Configuration**

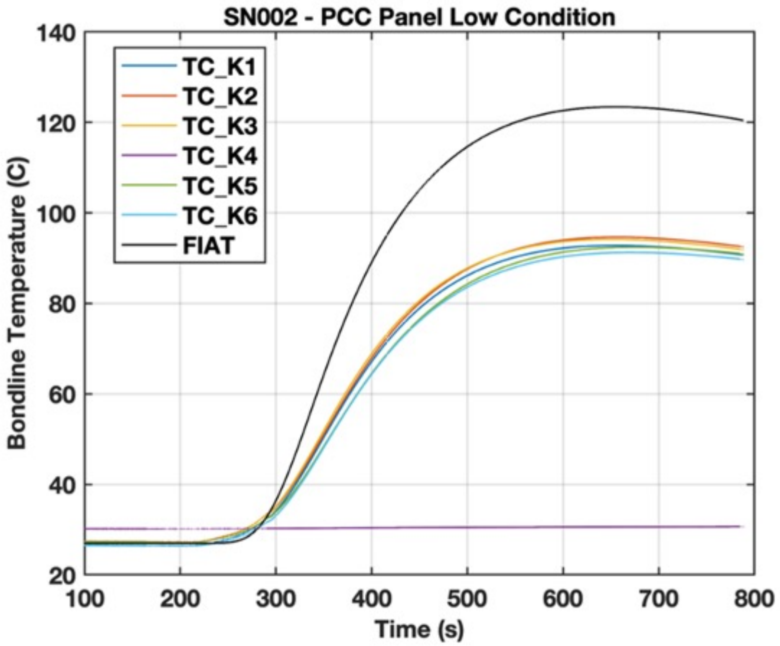
**RTV Gap Filler Swelling**



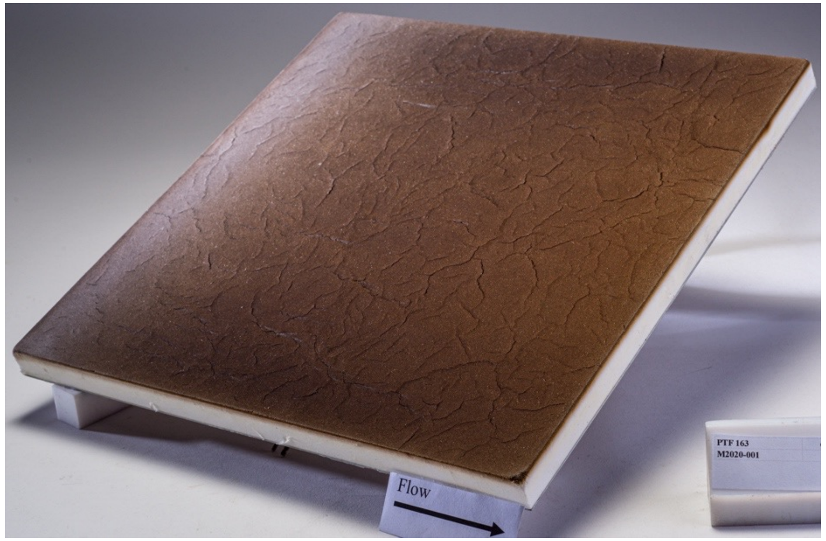
# Acusil-II Flight Lot Testing

- Flight lot Acusil-II material was tested in a panel configuration in the PTF arc jet facility
  - Low and high conditions representative of predicted flight heating range
  - Two structure stack-ups, representative of the flight vehicle design, were tested
  - The material performed as expected and no flaws or failures were observed
- Comparison of bondline temperature data with FIAT predictions showed that the Acusil-II thermal response model used in TPS sizing is conservative

**Comparison of Response Model Predictions with Measured Temperature Data**



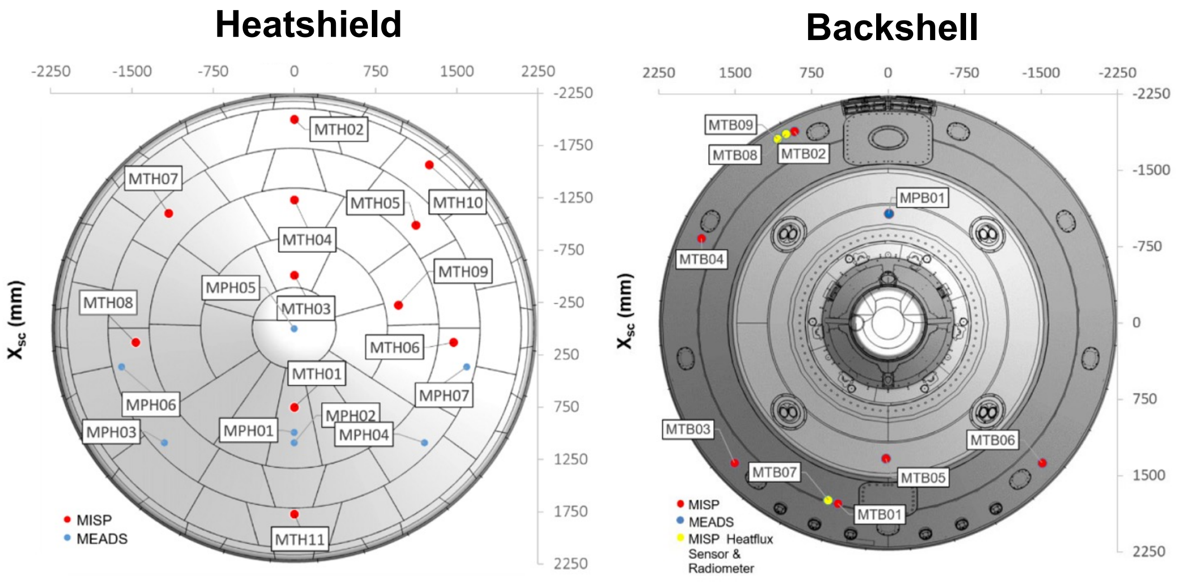

**Acusil-II at the Low Condition**

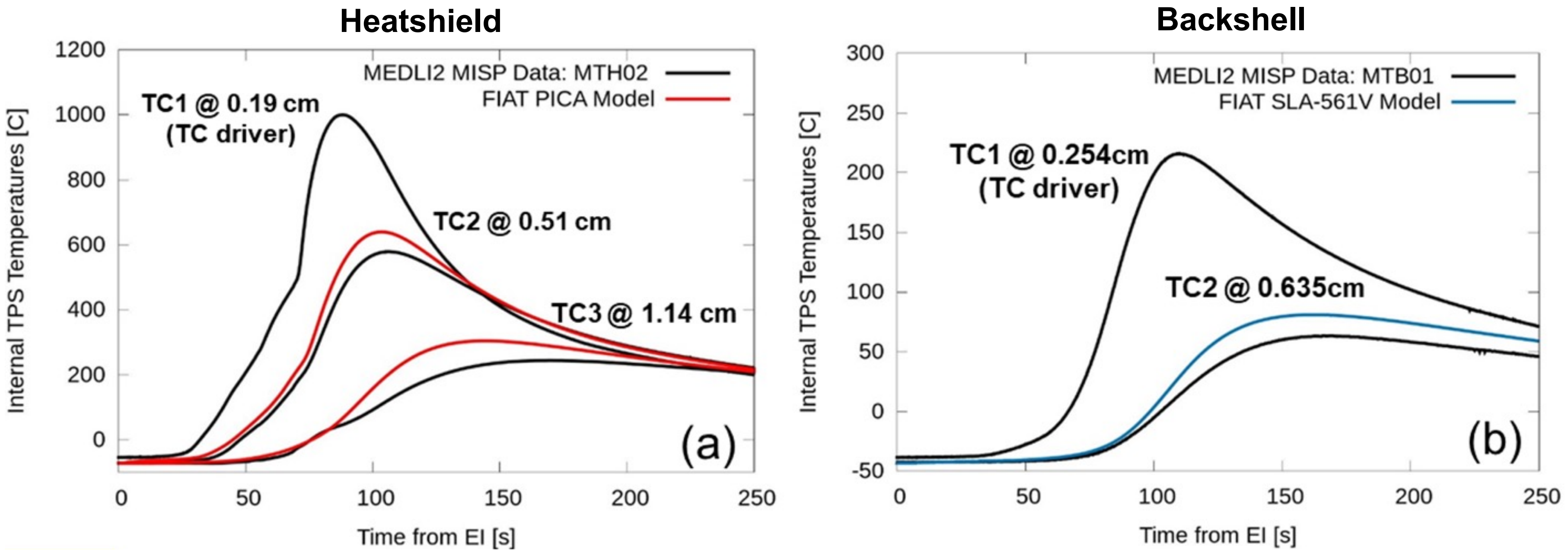



**Acusil-II at the High Condition**

# Comparison of Model Predictions with Flight Data

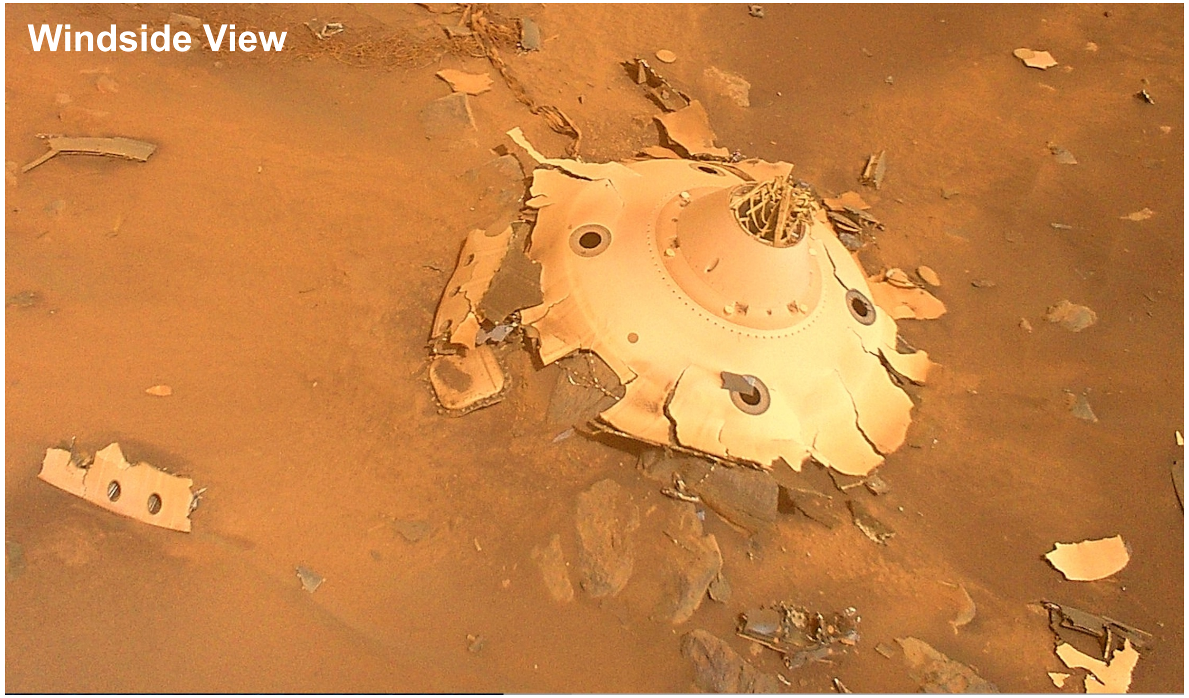
- The aeroshell was instrumented with pressure, temperature and heat flux sensors (MEDLI2)
  - Thermocouples (TC) were installed in TPS plugs at various locations
  - 11 PICA plugs in the heatshield (MTH) and 6 SLA-561V plugs in the backshell (MTB) with thermocouples at different depths
- Figure below shows a comparison of thermal response model predictions with flight temperature data
  - Using shallowest TC as the boundary condition to eliminate uncertainties in heating environments
- Demonstrates that the PICA and SLA thermal response models used in TPS sizing are conservative and sized thicknesses were sufficient
- A more complete review of MEDLI2 data and analysis is provided in other published work (see references in the paper)

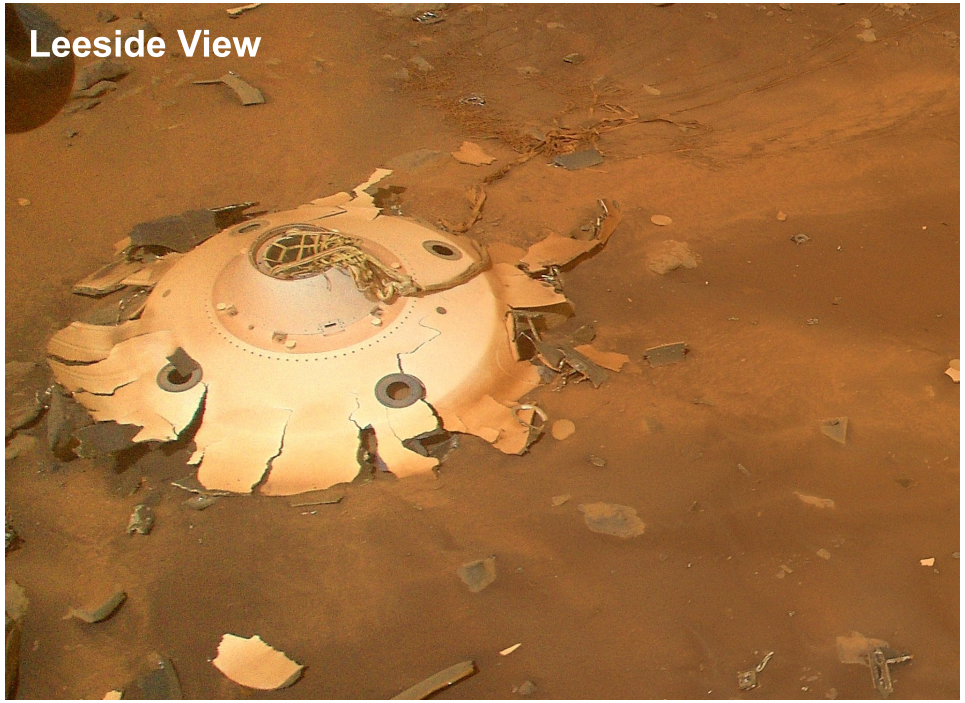


# Post Flight Images of the Backshell on Mars

- The Ingenuity helicopter recently captured images of the backshell crash site
- Examination of these images will allow the team to look for any TPS anomalies
- Examination of TPS color and char pattern will provide information on distribution of heating beyond MEDLI2 data available at discrete locations
  - The char color (SLA paint) seems to be consistent with nominal environments (no margins)
  - Darker color on the leeside edge is consistent with predicted location of highest heating on the backshell




**More images available at: https://mars.nasa.gov/mars2020/multimedia/raw-images/**

# Conclusions

- TPS sizing analysis, accounting for various sources of uncertainty, demonstrated that the design thicknesses of Mars 2020 TPS materials were sufficient to shield the aeroshell against predicted entry heating environments
  - A total of 20 sizing locations were investigated

- TPS testing in NASA arcjet facilities demonstrated that the flight-lot TPS materials performed as expected and their response was conservatively predicted by the thermal response models used in TPS sizing

- TPS testing also demonstrated that various anomalies/non-conformances encountered during TPS manufacturing and assembly, and the implemented repair techniques, did not negatively alter the TPS performance

- Comparison of the flight temperature data with analytical predictions showed that the thermal response models used in TPS sizing were conservative

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