Performance Characterization, Sensitivity and Comparison of a Dual Layer Thermal Protection System

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Motivation

With the goal of landing high-mass cargo or crewed missions on Mars, NASA has been aiming to develop new thermal protection technologies with enhanced capability and reduced mass compared to traditional approaches.[5] A study was conducted on a dual layer thermal protection system (TPS) to identify sensitivities in performance to uncertainties in material properties and aerothermal environments. A performance metric which is independent of the system construction was developed in order to directly compare the results of the traditional, dual layer and eventually, flexible thermal protection systems.

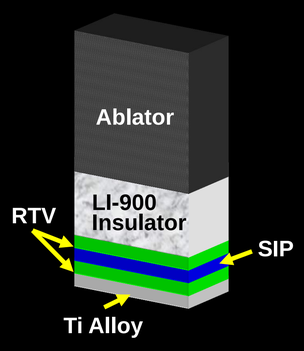

Fig. 1. Schematic of the Dual Layer TPS construction. From top to bottom: ablator, insulator (LI-900 shuttle tile), Room Temperature Vulcanized (RTV) adhesive, a strain isolation pad (SIP), a second RTV layer, and a titanium alloy backshell

Quantifying Performance

One of the primary goals of this study was to develop a metric to quantify and compare the performance of not just a dual layer or traditional TPS, but any thermal protection system. The purpose of developing such a performance metric is to assess TPS design efficiency while including characteristics of the trajectory rather than simply using the masses of the systems. In order to capture the ability of a thermal protection system in regard to both the trajectories it can fly and the mass required to do so, a new TPS performance metric was established. This metric, Specific Heat Load (Q_{SP}), is a ratio of the total integrated heat load seen by the TPS to the required areal mass to successfully fly that trajectory while protecting the vehicle.

$$\text{Specific Heat Load}, Q_{SP}, = \frac{\text{Total Integrated Heat Load}}{\text{Total TPS Areal Mass}}$$

Trajectory Investigated

The test case used for this study consisted of a mid L/D rigid aeroshell vehicle on a dual heat pulse trajectory. The first pulse would slow the vehicle from its hyperbolic approach trajectory to a parking orbit via aerocapture within Mars' atmosphere. Following a long on-orbit cool off period, the vehicle would then perform an entry maneuver through the atmosphere and down to the Martian surface.

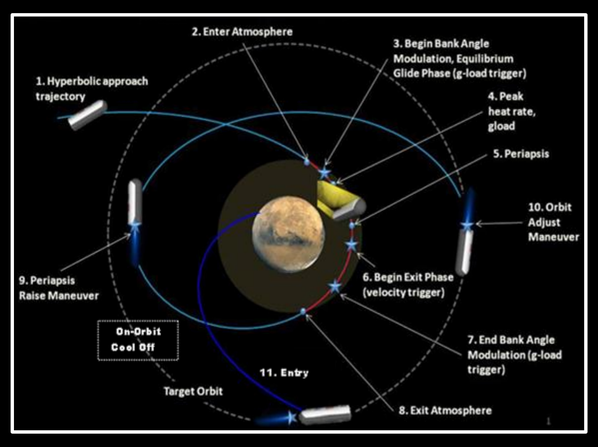

Fig. 2. Events leading from the hyperbolic approach trajectory to touchdown on the Martian surface. [3]

TPS Sizing Approach

To determine the required thickness of each layer for a given node on the vehicle, a three step sizing process was used for the dual layer system. First, only the entry portion of the trajectory was run with the insulator as the only protecting material ensuring that the RTV reaches exactly its allowable temperature (560 K). Next, keeping this thickness of the insulator, the entire aerocapture and entry trajectory is simulated with an ablator on top of the insulator. In this case, the ablator is sized such that the maximum temperature of the insulator surface is equal to its maximum specified temperature (1700 K for LI-900). Finally, the whole trajectory is simulated again with the optimized thickness of the ablator now remaining constant while the insulator is resized until its thickness is again optimal for keeping the RTV maximum temperature at its threshold.

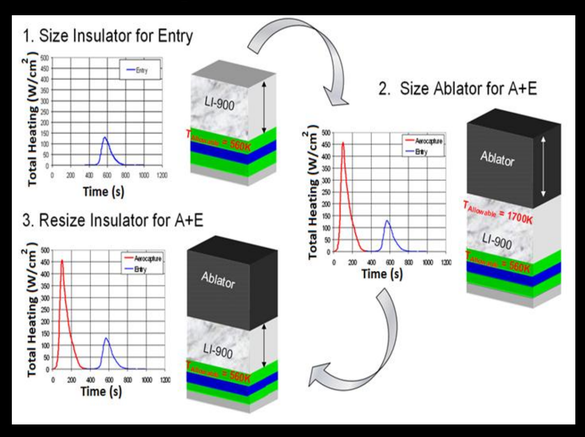

Fig. 3. Three step sizing process showing heat load experienced by the vehicle vs. time, the layer being sized in the material stack, and the constraining allowable temperature for each step.

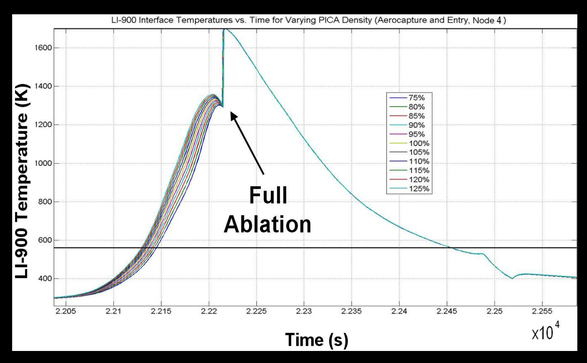

Fig. 5. LI-900 Surface Temperature vs. Time for the entry portion of the trajectory with varying PICA density. The temperature peak seen after full ablation is constrained to 1700 K to calculate optimal thickness of the ablator.

Computational Approach

The ablation and thermal analysis tool used in the study was the Fully Implicit Ablation and Thermal Response Program (FIAT). In order to carry out the high volume of input file modifications, FIAT simulations, data organization, and post-processing, a custom MATLAB™ architecture was constructed around FIAT.

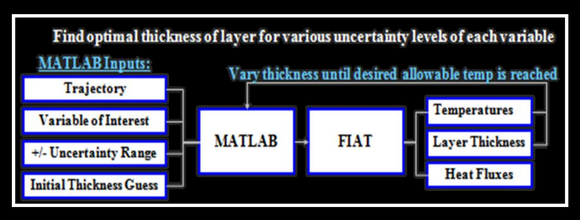

Fig. 4. Flow diagram depicting the computational tools used and the flow of information in the sizing process

Results

The TPS sizing method was used to perform sensitivity analyses and performance characterization on a Mid L/D vehicle at five different locations corresponding to five different values for the total integrated heat load seen throughout the aerocapture + entry trajectory. This was done with both dual layer and traditional TPS.

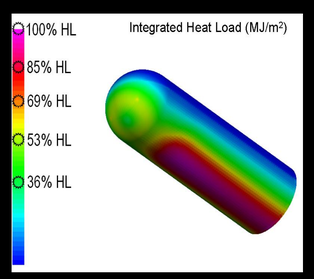

Fig. 6. The mid L/D rigid aeroshell vehicle with contours of total integrated heat load shown. The five circled heat loads represent the heat loads investigated in this study.[5]

Key Parameters

An important milestone in this study was the identification of the variables to which the areal mass of the TPS was most sensitive. This sensitivity analysis was conducted on a node subject to 85% of the total heat load for both TPS constructions with PICA (Phenolic Impregnated Carbon Ablator) as the ablator in each case.

Dual Layer: Most important variables for 85% Heat Load

Rank	Layer Sized	Trajectory	Variable	Min Areal Mass (% of nominal)	Max Areal Mass (% of nominal)
1	PICA	A&E	Surface Roughness	85.70%	114.14%
2	PICA	A&E	LI-900 Allowable Temp	81.90%	103.92%
3	LI-900	A&E	LI-900 Density	99.21%	100.81%
4	PICA	A&E	PICA Conductivity	99.46%	100.38%
5	PICA	A&E	PICA Density	99.68%	100.16%

Single Layer: Most important variables for 85% Heat Load

Rank	Layer Sized	Trajectory	Variable	Min Areal Mass (% of nominal)	Max Areal Mass (% of nominal)
1	PICA	A&E	Surface Roughness	89.73%	110.27%
2	PICA	A&E	RTV Allowable Temp	95.48%	104.52%
3	PICA	A&E	PICA Conductivity	96.72%	103.28%
4	PICA	A&E	PICA Density	98.35%	101.65%

Table 1. Summary of the areal mass variations due to +/- 3 sigma changes in system variables. The highlighted rows are the variables to which the system was most sensitive to.

Performance Sensitivities

After identifying the key sensitivities in the problem, the performance of both the dual layer and traditional TPS was compared directly using specific heat load, the parameter established in this study, as the metric of interest. Both the absolute performance and its sensitivity to changes in the variables previously identified were investigated. Below is a plot of specific heat load at the 85% node. The red and green lines are the nominal values for the dual and single layer constructions, respectively. The vertical bars indicate the range of variation in Q_{SP} due to +/- 3 sigma changes in each of the variables of interest.

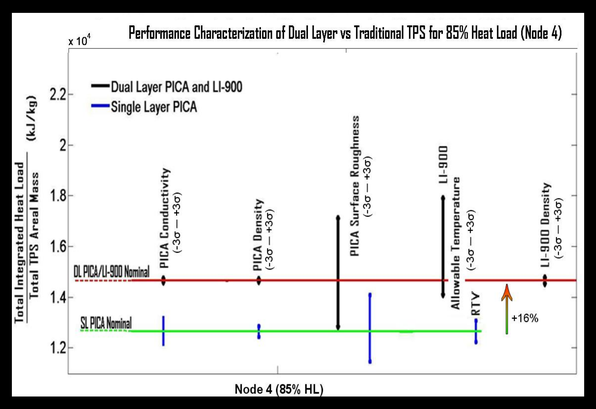

Fig 7. Variations in Q_{SP} for variations in key parameters from their -3σ to +3σ uncertainty values. Note that surface roughness and allowable temperature induce the greatest performance variation and the nominal performance of the dual layer is 16% greater than the traditional monolithic TPS.

Performance vs. Total Integrated Heat Load

When looking at results from only one reference node, as in Figure 7, one can see how changes in each variable impact the performance of the TPS. However, when this data is shown along with data from other heating conditions, conclusions about the relationship between heat load, overall performance, and sensitivity can be drawn. In Figure 8, this data is shown in the same form as in Figure 7, with the performance variations for due to each variable displayed. In Figure 9, the Root-Sum-Square of the all the sensitivities for each heating node is plotted to present a sense of overall variability in the system performance as a function of heat load.

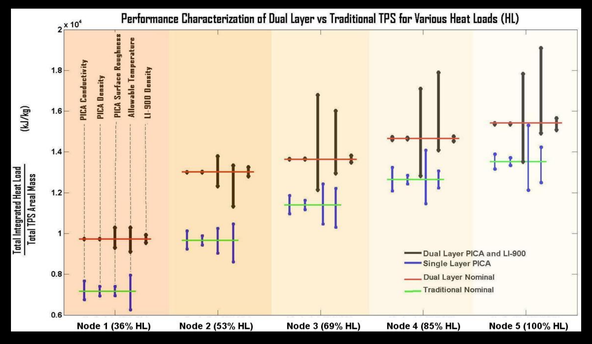

Fig 8. Variations in Q_{SP} for variations in key parameters - all nodes. Note that sensitivities increase with heat load.

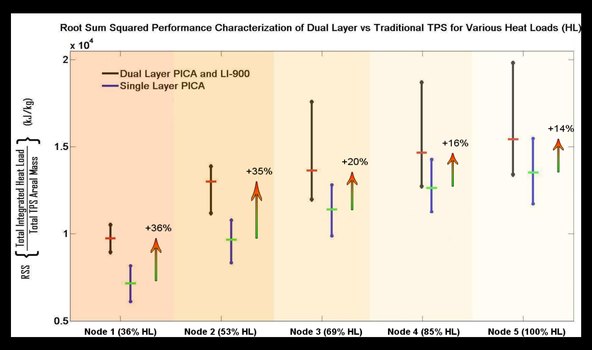

Fig 9. RSS Variations in Q_{SP} for variations in key parameters - all nodes. Note that the relative benefit of the dual layer system is highest in the low heating environment.

Conclusions

A study was conducted with a new dual layer thermal protection system and the traditional single layer TPS to identify sensitivities in performance to uncertainties in material properties and aerothermal environments. A performance metric, Specific Heat Load, was developed in order to directly compare the results of the traditional, dual layer and eventually, flexible systems. Overall sensitivity in performance increased with increasing heat load for both systems as well as absolute performance. The relative benefit of the dual layer system over the traditional TPS is substantial across the board, but decreases as the heat load increases. At the lowest heat load investigated here, the relative improvement was 36% and at full heat load the benefit was 14%.

Literature cited

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