

LESSONS LEARNED FROM AEROTHERMAL FLIGHT DATA ON NASA MARS ENTRY VEHICLES

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ABSTRACT

The NASA Mars Science Laboratory (MSL) and Mars 2020 entry vehicles included temperature measurements inside and direct heat flux on the surface of the thermal protection system (TPS) material. The instrumentation was included to begin addressing predictive capabilities for aerodynamic heating and ablative TPS material response. The MSL aeroshell included temperature measurements at seven heatshield locations, from which total aerodynamic heating was reconstructed. The Mars 2020 instrumentation suite included eleven heatshield measurement locations and new backshell measurements at nine locations: six with temperature sensors, two with sensors to directly measure total heat flux, and one to measure radiative heat flux. Both instrumentation suites returned full sets of data, with all temperature sensors nearest to the surface surviving entry, indicating minimal material recession. Heatshield boundary layer transition (BLT) was observed for both vehicles prior to the time of peak heating, with transition starting near the shoulder and progressing towards the stagnation area. MSL's higher speed on approach to Mars resulted in higher total heating compared to Mars 2020, with the maximum occurring near the heatshield's lee-side shoulder. The Mars 2020 backshell heating data indicate significant contributions from shock layer radiation. Aerodynamic heating calculations without ablative blowing are in family with reconstructed heating. The paper covers the instrumentation, BLT and reconstructed heating on both heatshields, backshell heating for Mars 2020, TPS performance, and predicted versus reconstructed heat fluxes. Opportunities for improved design approaches for future Mars missions are discussed, especially for the upcoming Mars Sample Return mission.

Index Terms— Mars Science Laboratory, Mars 2020, MEDLI, MEDLI2, Aerothermodynamics, Boundary Layer Transition, Turbulent Heating, Shock Layer Radiation

1. INTRODUCTION

NASA's Curiosity and Perseverance rovers were successfully delivered by the Mars Science Laboratory (MSL) entry system in 2012 and by the Mars 2020 entry system in 2021,

respectively. The rovers are the largest payloads delivered to the Martian surface to date. Both entry vehicles were based on the same capsule geometries: a 4.5-meter diameter, spherically-blunted conical heatshield with a half-angle of 70 degrees, and a three-segment backshell. The heatshield shape originally was developed for the two Mars Viking landers, which landed successfully in 1976, and has been used for every NASA Mars lander mission since then. Prior to the MSL mission, the only heatshield thermal protection system (TPS) material that was used was Super Lightweight Ablator (SLA-561V). A total of seven successful Mars landers have used a SLA-561V heatshield TPS. However, prior to the MSL mission, few attempts were made to equip the flight TPS with sensors that would allow a reconstruction of the aerodynamic heating and an assessment of material performance [1, 2].

The MSL entry system was the largest Mars entry system to date, which resulted in the prediction of turbulent conditions for most of the hypersonic entry phase and a substantial increase in the predicted aerodynamic heating. MSL ground testing results eventually led to the decision to use the Phenolic Impregnated Carbon Ablator (PICA) material for the heatshield [3]. Due to the predicted turbulent aeroheating environments and the first-time use of PICA for Mars, the Mars Entry, Descent, and Landing Instrumentation (MEDLI) hardware was proposed for the MSL heatshield in order to collect internal TPS temperatures during flight, from which the total aerodynamic heating at the TPS surface could be reconstructed using an analytical model of the PICA ablative thermal response. After the successful MSL mission, which included a full set of flight data that confirmed turbulent heating, the Mars 2020 aeroshell was designed as a rebuild of MSL and included an augmented MEDLI2 suite that included both heatshield and backshell aerothermal measurements. This paper reviews the MEDLI and MEDLI2 aerothermal instrumentation, flight data products, comparisons to computational fluid dynamics (CFD) results, and general lessons learned and possible opportunities to reduce conservatism for future Mars entry vehicle TPS design. Detailed discussions of MEDLI [4, 5, 6, 7] and MEDLI2 [8, 9, 10, 11, 12] are available, including in-depth analysis of the aerothermal data and pressure measurements that were used to reconstruct the atmospheric density profile and entry vehicle attitude.

2. MSL AND MARS 2020 AEROTHERMAL INSTRUMENTATION

The MSL and Mars 2020 aeroshells are shown in Figure 1 and Figure 2. Both entry vehicles were designed to fly at an angle of attack near 16 degrees near the time of peak heating, which placed the stagnation region on the heatshield's windward conical flank rather than on the spherical nose. On both heatshields, plugs of PICA were equipped with one or more thermocouples and inserted into the heatshield. The thermocouples measured temperature throughout the atmospheric entry sequence. The MSL heatshield included seven temperature measurement locations (T1-T7) and the Mars 2020 heatshield included eleven (MTH01-MTH11). The MEDLI objectives were to measure in-depth temperatures, inversely reconstruct heating at the surface, detect boundary layer transition, and demonstrate positive thermal margin for the TPS. An objective to measure material recession was not met, but recession for both missions was informed by near-surface thermocouples.

An analytical model of PICA thermal response was combined with the thermocouple temperature measurements to inversely estimate total surface heating [6, 11]. The plug locations were distributed in order to spatially and temporally reconstruct the total aerodynamic heating, convective (q_{conv}) plus absorbed radiative (q_{rad}), at the TPS surface. This reconstruction process accounts for uncertainties in several parameters, including material properties, thermocouple locations, and the temperature measurements themselves. Special interest was given to capturing the onset of BLT, since it was expected to occur and it was the reason for designing both heatshields to withstand fully-turbulent conditions [7].

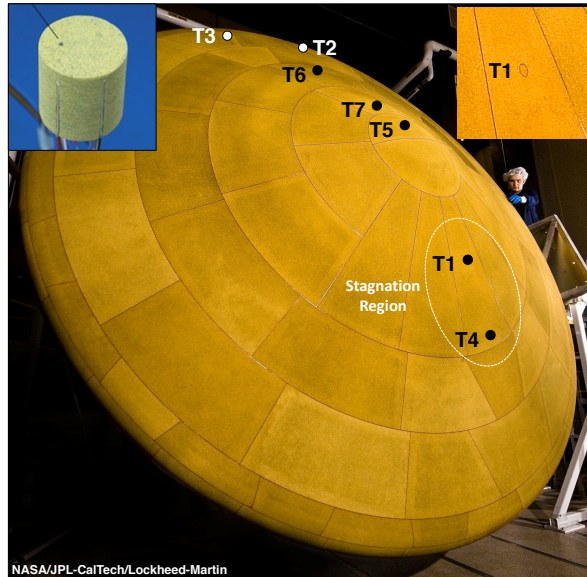
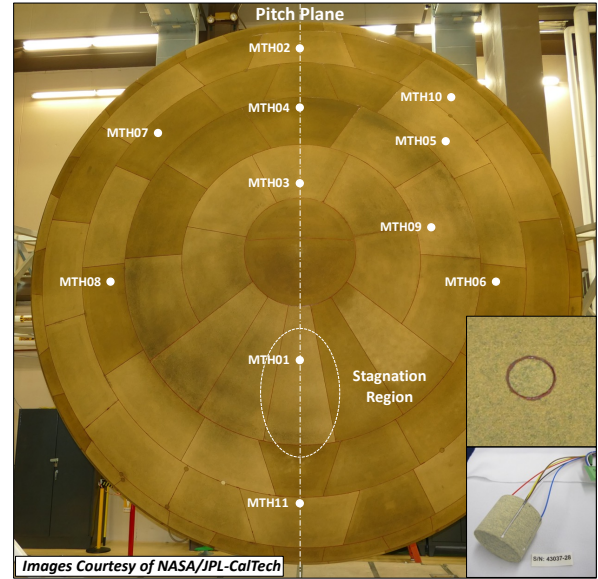
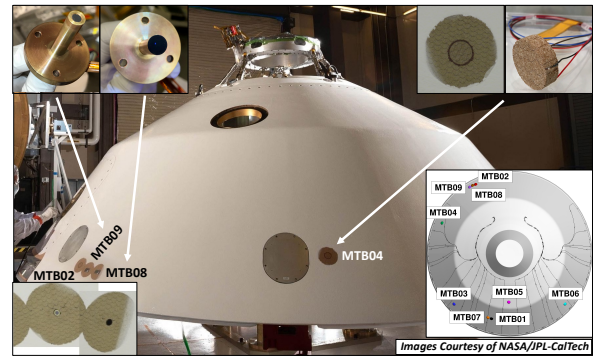


Fig. 1. MSL PICA heatshield and MEDLI2 aerothermal instrumentation locations [6, 7]



(a) PICA Heatshield



(b) SLA-561V Backshell (painted, not all sensors are shown)

Fig. 2. Mars 2020 aeroshell and MEDLI2 aerothermal instrumentation locations

On the Mars 2020 backshell, new aerothermal measurements were added to the SLA-561V TPS: six thermocouple plugs (MTB01-MTB06, only MTB02 and MTB04 are visible in Figure 2), two direct total heat flux measurements (MTB07 and MTB08), and a radiometer (MTB09) to measure the radiative component of heating. This paper focuses on the total heating reconstructed at the thermocouple plug locations for both missions, but it also discusses the direct measurements. Although not discussed here, surface pressure was measured on both heatshields and the Mars 2020 backshell. The pressure measurements were used to reconstruct the entry trajectory, including vehicle attitude and atmospheric density [5, 10]. Analysis and testing is ongoing within NASA in order to continue refining the data products derived from all MEDLI2 measurements.

3. MSL AND MARS 2020 TEMPERATURE DATA AND RECONSTRUCTED HEATING

Table 1 shows key entry trajectory parameters for both missions. The full atmospheric entry trajectories were reconstructed from heatshield pressure measurements and other on-board sensors [5, 10]. The different entry conditions, landing dates, and landing locations all contributed to different entry trajectory profiles for each mission. The as-flown Mars 2020 entry trajectory had a lower entry speed compared to MSL, which was expected to result in lower aerodynamic heating and dynamic pressure for Mars 2020, even though the mass was higher.

Table 1. MSL and Mars 2020 entry and landing conditions

	MSL	Mars 2020
Day of landing	6 Aug. 2012	18 Feb. 2021
Entry mass (kg)	3153	3369
Entry speed (m/s)	5845	5334
Inertial flight path angle (deg)	-15.48	-15.48
Dynamic pressure (Pa)	15,915	14,685
Rover mass (kg)	899	1025
Landing site	Gale Crater	Jezeru Crater
Landing latitude (deg)	-4.59	18.44
Landing longitude (deg)	137.44	77.45

The expectation was that heatshield BLT would occur for both entries and that peak heating would be under turbulent conditions. There was no pre-flight analysis aimed at predicting the timing of BLT, so the TPS was designed to withstand environments based on turbulent calculations along the entire entry trajectory. Figure 3 shows the measured temperatures at select thermocouple locations closest to the surface: the stagnation region (T1 and MTH01), downstream of the heatshield nose (T7 and MTH03), and on the leeside shoulder where turbulent heating was expected to be the highest (T2/T3 and MTH02). No thermocouple data channels dropped out, which means that the PICA recession never reached the top-most thermocouple depths at any location (2.54 millimeters for MSL, 1.905 millimeters for Mars 2020). Specific recession sensors for MEDLI did not return conclusive data. The abrupt changes in the temperature curve slopes indicate BLT at the nose and leeside shoulder locations, but not at the stagnation location, as expected. Prior to BLT, the temperatures at the stagnation location exceed the other temperatures due to having higher laminar heating. The MSL T7 location reached the highest temperature even though the thermocouple was at a slightly deeper location compared to the Mars 2020 thermocouples. This result is believed to be due to MSL's higher entry speed leading to higher convective heating.

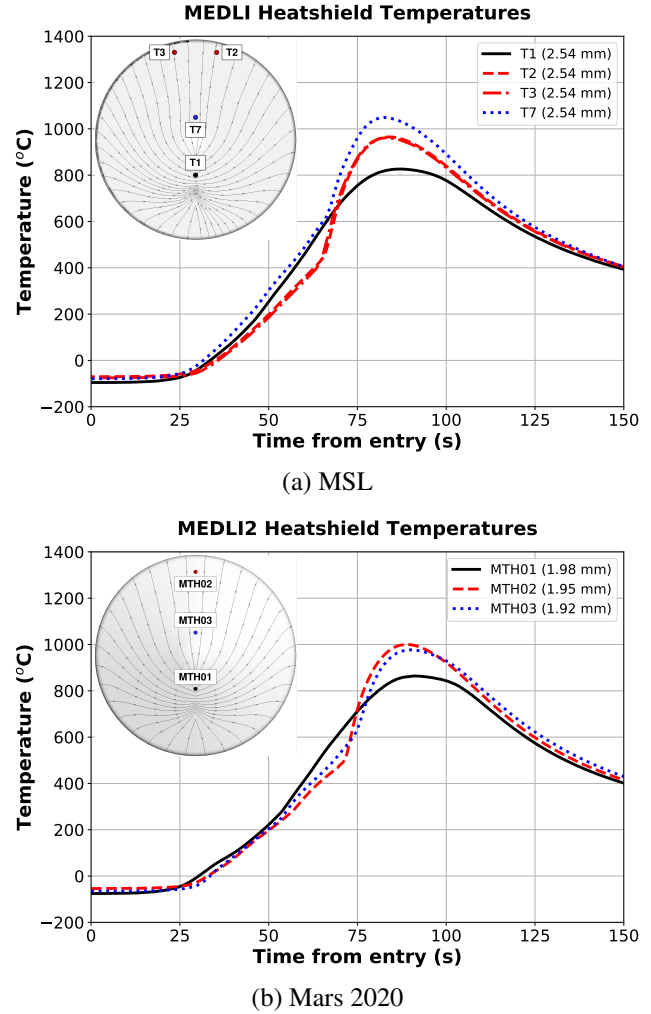


Fig. 3. Measured heatshield temperatures at select near-surface thermocouples

The thermocouples installed at deeper locations in the plugs allowed for the assessment of the TPS thermal response. For both missions, the analytical models over-predicted the measured temperature data, confirming that the PICA and SLA-561V thermal response models used in TPS sizing and design were conservative [6, 8]. The MEDLI2 reconstruction included refined response models based on material property testing of the flight materials. These models matched the ground and flight data more closely than the design models, and therefore were used in surface heating reconstruction [13]. A similar approach is recommended for future missions. A major source of uncertainty in the heatshield reconstruction was the impact of NuSil coating that was sprayed on the heatshield for contamination control. A thermal response model for NuSil-coated PICA combined with better characterization of the amount of NuSil on the flight heatshield will significantly reduce reconstruction uncertainty for MEDLI/MEDLI2 and future missions.

Table 2 shows the estimated times of BLT for all heatshield measurement locations, in order of occurrence. Transition was not detected at measurement locations in the stagnation area, as expected. The first areas to experience BLT were located on the shoulder along the pitch plane and furthest from the stagnation area. Transition progressed from the shoulders inward towards the heatshield nose within a few seconds.

Table 2. Estimated BLT onset times

MEDLI Location	MEDLI BLT (seconds)	MEDLI2 Location	MEDLI2 BLT (seconds)
T3	63	MTH02	71
T2	64	MTH04	72
T6	65	MTH03	73
T7	65	MTH10	74
T5	73	MTH05	75
T1	–	MTH07	76
T4	–	MTH09	77
		MTH06	79
		MTH08	81
		MTH01	–
		MTH11	–

Reconstructed total heating at select locations is shown in Figure 4 [6, 9, 11]. Recession was not included in the analysis, since the thermocouples closest to the surface survived the entry. Also, the analytical model for MEDLI2 reconstruction was tuned to the specific flight TPS material. Overall, the trend for similar plug locations is that MSL experienced earlier BLT and higher total heating, mainly due to MSL's higher entry speed. Early in the entry trajectory and prior to BLT, the highest heating occurred in the stagnation area (T1 and MTH01). After BLT, the thermal plugs on the opposite side of the stagnation area (T2/T3 and MTH02) experienced the highest heating. The T2/T3 and MTH02 plugs were situated near the location of maximum predicted turbulent heat flux. The reason for the spikes in the T2/T3 and MTH02 heating curves is not known at this time. Possible causes include a transitional overshoot prior to reaching turbulent conditions, an unknown thermocouple response to the rapid temperature rise during BLT, or a numerical artifact of the reconstruction.

Backshell reconstructed and measured heating are shown in Figure 5. The plug locations on the windward side (bottom half) were expected to be in attached flow during entry, with higher convective heating. However, the highest heating occurred at the MTB02 location, which was expected to be in separated flow for most of the entry sequence. The fact that the MTB02 heating is higher than it was at locations on the windward side is suspected to be the result of higher shock layer radiation. The cause of the double peak in the MTB02 curve is not known at this time. The lowest heating was at MTB05 on the second backshell cone. Data from closely-situated sensors on the windside (MTB01 and MTB07) and

leeside (MTB02, MTB08, and MTB09) allow comparisons between reconstructed and directly-measured heating, as well as proportions of convective and radiative heating. There is a difference of 1.2 W/cm^2 between the peak reconstructed heating at MTB01 and measured total heating at MTB07. The direct heat flux measurement is complicated by the fact that the surface temperature is different than the surrounding TPS temperature. A similar difference exists between the reconstructed and measured heating at MTB02 and MTB08. The radiometer reading shows that shock layer radiation is the cause of most of the total heating. However, the reading was subject to signal attenuation due to ablation product deposition on the sapphire window. Therefore, the radiometer measurement is viewed as a lower bound until further testing can be completed [8].

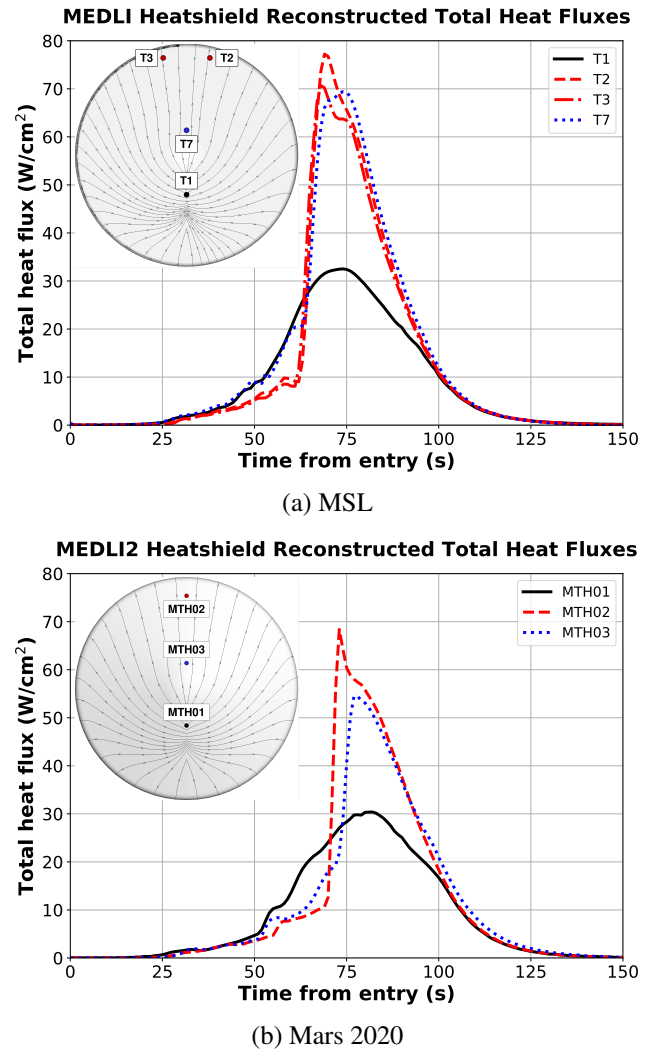
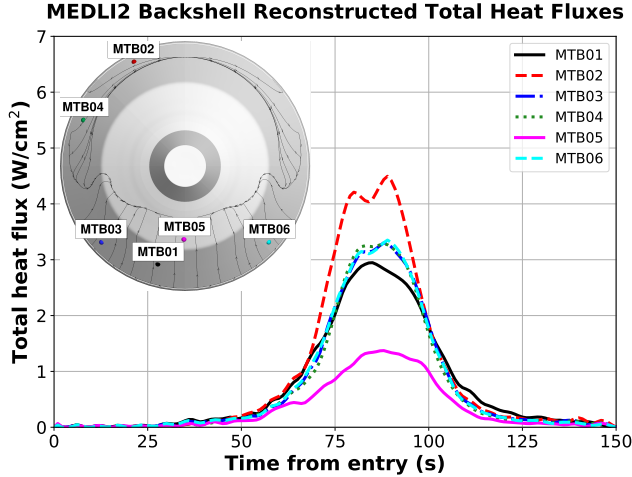
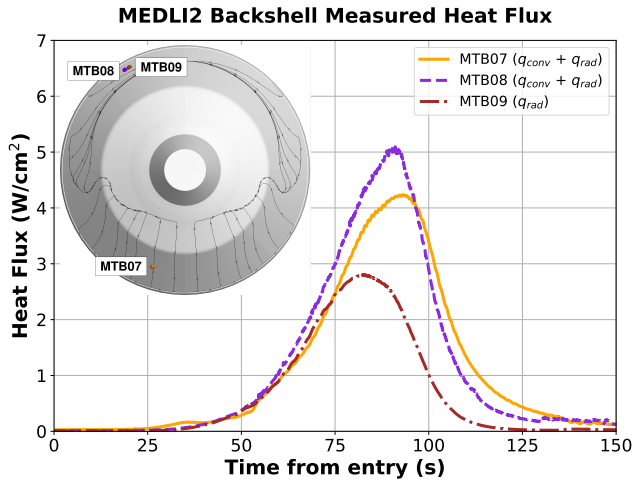


Fig. 4. Reconstructed heat flux at select heatshield locations



(a) Thermocouple plug locations



(b) Direct measurement locations

Fig. 5. Mars 2020 backshell heating at select locations

4. COMPARISONS OF CFD AND RECONSTRUCTED HEATING

Conditions along the reconstructed entry trajectories were selected for CFD analysis. The same tools that were used for pre-flight aeroheating analysis were used as as-flown conditions: the *Langley Aerothermodynamic Upwind Relaxation Algorithm* (LAURA) [14] Navier-Stokes flowfield solver and the *High-Temperature Aerothermodynamic Radiation Algorithm* (HARA) radiation code. LAURA provides convective heat flux and HARA provides radiative heat flux using a three-dimensional ray tracing algorithm [15]. The LAURA calculations shown here assume a *fully-catalytic* surface, including recombination of CO_2 and CO at the TPS surface, whereas the design environments assumed a more conservative *super-catalytic* surface (full recombination of all species to their freestream mass fractions). The fully-catalytic conditions are

believed to better represent the gas-surface interactions at the TPS surface during flight. Both laminar and turbulent calculations were generated with LAURA at the reconstructed freestream conditions. The turbulent calculations were obtained using the Cebeci-Smith algebraic model [16]. The converged LAURA flowfield was used by HARA to calculate shock layer radiation. Since there is no indication of significant recession at any of the heatshield thermal plugs, no roughness augmentation effects are applied to the LAURA turbulent convective heating. The heat flux comparisons are shown only for locations where the in-depth TPS temperatures were measured. There is ongoing analysis to better refine the inverse heating estimation uncertainties and the raw data products where heat flux was directly measured.

Comparing CFD to reconstructed heating is approximate, due to different assumptions involved in the analyses. The inverse reconstruction method produces the convective plus absorbed radiative heating, $q_{conv} + \alpha_w q_{rad}$, where α_w is the absorptivity factor, and also includes the cooling effects of pyrolysis gas blowing. The LAURA cases are non-blowing and use a radiation-equilibrium wall temperature (T_w) calculated using $q_{conv} = \sigma \epsilon T_w^4$, where σ is the Stefan-Boltzmann constant and ϵ is the surface emissivity. This equilibrium temperature differs from the actual surface temperature. Finally the HARA results were not adjusted with an estimated absorptivity factor. Future analysis will include LAURA calculations coupled with a material response model, a method that results in a prediction of surface temperature.

Figure 6 shows reconstructed heating compared to LAURA and HARA results for the stagnation region, where BLT was not expected nor was it detected in the temperature data. The reconstructed heating curves include the 95% confidence interval, based on uncertainty analysis of the temperature data and material response [11]. Laminar and turbulent calculations were generated with LAURA, but no differences in predicted heating were expected for this location. The general trends of the calculated heating are as follows. First, the prediction for both entries is that convective heating constitutes the majority of the total heating. Second, the predicted total heating qualitatively matches the reconstructed curves, with some difference in magnitude prior to peak total heating. After the time of peak total heating, when the calculated radiative heating starts to increase, the differences between the calculated and reconstructed total heating decrease. The calculated maximum heating values are within 11% of the reconstructed values, with the MSL predicted peak heating higher than the reconstructed heating, and vice versa for Mars 2020 conditions. Maximum design heating values are shown and exceed the as-flown values, as is the case for all locations.

Comparisons for the heatshield shoulder area are shown in Figure 7. This region is where BLT was expected and observed, and turbulent convective heating was predicted to be near the highest of any heatshield location. Again, prior to BLT, the laminar predicted total heat flux is low, but still

higher than the reconstructed heating. Immediately after BLT, the reconstructed heating increases by a factor of 7 to 8 above laminar heating. After BLT, the turbulent LAURA/HARA total heating better matches the reconstructed heating qualitatively and quantitatively.

The differences between the reconstructed and CFD-based heating could be caused by a number of items, such as unknown uncertainties in the inverse reconstruction and parametric or model form uncertainties in the CFD results. Thus, it is difficult to pinpoint the main reason for discrepancies between reconstructed and predicted heating. Possible causes on the CFD side include uncertainties in surface catalysis, turbulence modeling, and assumed wall temperature. Nevertheless, the general LAURA/HARA agreement is encouraging from a predictive capability standpoint. Additional detailed investigations of all Mars 2020 data products and more in-depth CFD calculations are forthcoming.

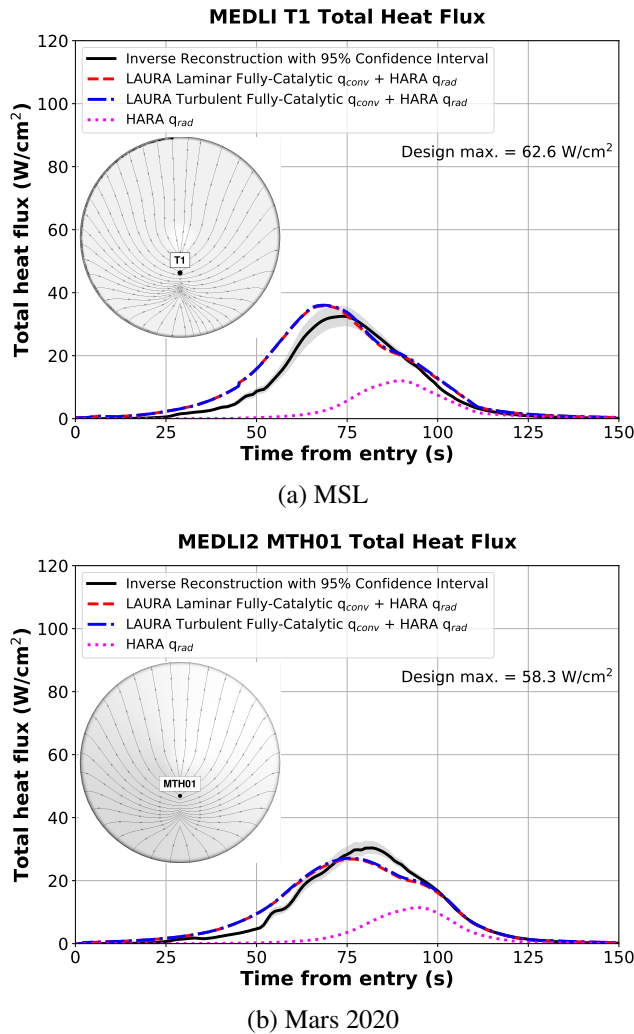


Fig. 6. Reconstructed and CFD heat fluxes in heatshield stagnation region

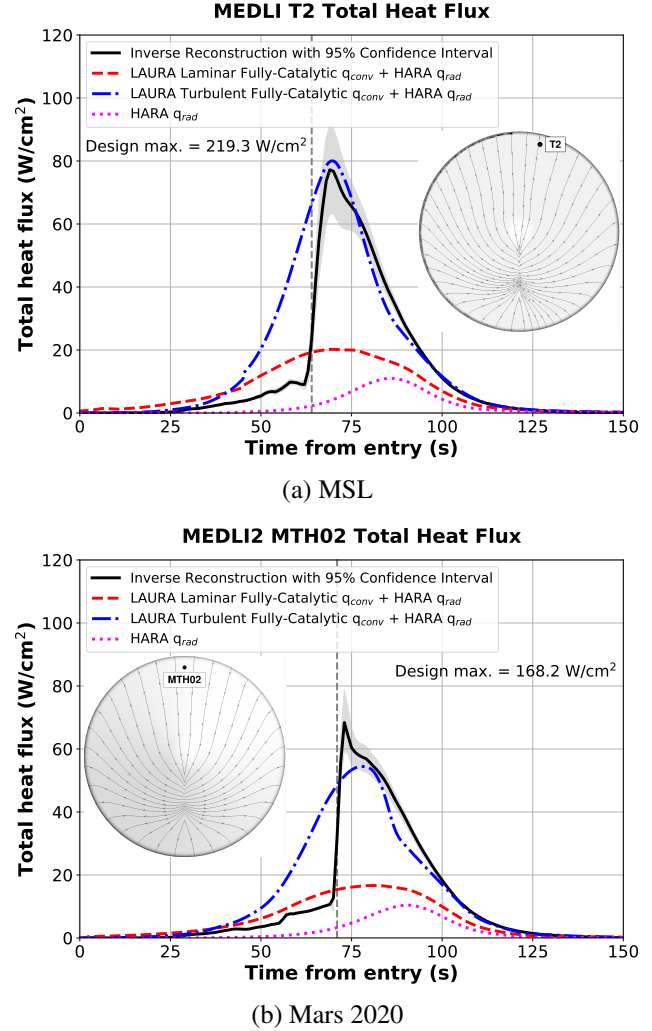


Fig. 7. Reconstructed and CFD heat fluxes in heatshield lee-side shoulder region

Comparisons between reconstructed Mars 2020 backshell heating and laminar LAURA/HARA results are shown in Figure 8 at two locations: the outer conical surface at windside (MTB01) and leeside (MTB02) points. The MTB01 location was in predicted attached flow, which was expected to result in higher convective heating compared to other measurement locations. However, the total reconstructed heating is higher at the MTB02 location, presumably due to the effects of shock layer radiation. The CFD results indicate that radiative heating constitutes the vast majority of the total heating, especially at MTB02. In fact, the HARA radiative heating alone is in family with the reconstructed total heating.

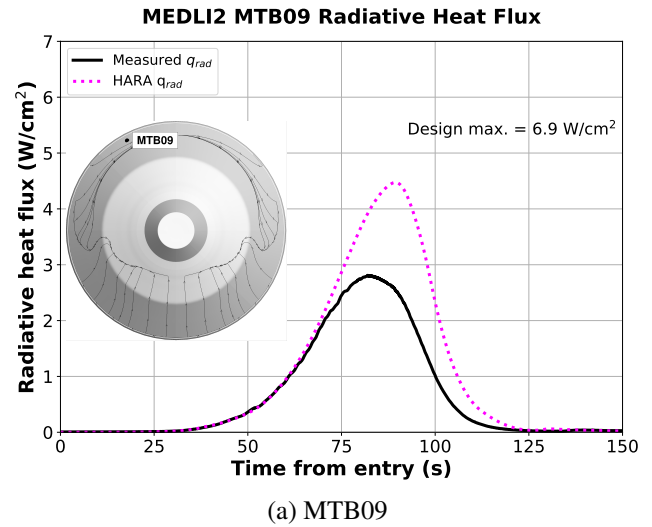
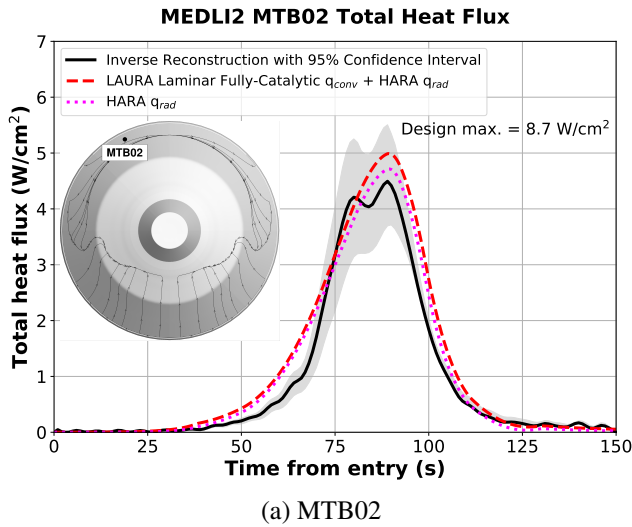
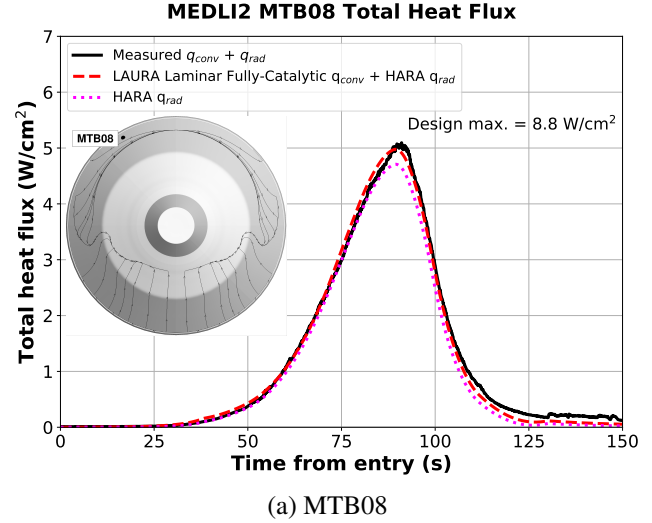
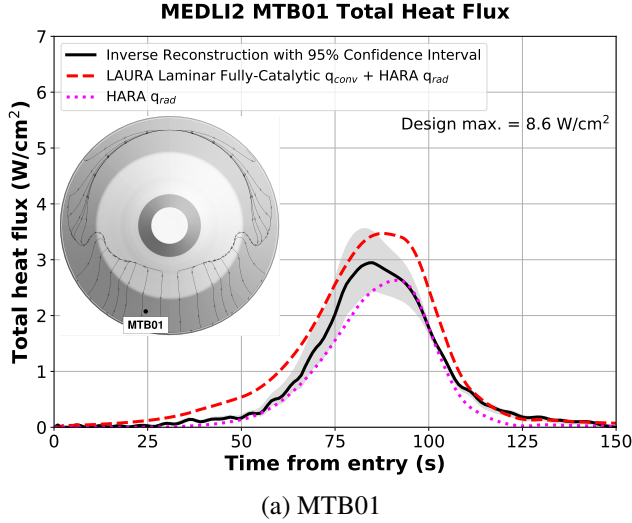


Fig. 8. Mars 2020 reconstructed and CFD heat fluxes on backshell

Fig. 9. Mars 2020 measured and CFD heat fluxes on backshell

Results at MTB08 (measured total heating) and MTB09 (radiometer) are shown in Figure 9. The LAURA/HARA result matches the MTB08 measured total heating quite well throughout the entry sequence. Also, the prediction is that almost all heating is from shock layer radiation. The initial result from the radiometer is that the maximum radiative heating was near 2.8 W/cm^2 at MTB09, using the actual field of view. The HARA predicted maximum at MTB09 is 4.5 W/cm^2 . The HARA radiative heat flux matches the measurement early in the trajectory, perhaps supporting the possibility of heatshield ablation products affecting the radiometer measurement later in time. For both the heatshield and backshell, the reconstructed heating levels and new CFD analysis show as-flown aerothermal environments that are well below the design values [7, 9], which indicates opportunities for reducing conservatism in the analysis and uncertainties.

5. CONCLUSIONS

Instrumentation on MSL and Mars 2020 successfully recorded in-depth temperature at multiple heatshield locations, from which convective plus absorbed radiative heating was reconstructed. The addition of backshell measurements for MEDLI2 informed both total heating and relative magnitudes of convective and radiative heating. The entry vehicles' large size and high mass led to heatshield boundary layer transition first near the leeside shoulder, followed by locations closer to the vehicle nose. Transition occurred for 5 of the 7 MEDLI heatshield locations and 9 of the 11 MEDLI2 locations, the exception being the stagnation area. Turbulent heating reached peak values in the leeside shoulder area for both heatshields. Heatshield geometries like MSL and Mars 2020 will experience transition, even earlier in the entry sequence with higher ballistic coefficient or steeper flight path

angle. It is recommended that future mission analysts consider heatshield TPS mass savings by incorporating BLT in the design environments, rather than using fully-turbulent conditions. Also, mass savings may be possible with a heatshield of variable TPS thickness tailored to the environments, rather than a uniform thickness. On the backshell, the reconstructed total heating results indicate that the highest magnitudes occurred in areas that were predicted to be in separated flow, presumably because of shock layer radiation. The MEDLI2 radiometer measurement showed that the majority of heating is from radiation.

Computational fluid dynamics calculations on the reconstructed entry trajectories compare favorably with the data, resulting in improved confidence in aerodynamic heating predictive methods. Prior to heatshield transition, laminar calculations tend to over-predict the low reconstructed heating. It is recommended that Direct Simulation Monte Carlo methods be used for the early portion of the heat pulse to improve high-altitude predictions. After transition, smooth-wall algebraic turbulence model convective heating, with a fully-catalytic surface, plus radiative heating is in family with reconstructed heatshield heating where transition occurred. Continued use of algebraic turbulence models for attached flow convective heating is recommended, as is the use of a fully-catalytic surface since it is more realistic than super-catalytic. Future mission designers should re-evaluate the use of surface roughness augmentation of heatshield turbulent convective heating, given the results from smooth-wall predictions and little evidence in the data. For the backshell, laminar fully-catalytic convective plus radiative heating is consistent with reconstructed and measured total heating. Calculated radiative heating exceeds the radiometer measurement, which likely is impacted by ablative products coating the sensor window. Therefore, for entry vehicle geometries similar to MSL and Mars 2020, and with an accurate prediction of the entry trajectory, one would expect the existing prediction methods to produce total heating that is similar qualitatively and quantitatively to the actual conditions. This conclusion does not preclude using environments uncertainties that are appropriate for the mission.

Overall, the MEDLI and MEDLI2 data provide an opportunity to assess the approach for designing future Mars entry vehicle thermal protections systems. Decisions on whether to modify the approaches used for MSL and Mars 2020 will depend on the overall mission risk, and the testing and analysis required to make changes to a process that has resulted in successful thermal protection system performance. Additional analyses and testing of all MEDLI2 data products will be documented in the open literature.

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