Mars Sample Retrieval Lander Thermal Protection System Design

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Background: The Mars Sample Return (MSR) Sample Retrieval Lander (SRL) was slated to launch in 2031 and enter Mars' atmosphere after a 15-month cruise. After several iterations of vehicle design and trajectories, the latest mission architecture included a 4.72-meter diameter entry capsule entering the Martian atmosphere at 8 km/s, marking a 3.5x increase in kinetic energy when entering the atmosphere in comparison to Mars 2020. Designed to be the heaviest and fastest vehicle to enter Mars' atmosphere, SRL required slim mass margins, and as such, the thermal protection system (TPS) design methodology needed to be tailored appropriately. The entry capsule aeroshell is composed of a heatshield, backshell, parachute support cone, and parachute lid, as shown in Fig. 1.

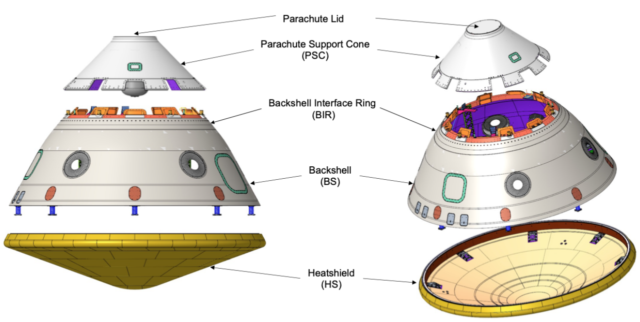

Figure 1: **Overview of SRL aeroshell structure.**

The SRL aeroshell uses the same TPS materials as Mars Science Laboratory (MSL) and Mars 2020: PICA-D tiles with RTV-560 gap filler for the heatshield, SLA-561V for the backshell, and Acusil-II for the backshell interface ring, parachute support cone, and parachute lid.

The heatshield structure consists of aluminum honeycomb sandwiched between two carbon facesheets. The PICA is adhered to top of the structure using RTV-560 and then the surface is sprayed with NuSil coating for contamination control, as PICA is known to generate dust during assembly, test, and launch operations. The PICA is sized to ensure that the performance temperature limits of the substructure components are not exceeded. Thus, the main temperature constraint is that between the adhesive and the top facesheet; this is known as the bondline temperature (BLT).

Aerothermal Design Environments: TPS sizing is done at select body points. These body points are selected based on the predicted environments and the substructure across the aeroshell – i.e., which locations on the aeroshell may results in the thickest required TPS. First, CFD simulations are run to get smooth wall heating predictions. For the forebody, empirical correlations are used to convert those to rough wall heating predictions, while for the aftbody the smooth wall predictions are used in the analysis. For this analysis, the majority of the CFD was performed at an angle of attack (AoA) of -20° with some points at -15° and -25° to cover the trajectory space. Much of the CFD was conducted with velocities greater than 6 km/s to improve understanding of radiative heating at these relevant higher velocities.

Indicator equations are applied over appropriate trajectories to provide the environmental variables of interest, namely convective and radiative heat flux (q_{conv} and q_{rad}), film coefficient (C_H), recovery enthalpy (H_e), pressure (p_w), and shear (τ_w) [1]. The various indicator equations for the forebody are shown in Fig. 2.

Forebody/Heatshield

$$q_{conv} = A\,(\rho_\infty)^B\,(v_\infty)^C$$

$$q_{rad} = A(\rho_{sh} c_{CO,sh})^B (T_{sh})^C + D(\rho_{sh} c_{CO2,sh})^E (T_{sh})^F$$

$$C_H = A\,(\rho_\infty)^B\,(v_\infty)^C$$

$$P_w = A\,(\rho_\infty)^B\,(v_\infty)^C$$

$$H_e = A(T_\infty) + B\,(v_\infty\, v_{\infty/2}) + C$$

$$\tau_w = A\,(\rho_\infty)^B\,(v_\infty)^C$$

Figure 2: **Aeroheating indicator equations.**

In these equations, ρ_∞, v_∞, and T_∞ are the freestream density, velocity, and temperature, respectively; the subscript sh represents post-shock quantities; c is gas concentration; and the capital letters A, B, C, D, E, and F are constants. The angle of attack (α) can be incorporated into the indicator by including an additional multiplicative factor of ($m + n\,\alpha + p\,\alpha^2$) where m, n, and p are also constants. This applies to all of the indicator equations except for H_e, which is not impacted by α. These indicator equations are identical to those used for Mars 2020, with the only change being the addition instead of multiplication of the two terms in the forebody q_{rad} indicator, to account for a two-peaked radiative pulse.

A set of 8001 dispersed trajectories was examined in order to identify the stressing trajectory, to generate design environments, inform testing, and conduct TPS sizing analysis. The indicator equations were used to calculate the peak convective and radiative heat flux and heat load, as well as the other parameters of interest, for each trajectory, at each body point. The stressing trajectory is defined as the one that is closest to both the 99th percentile high peak heat flux and heat load. An example of the trajectory space for the body point on the nose is shown in Fig. 3; the green dot represents the stressing trajectory.

Once the stressing trajectory is identified, additional aerothermal margins are added on top of that, to inform the design environments. These margins are shown in Table 1. SRL's aerothermal margins are derived from Mars 2020, with efforts to refine and update them underway.

Table 1: **SRL Aerothermal Margins**

	Aerothermal Margins	
	Forebody	Aftbody
Convective heat flux (q_{conv})	1.22	2.0
Radiative heat flux (q_{rad})	1.5	1.47
Pressure (P_w)	1.05	1.25
Shear Stress (τ_w)	1.25	1.5

The design environments that are arrived at are used to inform TPS test planning. Fig. 4 shows two butterfly plots

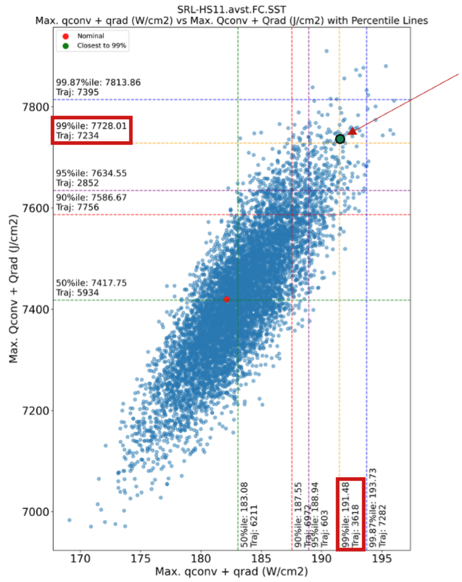

Figure 3: **Trajectory space for the body point on the nose, with the green dot showing the stressing trajectory.**

that include the design environments for each body point on the heatshield. Plots like this can be used to bound the pressure, heat flux, and shear at which the test articles must be tested. The same analysis was done for the backshell and parachute cone/lid.

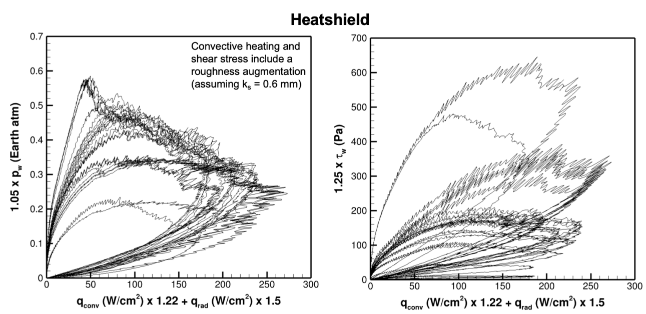

Figure 4: **Butterfly plot showing design environments at each body point on the heatshield to inform testing approach.**

TPS Sizing: TPS sizing analysis is conducted to ensure that the performance temperature limits of the substructure components are not exceeded. An example TPS stackup is shown in Fig. 5. The driving temperature constraint, between the top facesheet and the adhesive, is denoted as the bondline temperature (BLT).

TPS sizing for SRL was done using the Fully Implicit Ablation and Thermal response program (FIAT) [2], a one-dimensional thermal analysis code that includes in-depth decomposition, pyrolysis, and conduction for charring materials. The same process as had been used for MSL and Mars 2020 was used here. In this process, three FIAT cases (called "branches") are run – nominal, aerothermal margin, and material margin – and then root-sum-squared (RSS) to avoid stacked conservatism. For the nominal branch, FIAT is run on the stressing trajectory environment with no additional aerothermal or material margins, and a TPS thickness (T_1) is calculated. For the next branch, the aerothermal margins

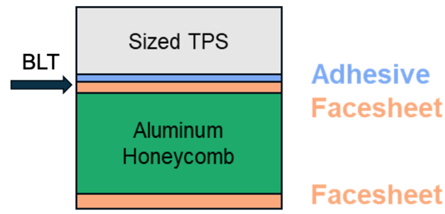

Figure 5: **Example TPS stackup. The bondline temperature (BLT) is between the top facesheet and the adhesive.**

from Table 1 are applied to the environment to account for uncertainties in the aerothermal analysis and a new thickness (T_2) is obtained. In the third case, a margin is applied to the bondline temperature limit to account for variability in material properties, and a third thickness is calculated (T_3). The RSS thickness is calculated as: $T_{RSS} = T_1 + \sqrt{(T_2 - T_1)^2 + (T_3 - T_1)^2}$. The final thickness includes a 20% recession margin (for ablating materials) as well as a manufacturing tolerance and any other required design features (such as a facesheet overwrap) when needed.

Generally, the margin applied to the bondline temperature in the third branch is estimated by performing a Monte Carlo analysis with FIAT. For each driving body point location, 8,000 FIAT cases were run with varying TPS and substructure material properties. The distribution of these material property uncertainties is based on data and engineering judgment. The maximum bondline temperature is recorded for each run and the margin is calculated as the temperature at which 99% of cases remain below it.

Initially, the material property uncertainties used were identical to those used in Mars 2020 analysis. However, recent PICA-D testing showed an increase in uncertainty of density and thermal conductivity, raising those values from 5% and 20% to 11.2% and 31.9%, respectively. When propagated through the Monte Carlo analysis, this resulted in significantly higher bondline temperature margins than before. For example, the nominal allowable bondline temperature at the heatshield shoulder location is 177°C. The bondline temperature margin using Mars 2020 uncertainties was 80°C; incorporating the new uncertainties increased that margin to 128°C. With this new margin, the material margin dominates the entire RSS thickness calculation.

An alternative margining strategy was investigated to ensure the design thicknesses are appropriate without being overly conservative. In this approach, another Monte Carlo analysis was run. In addition to TPS and substructure material properties, the aerothermal uncertainty, recession factor, and trajectory were also varied. The aerothermal uncertainty factors for convective and radiative heat flux were selected from uniform distributions between 1 and the limits given in Table 1 (1.22 and 1.5, respectively). The recession factor, which modifies the recession prediction by scaling the blowing coefficient, was selected from a Gaussian distribution centered around 1 with a standard deviation of 0.1. FIAT was then run using a set TPS thickness to calculate the bondline temperature. Results from the heatshield shoulder body point are shown in Fig. 6.

When the full design thickness was used, not a single case exceeded the allowable temperature of 177°C, and the 99th percentile case peaked at 75°C, more than 100°C below the allowable. When the same analysis was run using 80% of the baseline design thickness, just 1 of the 8000 cases exceeded the allowable and the 99th percentile case was still 37°C below the allowable. Running this analysis with the thickness

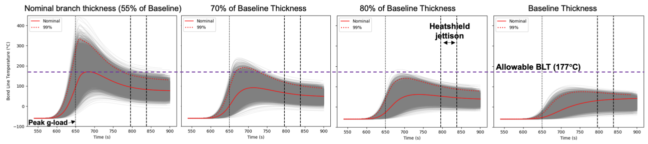

Figure 6: **Monte Carlo results of bondline temperatures calculated at a heatshield shoulder location with four different TPS thicknesses.**

from the nominal branch, which is 55% the baseline design thickness, about 60% of the cases exceeded 177°C. These results are summarized in Table 2.

Table 2: **Results from Monte Carlo Analysis on Heatshield Shoulder Body Point**

% of Baseline Design Thickness	# of Cases Over 177°C	99^{th} %-ile Case Peak Temperature	99% Margin
100%	0	75°C	102°C
80%	1	140°C	37°C
70%	160	191°C	-14°C
55%	4800	333°C	-156°C

These results suggest that the chance of exceeding the allowable temperature using our baseline design TPS thickness is exceedingly low. In order to achieve 99% confidence in remaining below the allowable, the thickness could be 75% of the baseline design thickness.

A study was done to assess which Monte Carlo parameters were responsible for an increased peak bondline temperature over the nominal case. Four Monte Carlo analyses were performed with different parameters varied, as given in Table 3.

Table 3: **Monte Carlo Analysis Matrix**

	Dispersed Trajectory	Material Properties	Aerothermal Uncertainty
Case 1		X	
Case 2	X		
Case 3	X	X	
Case 4	X	X	X

The results from the four Monte Carlo analyses show that including the trajectory dispersions does not change the peak bondline temperature significantly, while just including the material property uncertainties has a significant impact. Adding the aerothermal uncertainties on top of the trajectory dispersions and material property uncertainties also only has a small impact. In order to confirm that 8001 cases were sufficient for the analysis, the standard deviation of peak bondline temperatures was evaluated as each subsequent iteration was added. The standard deviation had converged by 3000 iterations, suggesting that more iterations beyond 8001 would not add value to the analysis.

Summary and Future Work: The SRL team demonstrated a framework to identify the stressing trajectory from a full dispersed trajectory set, and turn them into design environments, used to inform TPS testing. It was found that the traditional margining approach resulted in extremely high bondline temperature margins, which dominated the RSS sizing. An alternative, less conservative, margining approach was explored. A Monte Carlo analysis that included trajectory dispersions, aerothermal uncertainties, and material property uncertainties was performed, where the TPS thickness set at a constant design thickness, based on the traditional TPS sizing approach. In this Monte Carlo analysis, not a single case of the 8001 cases exceeded the allowable BLT limit. Similar Monte Carlo analyses were run using decreased TPS thickness to assess the required thickness such that the BLT limit was exceeded in just 1% of cases. This analysis was only done for a single body point on the shoulder of the heatshield; as such, future work includes performing similar analyses across the rest of the aeroshell. The time at which the BLT temperature exceeds the allowable as well as the location on the heatshield may also factor into risk posture. Further analysis should be conducted to refine this method and determine if and how it may be used going forward.

References:

[1] Edquist, K., et al. (2009), *41st AIAA Thermophysics Conference*.

[2] Milos, F. and Chen, Y.K. (1999), *J. of Spacecraft and Rockets*.