MEDLI2 Material Response Model Development and Validation

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During the entry of Mars Science Laboratory (MSL) the heatshield was equipped with the instrumentation suite Mars Entry, Descent, and Landing Instruments (MEDLI). In-depth thermocouple (TC) data was used to reconstruct the surface heating and temperatures. Discrepancies between MEDLI's recorded in-depth heating data and the predicted thermal response and recession led to a campaign to characterize and test Mars Entry, Descent, and Landing Instrument 2 (MEDLI2) flight lot thermal protection materials (TPS) at relevant temperatures and pressures for Martian entry conditions.

This paper covers the development and validation of MEDLI2 flight lot material response models for the heatshield material Phenolic Impregnated Carbon Ablator (PICA) and the backshell material Super-Lightweight Ablator (SLA-561V). Virgin and char thermal conductivities were updated as a function of temperature and pressure in the MEDLI2 specific material response models. Other material properties such as virgin and char density, emissivity, absorptivity, and specific heat capacitance was also characterized and compared to the "Heritage" models used during the TPS design phase of Mars 2020. Fully Implicit Ablation and Thermal response (FIAT) simulations were completed using the Heritage and MEDLI2 material response models to provide evidence of the increased accuracy of the MEDLI2 model. FIAT predicted in-depth temperatures were compared to flight lot certification ground-test arc jet test data and MEDLI2 flight thermocouple data.

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I. Introduction:

On February 18th, 2021 the Mars 2020 capsule entered the Mars' atmosphere carrying the Perseverance rover. To protect the rover and scientific equipment payload during the entry and descent through the Martian atmosphere, the vehicle was encased in an aeroshell covered by the thermal protection systems(TPS). The Mars 2020 heatshield TPS was tiled Phenolic Impregnated Carbon Ablator (PICA) with Room Temperature Vulcanizing (RTV) silicone adhesive gap filler. The backshell TPS was selected as Super Lightweight Ablator (SLA)-561V and Acusil II was used on the backshell interface plate and parachute closeout cone. These materials were previously used on the Mars Sample Laboratory (MSL) mission that successfully landed in 2012. [1] Much like MSL, the Mars2020 heatshield was equipped with a Mars Entry, Descent, and Landing Instrumentation (MEDLI2) sensor suite. [2, 3] The Mars 2020 heatshield included eleven thermocouple (TC) instrumented sensor plugs that were flush mounted within the PICA tiles. Unlike MSL, the Mars 2020 MEDLI2 sensor suite also included six backshell TC plugs, a radiometer, and two heat flux gauges to provide NASA's first direct heat measurement during entry into the Martian atmosphere. [4]

In an effort to reconstruct the surface heat rate for the heatshield and backshell during Mars 2020 entry, inverse estimations are predicted using the MEDLI2 Instrumented Sensor Plug (MISP) data in combination with material response modeling. [5] MEDLI2 partial science success criteria included the attempt to predict the forebody heat rate within ±15 W/cm^2 and the aft body heat rate within ±3 W/cm^2. The accuracy of predicted heat rates is directly related to the accuracy of the material response models used during the inverse analysis. The MSL reconstruction effort shows the impact of varying the thermal conductivity properties of the virgin and char conductivities and how these updates would improve surface and in-depth temperature prediction. [6] Therefore, the MEDLI2 program conducted a campaign to characterize PICA and SLA-561V properties at various temperatures and pressures using coupons from the same flight lot billet used to fabricate the MISPs. Since the inverse analysis uses the 1D Fully Implicit Ablation and Thermal (FIAT) response software, this paper describes MEDLI2's effort to update the existing "Heritage" FIAT material models PICA v3.3 and SLA-561 v1.0 with measured MEDLI2 flight lot properties. [7, 8, 9, 10]

Section II of this paper provides an overview of the TPS characterization campaign completed by MEDLI2. Section III describes the updates to the PICA and SLA-561V FIAT material response models. Section IV provides details for arc jet testing environments used for ground test model validation. This section also compares the in-depth temperature predictions using the heritage and MEDLI2 FIAT models to determine if there is increased accuracy for the flight lot specific models. Finally, Section V compares the heritage and MEDLI2 FIAT model in-depth thermal predictions with the in-depth MEDLI2 flight data.

II. Characterization of Flight Lot TPS

The Mars 2020 heatshield TPS was tiled Phenolic Impregnated Carbon Ablator (PICA) with Room Temperature Vulcanizing (RTV) silicone adhesive gap filler. The backshell TPS was selected as Super Lightweight Ablator (SLA)-561V. No MISPs were placed within the Acusil II material, therefore flight lot material characterization was only completed on PICA and SLA-561V. PICA is an orthotropic material with higher in-plane thermal conductivity than through-the-thickness (TTT) which led to manufacturing limitations to machine the Mars 2020 PICA tiles with a limit on the local fiber orientation with respect to the surface normal to take advantage of the lower TTT conductivity in depth. 1D material response is commonly acceptable for the aeroshell analysis since the heating is determined to be gradual at locations where the MISP are located. The limitation on fiber orientation and acceptable 1D analysis allowed the material characterization campaign to focus on the TTT thermal conductivity to update the FIAT material models.

Table 1 and 2 provide details about the characterization methods used to obtain PICA and SLA-561V TTT virgin and char conductivities at various temperature ranges. Guarded Hot Plate (GHP) was used to measure thermal conductivity for low density materials over a range of -150°C to 230°C. Comparative Rod Apparatus (CRA) is capable of measuring the thermal gradient of specimens and thermal conductivity values can be derived from cryogenic temperatures to 815°C. Radial Inflow Apparatus (RIA) was used to evaluate thermal conductivity in the temperature range of 815°C to 1600°C. A char cycle was used to heat-treat the virgin CRA PICA specimens and PICA blanks for RIA specimens to 1600°C to create char specimens and char specimen blanks. SLA-561V char samples were generated using a char cycle to heat-treat virgin plates which were then tested without any machining post char. The heat-treated to 675°C were found to slightly shrink in size while maintain their shape. The filler material was found to shrink more than the matrix honeycomb, leaving a small portion of the matrix honeycomb jutting about the filler material. The Adiabatic Heat Calorimeter (AHC) used to measure the specific heat capacitance involved heating or cooling the specimens to the desired temperature then dropping them in the calorimeter cup. Adiabatic conditions are maintained during the test by adjusting the guard bath temperature. The absolute temperature measurements of the cup are determined by three thermocouples junctions. Virgin and char densities were also measured for flight lot test specimens. The specific elevated temperature property data for PICA is export controlled and will not be included in this paper. Room temperature data will be provided in the next section as comparisons between the FIAT heritage and MEDLI2 models.

Table 1 PICA Thermal Property Test Matrix

Property	Qty	Method	Conditions
Bulk Density (virgin, specimens)	>20	bulk density	
Conductivity, TTT (virgin)	4	CRA, ASTM E1225	RT to 260 °C, 1.0 & 0.01 atm
Conductivity, TTT (virgin)	16	CRA, ASTM E1225	RT to 260 °C, 1.0 atm
Conductivity, TTT (virgin)	1	GHP, ASTM C177	RT to 260 °C, 1.0 & 0.01 atm
Specific Heat Capacity (virgin)	2	AHC, ASTM D2766	RT to 260 °C
Bulk Density (char, specimens)	>10	bulk density	
Conductivity, TTT (char)	2	CRA, ASTM E1225	RT to 700 °C, 1.0 & 0.01 atm
Conductivity, TTT (char)	6	CRA, ASTM E1225	RT to 700 °C, 1.0 atm
Conductivity, TTT (char)	2	RIA	815 to 1600 °C, 1.0 atm
Inert furnace charring	-	-	Inert, 1600 °C

Table 2 SLA-561V Thermal Property Test Matrix

Property or Test	Qty	Conditions	Method
Bulk Density (virgin, specimens)			bulk density
Thermal expansion through pyrolysis	1	RT to 675 °C	dilatometry
Conductivity, TTT (virgin)	2	0.1 and 1.0 atm: ~23°C. 0.01 and 0.001 atm: RT to 250 °C	GHP, ASTM C177
Specific Heat Capacity (virgin)	3	RT to 250 °C	AHC, ASTM D2766
Bulk Density (char, specimens)			bulk density
Specific Heat Capacity (char)	3	RT to 500 °C	AHC, ASTM D2766
Conductivity, TTT (char)	2	0.1 and 1.0 atm: ~23°C. 0.01 and 0.001 atm: RT to 250 °C	GHP, ASTM C177
Conductivity, TTT (furnace char, non-flight)	2	0.1 and 1.0 atm: ~23°C. 0.01 and 0.001 atm: RT to 250 °C	GHP, ASTM C177
Conductivity, TTT (char)	2	0.1 and 1.0 atm: ~23°C. 0.01 and 0.001 atm: RT to 250 °C	CRA, ASTM E1225
Conductivity, TTT (char)	1	815 & 1000°C, 1.0 atm	RIA
Inert Furnace charring to 675 °C	1		

III. Updating FIAT models with measured data

A. PICA MODEL

NASA MSL and Mars 2020 missions used FIAT material response model PICA v3.3 for TPS sizing analysis. PICA v3.3 FIAT model is a generalized FIAT model developed by Orion Advanced development program and MSL flight project and has been validated with numerous ground-test data as summarized by Milos and Chen with well documented uncertainties. [8] These uncertainties are built into NASA TPS sizing margin policies and Monte Carlo analysis and account for the variability in PICA properties from billet to billet. [11] PICA v3.3 is considered the "Heritage" PICA model throughout this article and will be used to show the differences between the generic PICA model and the flight lot specific MEDLI2 model.

Previously MEDLI reconstruction analysis used this heritage model for inverse analysis to predict the surface heating environments during MSL entry. [6] To improve accuracy of the MEDLI2 predictions, MEDLI2 planned to cut the MISP plugs from the same TPS billet to reduce variability in the material properties observed for those plugs. In addition, a material characterization effort was performed to measure relevant properties for that single flight lot billet to update the FIAT PICA solid properties to align with the MEDLI2 flight lot material. The measured properties were also used to update the uncertainty bounds used for the MEDLI2 Monte Carlo inverse analysis effort. [5]

As stated in the previous section, these measurements included through thickness conductivity at 1.0, 0.1 and 0.01 atm pressures for virgin and charred PICA. Although there were limited samples due to the single billet source, there was good agreement for repeated tests at each pressure and temperature. Table 3 provides the room temperatures conductivities within the Heritage and MEDLI2 models at two pressures. To predict conductivity properties beyond the measured data (> 1700 °C), MEDLI2 used similar techniques used to predict the Heritage FIAT model parameters. The extrapolated flight lot conductivities showed a significant reduction in the predicted conductivity (> 30% for char conductivity) which is larger than the uncertainty bounds (±20%) used in the MSL Monte Carlo reconstruction effort. Because of these differences it was determined that the measured and extrapolated conductivities would be updated in the MEDLI2 FIAT material model.

Table 3 PICA Room Temperature Properties

Model	RT Virgin Conductivity (1 atm)	RT Char Conductivity (1 atm)	RT Virgin Conductivity (0.001 atm)	RT Char Conductivity (0.001 atm)	Virgin Density
	W/m-K	W/m-K	W/m-K	W/m-K	kg/m3
Heritage	0.174	0.224	0.520	0.202	274
MEDLI2	0.169	0.169	0.127	0.143	292

PICA's specific heat was measured as a function of temperature and compared to the Heritage PICA model. The uncertainty of the MSL Monte Carlo analysis was ±10% and the MEDLI2 measurements were within the ±10% range from the original model. Therefore, the MEDLI2 PICA model is the same as the heritage model. The density of the MISP plugs were also measured and used to update the PICA density within the FIAT model. The density was increased by 6.6% to match the average MISP plug density. Note the variability of the MEDLI2 plug densities was 1.86%. By updating the density, it removed any uncertainty bias that would have been carried over to the Monte Carlo analysis used to predict the surface environments during entry.

It is important to note that both MSL and Mars 2020 heatshields had a silicone coating (NuSil CV-1144-0) applied to the surface of the heatshield to prevent contamination of phenolic dust that often comes off of PICA. [13] The MEDLI2 arc jet test campaigns did coat the MEDLI2 MISP plugs with NuSil to replicate the flight MISP plugs. Arcjet testing of NuSil coated PICA samples have shown no degradation in the material's performance, but post-test recession measurements have shown reduced recession compared to uncoated PICA at relevant Mars 2020 flight environments. An engineering-level NuSil material response model has been developed at NASA Ames and further investigation will be conducted by the Entry Systems and Modeling project and MEDLI2 deep dive effort to increase the fidelity of the NuSil model. [14] However, inclusion of the NuSil coating in our material response analysis is outside the scope of the current MEDLI2 inverse analysis approach. Documented MEDLI and MEDLI2 inverse analysis predicts surface heating environments by conducting FIAT simulations that use an uncoated PICA material stackup with the time dependent boundary condition that solves a non-ablating (non-receding) surface energy balance with radiation. [5, 6]

B. SLA-561V Model

NASA MSL/Mars 2020 missions used the high fidelity thermal/ablation (HFTA) material response model developed at NASA Ames to size the TPS thickness of the MSL mission. [10] The HFTA model is considered the "Heritage" SLA-561V model throughout this paper. The heritage model was developed when SLA-561V was considered as a potential TPS option for the MSL heat shield. [1] The arc jet test conditions used to validate this model ranged from 30 W/cm^2 to 350 W/cm^2 with pressures greater than 0.1 atm. [12] Aerothermal predictions for the Mars 2020 backshell include convective and radiative heating that are not expected to exceed 10 W/cm^2 with peak pressures (<0.005 atm) which have been confirmed during the MEDLI2 reconstruction effort. [5] Therefore it was justified that the FIAT MEDLI2 SLA-561V model included conductivities at lower pressures conductivities to provide better in-depth material response estimates for backshell environments. Figure 1 shows the relation between the virgin and char conductivities (κ) for the Heritage [10] and MEDLI2 models. Besides updating the conductivities for the MEDLI2 FIAT model, the density of the MISP plugs were also measured and the average density was used for the SLA-561V flight lot model. The MEDLI2 flight lot model virgin density was increased by 0.5% from the Heritage model density.

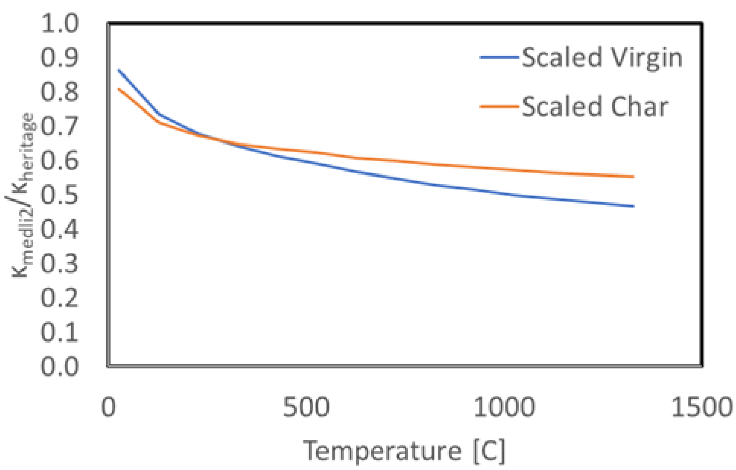

Figure 1 Comparison of thermal conductivities(κ) for Heritage SLA-561V and MEDLI2 SLA-561V FIAT models

IV. Ground Test Validation of FIAT models

A. Methodology

After modifying any material response models, it is important to validate these models with experimental results. NASA Ames research center (ARC) arc jet facilities enable ground testing capabilities to expose the TPS materials to relevant heating environments. With the use of calibration techniques, the facilities are able to target heat fluxes and with computational fluid dynamic (CFD) simulations, the recovery enthalpy, wall enthalpy, pressure, and film coefficients can be calculated for material response analysis. Note that using CFD analysis to predict the surface heating conditions does add uncertainty to the validation effort.

The arc jet test samples were also instrumented with thermocouples at depths comparable to MEDLI2 MISP TCs. Another method of analyzing the in-depth TC response is to solve the in-depth heat conduction within the plug using a TC as the imposed surface boundary condition in time. This approach effectively decouples the in-depth heat transfer and surface heating problems, thus allowing validation of the thermal conductivity and density properties without the knowledge of surface heating conditions. [6] The TC driver approach is traditionally used with arc jet data in cases where the surface boundary conditions were not characterized well or coatings on the TPS add additional complexity to model, such as the case of NuSil coated PICA. Therefore, it was decided that removing the need to model the coated PICA surface by running TC driver FIAT simulations for model validation purposes would be wise.

Comparison of the TC driver predictions and the in-depth TC test data provide a good assessment of accuracy of the models during ground test environments. "TC1" driver describes using this approach with the thermocouple sensor closest to the outer mold line surface. In the case where the near-surface TC1 burns out, there are instances where TC2 driver simulations are used. The TC driver option does not use a surface energy balance equation since the wall temperature and recession rate are input as a function of time in the FIAT environment file. Since the TC driver approach redefines the surface to the thermocouple data that persist during the entirety of the simulation, the recession rate is defined as zero. This reasoning is in line with the approach used by MEDLI and MELDI2 inverse analysis teams that assume a non-ablating surface energy balance with radiation within the FIAT simulations which results in zero recession estimates. Pre and post test arc jet samples for NuSil coated PICA and SLA-561V were laser scanned to quantify recession. Minimal recession was recorded for both TPS materials at conditions similar to the Mars 2020 entry environments.

B. Ground-testing MELDI2 TPS materials

To understand the impact of updating the density and conductivities within the FIAT model, in-depth thermocouple data of MEDLI2 flight lot samples were collected over a series of NASA Ames arc jet test campaigns. This paper will focus on two PICA tests and a single SLA-561V tests, specifically the MEDLI2 PICA and SLA-561V flight lot acceptance testing that occurred in 2019 and the latest PICA arc jet series that concluded in the fall of 2021. The arc jet campaigns completed in 2021 used preliminary MEDLI2 inverse analysis estimates of surface heating environments to determine the targeted conditions. The test IDs and descriptions are provided below and Table 4 provides the targeted conditions and duration for each test. Note that multiple conditions were run for select test series and test conditions were run twice to provide confidence in the collected data. The NASA Ames facilities available for this testing include the Interaction Heating Facility (IHF), Aerodynamic Heating Facility (AHF), and Panel Test Facility (PTF).

1. PTF162 – MEDLI2 SLA-561V flight lot acceptance panel test
2. IHF362 – MEDLI2 PICA flight lot acceptance test
3. AHF350 – Post-flight inverse analysis driven target conditions for PICA model validation

Table 4 Target conditions for MEDLI2 flight lot arc jet tests

Test Facility	ID#	Material	Target Hot Wall Heat Flux	Target Cold Wall Heat Flux	Estimated Stagnation Pressure	Exposure Duration
			W/cm^2	W/cm^2	kPa	seconds
IHF	362	PICA	176	210	17	33
			66	81	20	84
AHF	350	PICA	65	81	4	25
			50	63	3	25
PTF	162	SLA-561V	4.3	5.4	0.2	63
			8.6	9.7	0.8	25

The two PICA arc jet test series described in this paper use the same test coupon designs with representative TPS thicknesses that align with flight plug specifications. Figure 2 shows the stackup used in FIAT simulations which assumed an uncoated PICA sample since TC driver analysis was being performed. HT-424 paste adhesive, and an Aluminum honeycomb sandwiched with graphite facesheet plies. Small additions of RTV-560 were used to adhere the MISP plug into the bulk TPS. Due to the minimal amount of RTV-560 and lack of measured thicknesses the FIAT simulations presented do not include RTV-560 in the thermal analysis. Similarly, both SLA-561V arc jet test panels and FIAT stackups used the representative TPS material stackup with 1.27cm (0.5") SLA-561V, HT-424 paste adhesive, Aluminum honeycomb sandwiched by graphite facesheet plies. All substructure materials were simulated using the same thermal response models used in MSL analysis. The material properties for heatshield and backshell structure were based on extensive thermal property testing commissioned by Lockheed Martin in support of MSL. [15]

The MISP plugs used in the PICA ground tests have three TCs and are fabricated with the same target depth as the MEDLI2 flight MISPs. The TC depths for each ground test sample are measured using X-ray analysis to confirm the plug depths meet the ±0.0076cm (0.003in) specs. Each FIAT simulations presented in this article use the measured TC depths for better accuracy. The SLA-561V ground test MISP have two thermocouples TC1=0.254cm and TC2=0.635cm (0.1" and 0.25").

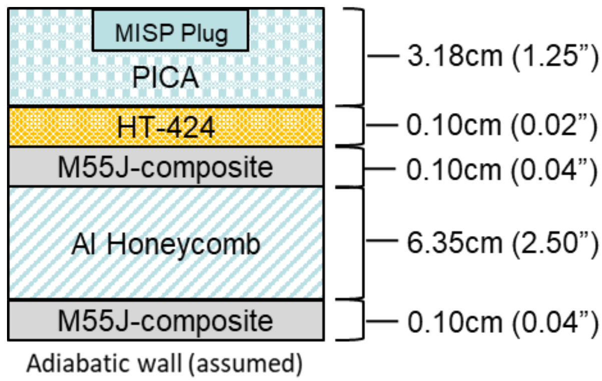

Figure 2 TPS/substructure stack up (not to scale) and dimensions for arc jet PICA test coupons

C. PICA FIAT Model Validation Test Results

Figure 3 shows the thermocouple data for the MEDLI2 PICA flight lot acceptance test IHF362. This test included two target heating environments, the upper bound of 210 W/cm^2 cold wall heat flux was chosen to replicate worst-case aerothermal conditions for Mars 2020 entry. The lower condition 81 W/cm^2 was targeting the predicted nominal aerothermal conditions for Mars 2020 entry. MEDLI2 also investigated the impact of lower initial temperatures prior to testing. Figure 3 shows "Ambient" results that were generated by samples that were equilibrated to room temperature in the facility prior to testing. The "Cold Soaked" samples were treated with liquid nitrogen with a target temperature of -190 ± 10°C for 15 minutes. Prior to testing the in-depth temperatures of TC2 read approximately -34°C. Note that the thermocouple closest to the surface (TC1) failed when it reached temperatures beyond the capability of the thermocouple sensors or burned out (the TC reached the receding surface). Due to the uncertainty in the high temperature reading of TC1 and the limited time that the TC1s remained, it was determined that the second TC would be used for model validation.

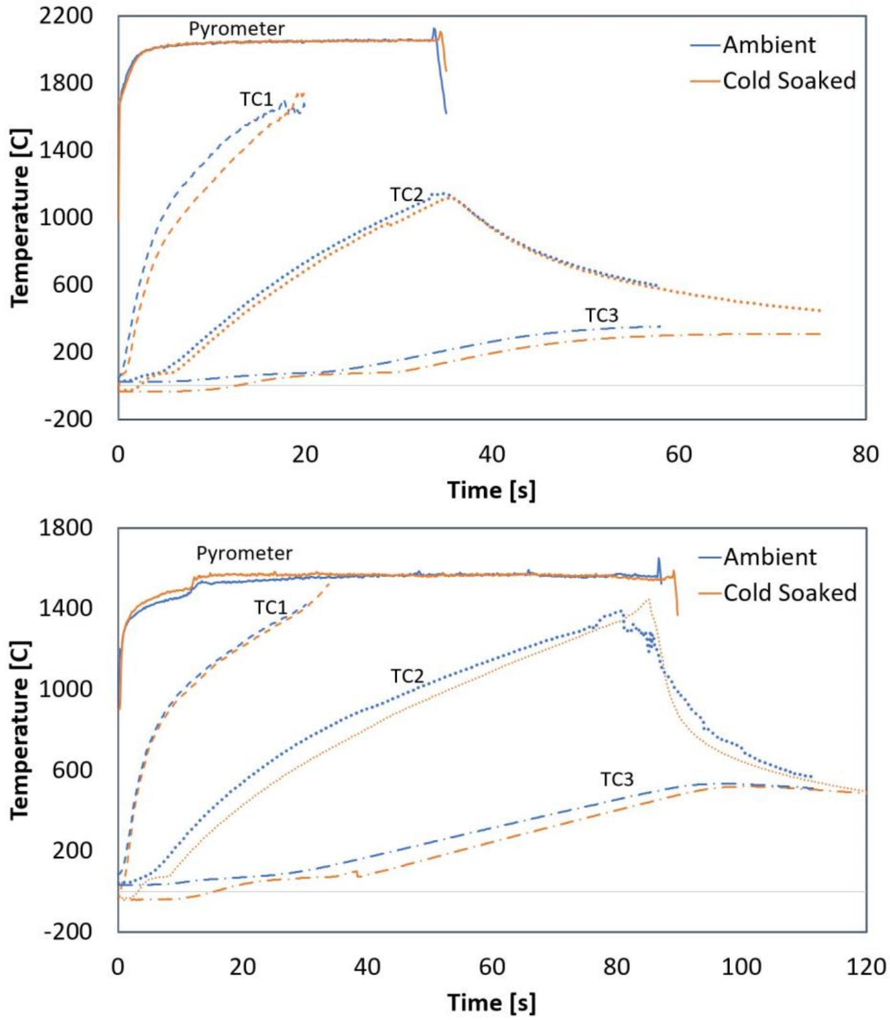

Figure 3 MEDLI2 PICA flight lot acceptance test TC data at two conditions (a) Target condition ~210 W/cm^2 cold-wall heat flux, ~17 kPa and test duration 33s.(b) Target condition ~81 W/cm^2 cold-wall heat flux, ~20 kPa and test duration 84s. (blue) Results for room temperature test samples. (orange) Results for liquid nitrogen cold-soaked samples.

Figure 4 shows the TC2 driver FIAT simulation predictions of the third thermocouple using the Heritage PICA model and the MEDLI2 model. The FIAT TC depths were adjusted to account for the change in the TC driver "surface" thereby moving the TCs closer to the surface by 0.508cm. Some TC data was only recorded for a limited time and cooling comparisons were not available for Figure 4(a,b). However, for all four cases (a-d) the MEDLI2 model showed better agreement than the Heritage model for the data that does exist.

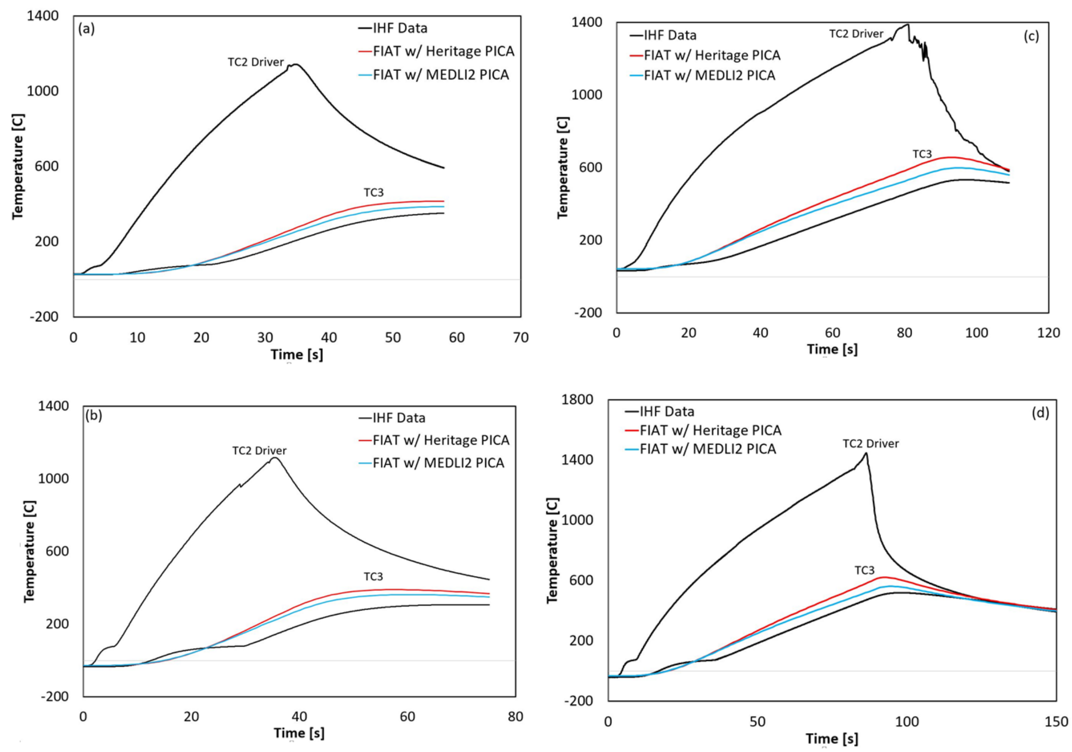

Figure 4 MEDLI2 PICA flight lot acceptance 2019 IHF test TC data at two conditions with FIAT TC2 driver results shown using the Heritage and MEDLI2 PICA FIAT models. (a,b) 210 W/cm^2 cold wall heat flux target, pressure ~17 kPa with an exposure time of 33s. (c,d) 81 W/cm^2 cold wall heat flux target, pressure ~20 kPa with an exposure time of 84s. (a,c) Samples are at room temperature prior to testing. (b,d) Samples are cold soaked prior to testing.

On Feb. 18th, 2021, MEDLI2 had completed its original objectives of collecting flight data during the Mars 2020 mission. Then began the second phase of MEDLI2 objectives which included estimating the surface heating environments using inverse material response analysis. The reconstruction team ran preliminary estimates using the Heritage FIAT PICA model. An upper and lower bound for the heat fluxes were provided as targets for the MEDLI2 material response model validation effort. Table 4 list these conditions as 81 W/cm^2 and 65 W/cm^2 cold wall heat flux. It was important to collect as much TC data as possible for TC driver simulations, therefore AHF350 was run in Nitrogen to reduce recession and the exposure time was shorter (25s) to ensure the near-surface TC1 did not burn out. Figure 5 shows the data for all three TCs in the MISP plugs at both conditions. In addition to the test data, the TC1 driver FIAT simulation results with the Heritage and MEDLI2 material models are also provided. It is clear at both conditions that the MEDLI2 FIAT simulations have better agreement with the test data than the Heritage PICA model. These results provided enough evidence to deliver the MEDLI2 PICA model to the inverse analysis team to run the final Monte Carlo analysis for the heatshield. [5]

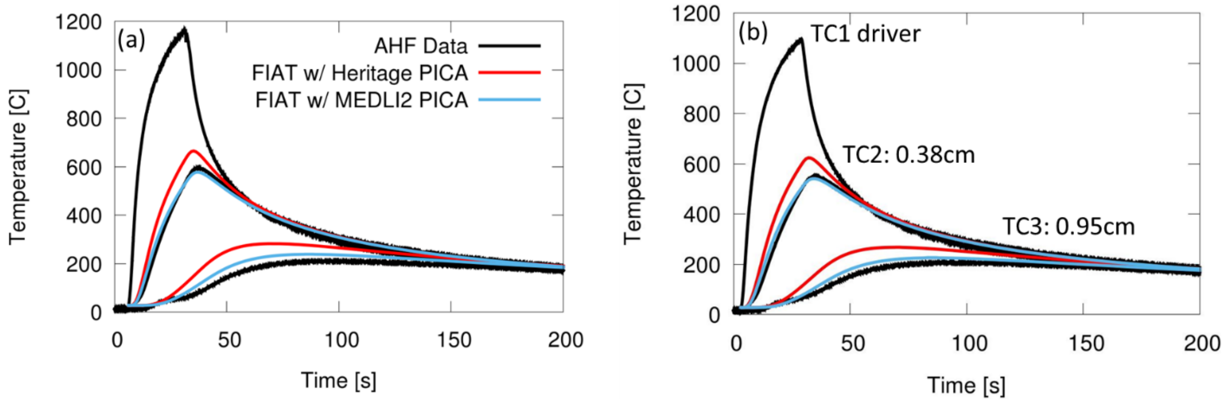

Figure 5 MEDLI2 PICA post-flight 2021 AHF test TC data at two conditions with FIAT TC1 driver results shown using the Heritage and MEDLI2 PICA FIAT models.(a) 81 W/cm^2 cold wall heat flux target, pressure ~4 kPa with an exposure time of 25s.(b) 63 W/cm^2 cold wall heat flux target, pressure ~3kPa with an exposure time of 25s. TC1 is located at 0.19cm (0.075in) within the MEDLI2 test sample plug.

D. SLA-561V Model Validation Test Validation Test Results

For SLA-561V, the flight lot acceptance test was conducted at the panel test facility to produce lower heat fluxes and pressures than what can be produced at other arc jet facilities. In this facility the TPS panel will go through a sequence of timed heat flux changes through arc current and table angles. This facility is difficult to properly model using FIAT surface energy balance options. Therefore, it was decided that TC driver analysis was be completed to compare the Heritage and MEDLI2 SLA-561V FIAT results at in-depth temperatures. Figure 6 shows the PTF test results for SLA-561V Flight Lot acceptance test. The top TC (TC depth =0.1") was used as the driver in these simulations. The measured TC data is compared to the FIAT simulations using the heritage SLA-561V and the MELDI2 flight lot model. It can be observed that the MEDLI2 model agrees better with the in-depth TC than the Heritage model. The MEDLI2 model includes updated thermal conductivities as a function of temperature and pressure as well as updated densities to align with the average SLA-561V MISP densities. Adjusting the density is also important because it reduced the bias for the uncertainty associated with the material density that is passed to the MEDLI2 reconstruction team. Details about defining the material property uncertainties are included in the reconstruction article and will not be discussed in this paper. [5]

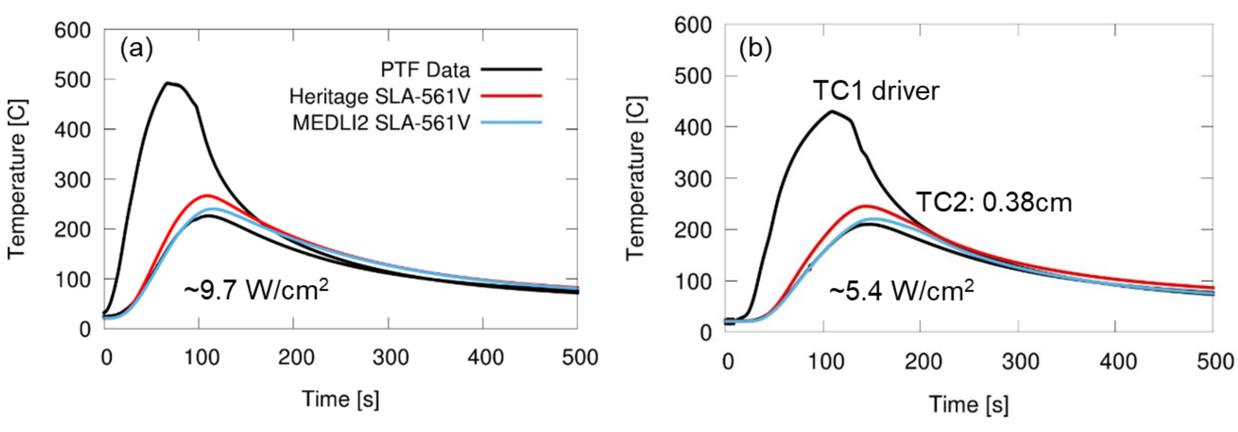

Figure 6 MEDLI2 SLA-561V flight lot acceptance PTF test results at two conditions with FIAT TC driver results shown using the Heritage and MEDLI2 SLA-561V FIAT models.(a) 5.4 W/cm^2 cold wall heat flux target, pressure ~0.2 kPa with table up exposure 63s. (b) 9.7 W/cm^2 cold wall heat flux target, pressure ~0.8 kPa with table up exposure time 34s.

V. Comparison of FIAT in-depth predictions with MEDLI2 flight data

Once material response models are validated with ground-test results and the general accuracy is understood, the MEDLI2 team studied the material response using the MEDLI2 flight thermocouple data as the TC driver. The MISP sensors contained multiple thermocouples on the heatshield. MTH01, 02, and 03 shown in Figure 7(a). The material stackups for the FIAT simulations are dependent on the location on the vehicle and represent the as-flown dimensions. The TC depths are also taken from the specific MISP plug measurements using X-ray analysis. The initial temperatures for the materials within the stackup are defined as the average temperature of the three TC measurements within each MISP location prior to entry into the Martian atmosphere. The results shown in Figure 7(b-d) use the recorded temperature data over time for the TC closest to the outer surface at 0.19 cm (0.075”). These temperatures are used to impose temperature boundary condition and the recession rates are set to zero as previously used in the arc jet simulations. In-depth temperature predictions using both FIAT PICA models are shown for all three MISP location in Figure 7(b-d) where the predictions are compared to flight data. The difference in the measured peak temperature and the simulated peak temperature are shown in Table 5 to quantify the impact of updating the material model to the MEDLI2 flight lot properties.

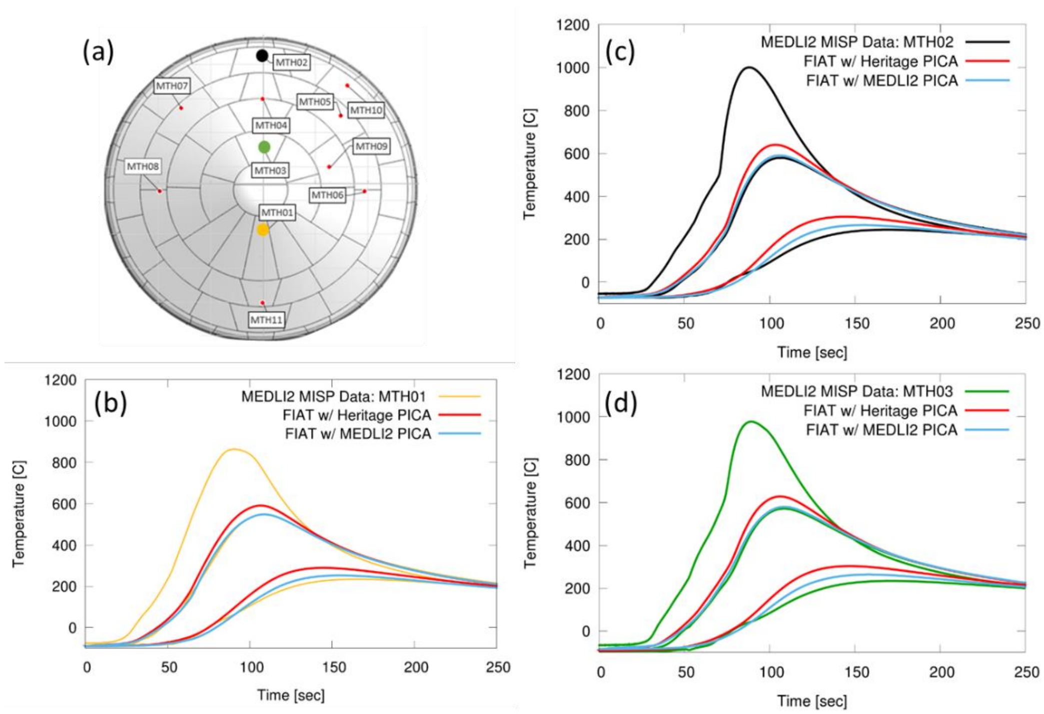

Figure 7 MEDLI2 Heatshield TC data is compared to FIAT heritage and MEDLI2 model results at two in-depth locations, TC2 and TC3 using TC1 data as the surface temperature boundary condition with zero recesison assumed. (a) Shows the heathshield MISP locations with three highlighted MISPs MTH01, 02, and 03. (b) MTH01 Stagnation point TC data (c) MTH02 Peak predicted heating TC data and (d) MTH03 TC data are compared to FIAT simulation with (red) Heritage model (blue) MEDLI2 model.

Table 5 Peak temperatures are compared for MEDLI2 Heatshield in-depth TC data and FIAT predictions

	Temperature (C°) at time of peak TC2 temperature (Difference to Flight)			Temperature (C°) at time of peak TC3 temperature (Difference to Flight)		
MISP Plug	MEDLI2 Flight Data	FIAT Heritage Model	FIAT MEDLI2 Model	MEDLI2 Flight Data	FIAT Heritage Model	FIAT MEDLI2 Model
MTH01	548	635(42)	548(0)	234	279 (44)	261 (27)
MTH02	579	636 (57)	590 (11)	244	289 (45)	261 (17)
MTH03	571	627 (56)	580 (9)	234	286 (52)	259 (25)

The MEDLI2 MISP locations on the Mars 2020 aeroshell are provided in Figure 8. Each location is color coded to match the measured in-depth temperature profiles and the TC depth chart. As shown in the TC depth chart, only one MISP location was instrumented with two thermocouples. The survival of each thermocouple was very important for an TC driver analysis therefore the 2-TC MISP was placed at a location that would not experience the highest heating. All six MISPs successfully provided thermal data until the backshell separation event. TC1 driver simulations were completed using the near-surface TC1 at 0.254 (0.1”) as the imposed temperature boundary condition to predict the heating at TC2 at 0.635cm (0.25”) in depth. Figure 9 Backshell MISP sensor MTB01 is compared to TC1 driver FIAT results using the Heritage and MEDLI2 flight lot SLA-561V modelsFigure 9 provides results of the TC driver analysis of the backshell MISP similar to the analysis completed the heatshield MISP locations. The material stackup was obtained from as-flown dimensions and initial temperatures were taken from the TC readings just before entry interface. The results show much better agreement for the MEDLI2 flight lot model as compared to the Heritage SLA-561V model.

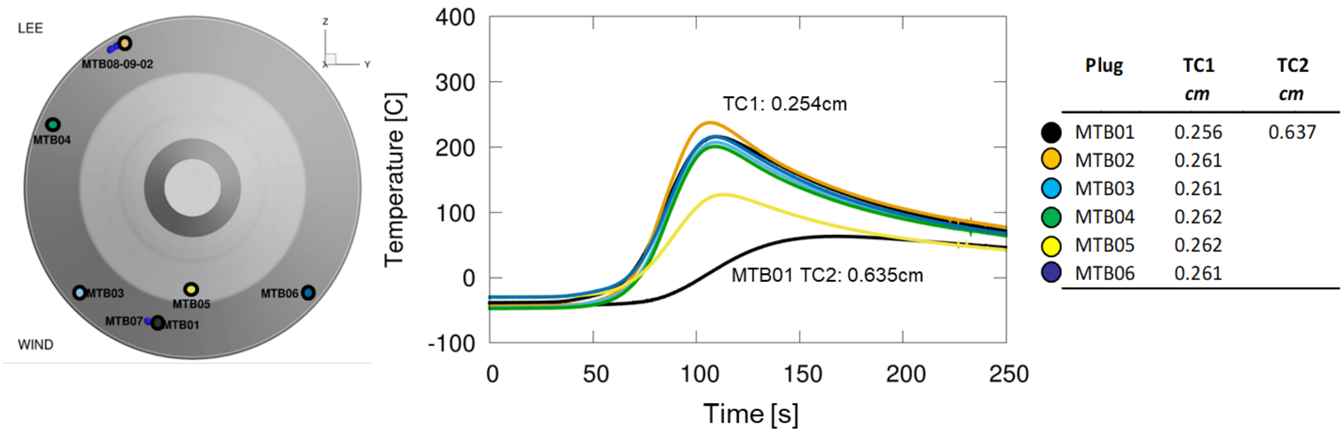

Figure 8 (a) MEDLI2 backshell MISP locations (b) Measured thermocouple data during entry where t=0 is at entry interface (c) Thermocouple depths with respect to the outer mold line of the aeroshell. Color references are consistent throughout all three images.

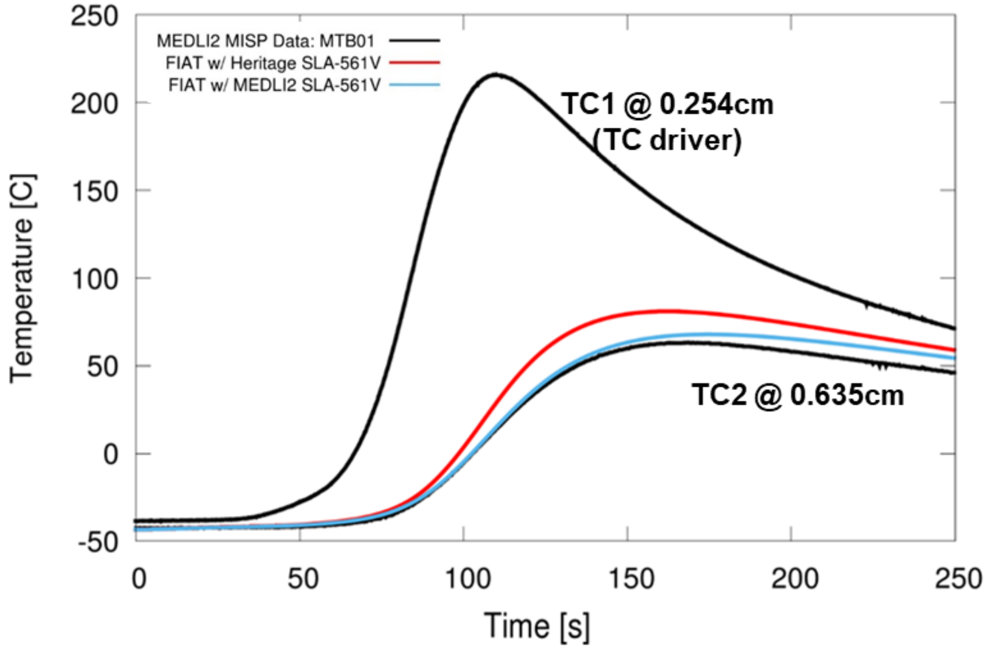

Figure 9 Backshell MISP sensor MTB01 is compared to TC1 driver FIAT results using the Heritage and MEDLI2 flight lot SLA-561V models

VI. Conclusion

In conclusion, modification to the bulk PICA and SLA-561V models to update the solid properties to the MEDLI2 flight lot properties greatly improved in-depth temperature predictions when compared to ground-test arc jet tests and with MEDLI2 flight data. Confidence in these models' in-depth predictions also translates to confidence in using these models for inverse analysis to predict the surface heating environments and temperatures. The reduced thermal conductivity and higher densities for the PICA MEDLI2 model has resulted in surface heating estimates ranging from (5 W/cm^2 to 15 W/cm^2) higher than the same heatshield MISP using the Heritage model. The largest change was found at MTH02 which is expected since it observes the highest heating of all of the MISP locations. [5] Further evaluation of MEDLI2 data is planned during the MEDLI2 deep dive effort with the Entry Systems and Modeling project at NASA Ames. A subset of the deep dive effort will include solving the surface energy balance equation with FIAT using CFD aerothermal Mars 2020 Best Estimated Trajectory (BET) environments. This study will look at the impact of NuSil coating on in-depth heating predictions and aerothermal effects such as transitioning from laminar to turbulent flow.

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