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April 2018

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Abstract

Vehicle size and weight are driving cost factors in sending vehicles into space because the cost of launch is directly related to the payload mass being delivered. Vehicle size and weight have a larger impact on deep-space missions compared to sending a payload to low Earth orbit due to the extra fuel and supplies required to complete the longer duration mission. One area of study for possible vehicle volume or weight reduction is the thermal protection system (TPS) of a vehicle. Hot structures have been proposed as a TPS concept which can carry both primary structural loads and thermal loads. The use of hot structures on a Mars entry vehicle may be feasible and have potential volume and weight savings over the current state of the art ablative TPS technology.

A preliminary trade study was performed on a mid lift-to-drag aeroshell Mars entry concept vehicle; comparing the weight and skin thickness of a vehicle using ablative TPS with a vehicle using hot structures. Independent thermal and structural analyses were performed to determine the minimum mass designs. The goal of this study was to determine if the use of hot structures was feasible and had potential for significant vehicle volume and weight savings over the current state of the art. This trade study found that use of a hot structures leads to a feasible alternative to ablative TPS technology, with potential 53% weight and 22% thickness (volume) saving benefits that could enable future missions.

1 Introduction

Thermal protection is a requirement for planetary entry vehicles to protect them from the extreme aerodynamic heating encountered when entering an atmosphere from space. The cargo and crew of the vehicle must be protected from the high temperatures while the velocity is reduced for landing on the surface. A goal of NASA is to send humans to the surface of Mars requires the landing of large payloads on the surface. The current state of the art can deliver 1.5 metric tons, however human exploration of Mars will require the capability to deliver 20 metric tons or more [1]. The development of innovative entry vehicle systems is necessary to improve current technologies for delivering large payloads to Mars [2].

Existing thermal protection system (TPS) approaches use an ablative or insulating material attached to an underlying structure. The underlying structure carries the structural loads on the vehicle at a non-elevated temperature. Ablative TPS is used for vehicles with ballistic entry that experience relatively high heating rates, like Apollo and Orion. Insulating TPS is used for vehicles with shallower trajectories that experience realitively lower heating rates, such as the Space Shuttle [3].

An innovative multifunctional hot structure (HOST) heatshield design has recently been proposed [4] as an alternative to the previously discussed technologies. The HOST concept is a rigid heatshield, an aeroshell with a high temperature ceramic matrix composite (CMC) on the outer surface covering a lightweight flexible insulation. The fundamental difference with the ablative TPS design is that with an ablative TPS design the mechanical loads are carried by an underlying structure that is temperature limited, thus it is necessary to insulate the structure via the ablator. Alternatively, in HOST the CMC carries the mechanical loads at elevated temperatures with insulation behind the structure to protect the payload from the heat loads acting on the CMC. Potential advantages of the HOST concept include reduced weight, lower volume, and reusability.

The Mars Science Laboratory (MSL) used a phenolic impregnated carbon ablator (PICA) for the ablative TPS (heatshield) material [1] and demonstrated the capability to deliver 1.5 metric tons to Mars. The vehicle size and weight of MSL, as well as Apollo and Orion, were constrained by the launch vehicle. The MSL vehicle diameter was limited by the launch vehicle diameter, which was approximately five meters.

Emerging technologies being studied for delivering larger payloads which increase the size of the vehicle forebody, include Hypersonic Inflatable Advanced Decelerator (HIAD) concepts [5] and the Adaptive Deployable Entry Placement Technology (ADEPT) [6]. The HIAD utilizes a stack of inflatable toroids to increase the surface area of the entry vehicle. A large aeroshell is mechanically deployed by the ADEPT. Although HIAD and ADEPT are both ballistic entry designs, the mid lift-to-drag (Mid L/D) vehicle is a lifting body concept being studied for sending large payloads to the surface of Mars [7, 8]. The differences in entry trajectories of the ballistic and lifting body designs will lead to different heating loads and potentially dissimilar TPS designs.

Another recent concept for mission operations that directly affects the TPS design of a vehicle is using an aerocapture maneuver prior to entry, descent, and landing (EDL), for a total of two distinct trajectories and, therefore, subjecting the vehicle to two different heating loads. The aerocapture maneuver involves briefly dipping into the atmosphere of the planet to induce aerodynamic drag, and therefore, slow the vehicle down before the vehicle exits the atmosphere and returns to an orbit. The vehicle then performs EDL at this reduced velocity to the planetary surface. Aerocapture coupled with EDL was first successfully performed on the MSL mission. The work in this paper assumed an aerocapture and EDL mission operation.

The work by Walker, et al. [4] performed a thermal and structural sizing analysis using the HOST concept for the MSL heatshield. In this study, the authors used a stiffened carbon-carbon outer skin, sized by the structural loads, and a fibrous insulation behind the outer skin, sized by the thermal loads. The loads were representative of the actual MSL mission. The study then compared the HOST concept and the original

MSL design, finding a mass savings when using the HOST methodology. Following the work on the MSL heatshield design [4], this study compared the ablative TPS and HOST aeroshell designs for a Mid L/D vehicle with thermal and structural design optimization to minimize the structural and TPS contributions to the total vehicle weight. The current work was added to the previous study by determining if the HOST concept was favorable over a wide variety of vehicle shapes. Structural sizing was performed for launch and entry with constraints on the buckling and material stress limits under pressure and acceleration loads. A thermal analysis was conducted with a constraint on the material and backside temperature limit to size the insulation thickness under stagnation point heating during entry. This work focused on the preliminary sizing of a Mid L/D vehicle HOST aeroshell for the delivery of a 100 metric ton payload to Mars. The idealized vehicle geometry and aeroshell configurations are described in Section 2. The structural and thermal analysis models, as well as the loads and sizing approaches, are discussed in Sections 3 and 4, respectively. Finally, in Section 5, a comparison is presented of the weight and volume differences between the optimized HOST aeroshell and ablative TPS designs.

2 Conceptual Vehicle and TPS

A previous study conducted on the ablative TPS design for the Mid L/D vehicle included the creation of a parametric model built using Python[1] scripts. Python is an object-oriented high-level programing language. The script generated multiple finite element models according to a varying set of input parameters, which included the structural layout and dimensions [7]. A structural sizing of the Mid L/D vehilcle using the ablative TPS design was performed for the same loading conditions to be described in the following sections [8].

Two designs were studied for the Mid L/D vehicle: an ablative TPS design and a HOST design. The structural dimensions for the skin and stiffeners were sized for weight which satisfy material limits and buckling for aerodynamic pressure and acceleration loads during Earth launch and Mars entry. The insulation thickness was sized to minimize weight for the convective and radiative heating during Mars entry. The geometry, analysis models, and loading conditions for the structural and thermal optimization are defined in the current and following sections, respectively.

2.1 Idealized Vehicle Configuration

An idealized vehicle geometry was chosen for simplicity and consistency with the previous study [7,8]. The cylidrical aeroshell was 30-meters long

[1] www.python.org

with a 10-meter diameter and a hemispherical nose. It was supported by stiffeners in the form of rings (frames) and longerons. The structurally optimized ablative TPS design had 6 rings and 8 longerons [8], which was the starting point for the HOST design to begin optimization. The dimensions of the vehicle with a sample stiffener combination are shown in Figure 1. The stiffeners are highlighted in red.

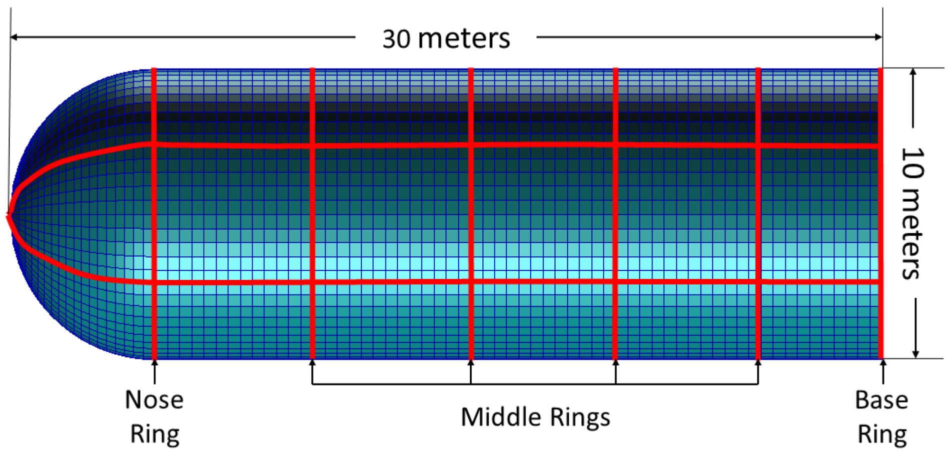
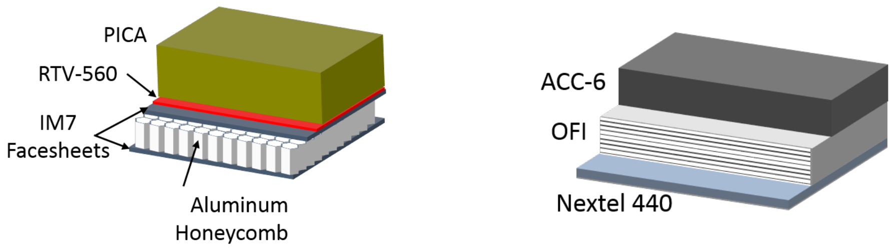


Figure 1: The idealized Mid L/D aeroshell geometry and a potential stiffener arrangement.

2.2 Ablative TPS and HOST Designs

A visual comparison between the ablative TPS (baseline) design and HOST design is depicted in Figure 2. Generally, the ablative TPS design consisted of an ablator, adhesive layer, and a sandwich composite load carrying structure. Specifically, the ablative TPS design consisted of PICA installed over 0.3-mm thick room temperature vulcanizing (RTV-560) silicone adhesive which was bonded to the honeycomb structure. The honeycomb structure consisted of HexTow$^{\text{TM}}$ IM7 carbon fiber facesheets and an aluminum honeycomb core.

Generally, the HOST design consisted of a carbon-carbon or ceramic matrix composite structure, insulation, and a blanket layer. Specifically, the HOST design in this study used advanced carbon-carbon (ACC) that has undergone six pyrolysis cycles, hence forth called ACC-6 for the material at the outer surface, opacified fibrous insulation (OFI) [9], and a 0.5-mm thick Nextel 440$^{\text{TM}}$ fabric blanket which held the fibrous insulation in place.



(a) (b)

Figure 2: Schematic of the different TPS designs: (a) ablative TPS and (b) HOST.

3 Structural Analysis and Sizing

Structural analysis and sizing was preformed using linear finite element methods. An existing finite element model [7, 8] was modified for the HOST design.

3.1 Finite Element Model

The finite element model consisted of rod and beam elements, shell elements, and point masses. The rings and longerons were modeled using bar elements with a channel cross-section, shown in Figure 3. The dimensions labeled on the figure correspond to the variables that were optimized for each stiffener set. The skin of the vehicle was modeled using shell elements, shown in Figure 1.

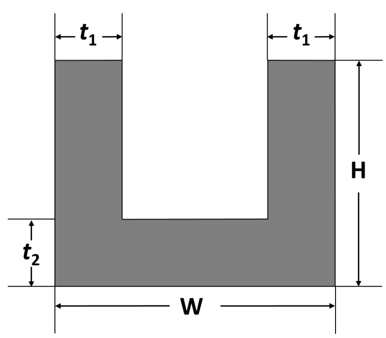


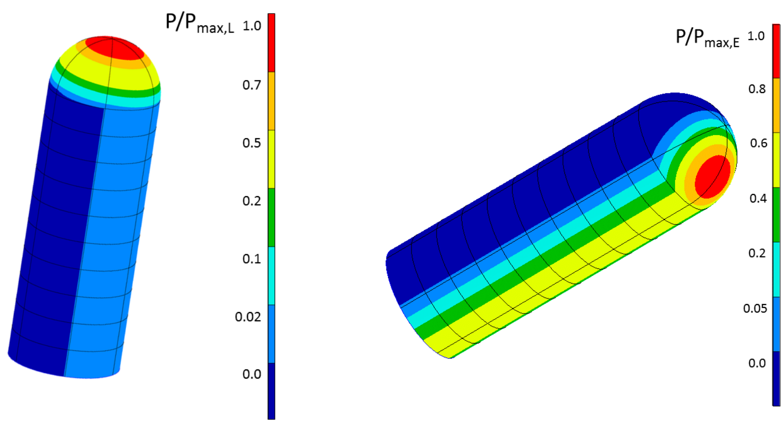
Figure 3: Channel stiffener cross-section with the variables labeled.

The payload was modeled by point mass elements equally distributed between the center rings. These point masses were attached to each other and the outer rings using rod elements. The beam and shell elements were given mass properties corresponding to the materials being considered. The TPS (PICA and OFI) did not provide structural support, but the mass of the TPS contributed to the inertial load on the vehicle. Therefore, the TPS was represented in the model by including a non-structural mass on the shell elements.

The HOST design was added as a capability to the parametric model previously discussed. The area of interest for this study was the number and combination of rings and longerons, therefore, all other aspects of the vehicle (overall vehicle dimensions, skin thickness, and loads) were held constant. The parametric model could quickly create finite element models with different combinations of stiffeners.

3.2 Loads and Boundary Conditions

Load cases for both Earth launch and Mars entry were approximated using methods described in this section. Earth launch loads consisted of the aerodynamic pressure load and the inertial loads experienced during launch [8]. The Earth launch aerodynamic load was modeled as a distributed pressure load on the vehicle at a 5° angle of attack, depicted by the contour plot in Figure 4a. The Earth launch inertial loads were 4g axial and 0.75g lateral. The Mars entry load case consisted of a distributed pressure load with the vehicle at a 55° angle of attack, depicted by the contour plot in Figure 4b.



(a) (b)

Figure 4: Normalized Mid L/D pressure loads for (a) Earth launch and (b) Mars entry.

The boundary conditions for the launch load case were single point constraints on each longeron at the base of the model. The entry load case did not have any fixed boundary conditions and, therefore, inertial relief was used to model the reaction forces that the vehicle would experience as it entered the martian atmosphere. Properly modeling both the structural and non-structural mass allowed for inertial relief to be used for the entry load case.

3.3 Design Variables and Constraints

The design variables for the ablative TPS design included the four cross-section dimensions (as seen in Figure 3) for the longerons, nose ring, base ring, and middle rings. The thickness of the honeycomb core and facesheets was also included as a design variable in the sections created between the rings. For the design with 8 rings and 6 longerons, this resulted in 28 variables as listed in Table 1. Structural sections 1 to 5 in Table 1 refer to the areas created between the rings on the vehicle. For the HOST design, the design variables consisted of the cross-section dimensions of the stiffeners. The dimensions for the cross-sections led to 16 design variables for all stiffener configurations as listed in Table 2.

Table 1: The design variables for each component in the ablative TPS design.

Structural Component	Design Variables
Longerons	H,W,t_1,t_2
Nose Ring	H,W,t_1,t_2
Middle Rings	H,W,t_1,t_2
Base Ring	H,W,t_1,t_2
Nose Section	Facesheet thickness, Core thickness
Section 1	Facesheet thickness, Core thickness
Section 2	Facesheet thickness, Core thickness
Section 3	Facesheet thickness, Core thickness
Section 4	Facesheet thickness, Core thickness
Section 5	Facesheet thickness, Core thickness

Table 2: The design variables for each component in the HOST design.

Structural Component	Design Variables
Longerons	H,W,t_1,t_2
Nose Ring	H,W,t_1,t_2
Middle Rings	H,W,t_1,t_2
Base Ring	H,W,t_1,t_2

The vehicle was optimized under four conditions: static analysis of launch and entry loads; and buckling analysis of launch and entry loads. The static analysis was performed without using a factor of safety and required that the material limits not be exceeded. The buckling analysis required that the buckling eigenvalues be greater than one to ensure that the critical buckling load was higher than the applied loads. Geometric constraints on the stiffener dimensions given in equations (1) to (4) were included to avoid infeasible cross-section dimensions and local buckling to the stiffeners [7]. These constraints were specific to the channel cross-section and correspond to the dimensions in Figure 3.

$$\frac{t_1}{\text{W}} \leq 0.5 \tag{1}$$

$$\frac{t_2}{\text{H}} \leq 1.0 \tag{2}$$

$$\frac{t_2}{\text{W}} \leq 0.125 \tag{3}$$

$$\frac{t_1}{\text{H}} \leq 0.125 \tag{4}$$

The material constraints for the optimization stated that the finite element stress be less than or equal the material limit for the skin and stiffeners in both the ablative TPS and HOST designs. For the HOST design this constraint included both the launch and the entry loading conditions, while the ablative TPS design only included the launch condition. The ablative TPS design was previously optimized without considering the buckling entry loads, as prior work had shown that the entry cases were not design drivers. Therefore, the structural dimensions for the ablative TPS design were optimized according to the static and buckling analysis of the launch load case [7,8]. Minimum frequency constraints were not considered.

Each finite element model with a unique stiffener configuration was structurally optimized using Nastran solution 200, a linear gradient-based search optimizer. The objective function of the optimization was to minimize the total vehicle weight. The vehicle weights of various stiffener arrangements were then compared to identify trends and the lowest weight vehicle design in the identified design space.

3.4 Model Convergence

A convergence check was performed on the finite element model to determine the appropriate mesh size for this study. Two different approaches were taken. Each approach doubled the number of elements in the radial and axial directions. The first approach studied the Nastran solution 101 static analysis results of two un-optimized designs, comparing the maximum stress for the launch and entry load case. The entry case had a larger percent difference of 7.8% between the two mesh sizes. The effect of the mesh on the optimized weight, the key quantity of interest, was also analyzed and showed a difference of 1.4%. The results from the two approaches indicated that the mesh size was appropriate for the analysis performed in this study.

3.5 HOST Results

The HOST results are summarized in Figure 5 and Table 3. Each column in Figure 5 represents a single design combination of stiffeners with optimized stiffener dimensions. The number of rings and number of longerons are on the primary horizontal and depth axes respectively, while the total design weight is on the primary vertical axis. Designs with a weight of zero represent a stiffener combination for which a feasible design was not found which satisfied the constrain conditions.

From this graphic the trend toward an optimum can be seen. It should also be noted that the rings had a much greater effect on the design weight than the longerons. The 10 longeron arrangement with 5 and 13 rings may be showing slightly different trends on the bounds of the problem, or they may be indications that the optimizer found a local minimum rather than a global minimum. The design with 11 rings and 8 longerons was used for comparison with the ablative TPS design because that design was the minimum weight design.

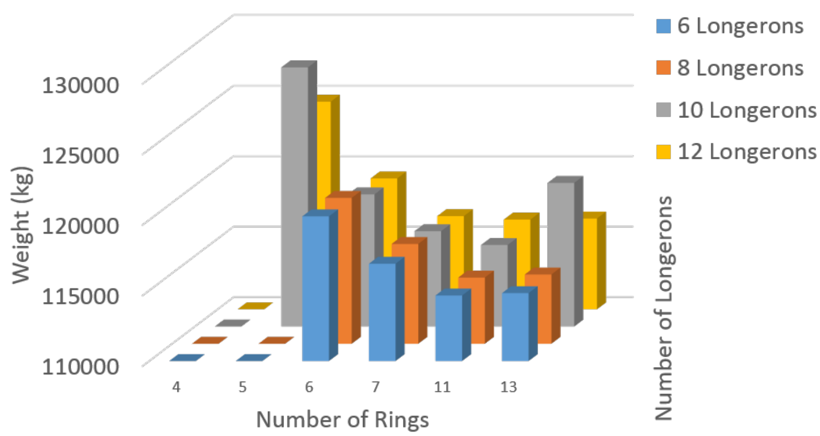


Figure 5: Total vehicle weight of structurally optimized HOST designs using 24 different stiffener combinations.

4 Thermal Sizing

The Fully Implicit Ablation and Thermal Response (FIAT) code [10] was used to perform thermal analysis and sizing for both the ablative TPS and HOST concepts. FIAT is a one-dimensional transient ablation and thermal analysis and sizing code for multilayer TPS concepts subject to aeroheating on one surface. The thermal analysis accounted for pyrolization, ablation, and surface recession of the heated material and heat conduction through the insulation.

Due to the coupling of design variables between the structural (required insulation thickness) and thermal (required skin material thickness) analyses, the study took an iterative approach. After each design was structurally sized using an estimated insulation thickness for the

Table 3: Feasibility and total weight for each design combination considered. Weight is measured in metric tons (Tonne).

Rings	Longerons	Feasible?	Weight (Tonne)	Rings	Longerons	Feasible?	Weight (Tonne)
4	6	No	N/A	7	6	Yes	116.89
4	8	No	N/A	7	8	Yes	117.10
4	10	No	N/A	7	10	Yes	116.76
4	12	No	N/A	7	12	Yes	116.60
5	6	No	N/A	11	6	Yes	114.71
5	8	No	N/A	11	8	Yes	114.69
5	10	Yes	128.37	11	10	Yes	115.93
5	12	Yes	124.79	11	12	Yes	116.36
6	6	Yes	120.20	13	6	Yes	114.87
6	8	Yes	120.34	13	8	Yes	114.87
6	10	Yes	119.37	13	10	Yes	120.18
6	12	Yes	119.28	13	12	Yes	116.43

non-structural mass terms of the model, the sized skin thicknesses were used as inputs into the FIAT program. The TPS thicknesses determined by FIAT were updated in the finite element model and re-analyzed. It was found that the updated non-structural mass quantity (derived from the TPS thickness determined by FIAT) was similar to the estimated non-structural mass and that the structural sizing of the model was not sensitive to the difference.

4.1 Model

Flight trajectory and aeroheating data were provided as velocity, altitude, density, and total heat flux as a function of time for both the aerocapture and EDL portions of flight [11]. The total heat flux included the radiative heating in the shock layer and the convective heating. The trajectory data was calculated using POST [12], and the aeroheating data was calculated using the Sutton and Graves approximation [13] for stagnation point heating. The stagnation point heating was applied uniformly over the entire vehicle. The FIAT surface environment files consisted of recovery enthalpy, enthalpy-based heat transfer coefficient, and pressure. Dynamic pressure was required for pyrolization and ablation calculations in FIAT for PICA while, the static pressure was used for the thermal conductivity calculation of the OFI. The blowing parameter required in FIAT was set at 0.5 for both concepts.

The material property database file provided with FIAT included most of the materials used for this study. For the ablative TPS design, existing PICA and RTV-560 models in the FIAT database were utilized. The existing aluminum honeycomb model in FIAT was used with the density of the honeycomb adjusted to match the desired honeycomb density for this study. The graphite BMI model in FIAT was used to represent the composite IM7 facesheets, with the density of graphite BMI adjusted to IM7 density values. For the HOST design, an existing FIAT reinforced carbon carbon (RCC) ablation model was used in conjunction with recent thermal and radiative properties of ACC-6. OFI thermal properties from Ref. [9], recently extended at NASA Langley Research Center up to 1700°C for an effective density of 192.2 kg/m^3 were used. Nextel 440 fabric thermal and radiative properties up to 1100°C, developed for Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Flexible TPS program [14], were used. All calculations were performed assuming a carbon dioxide environment. The material layup for each design is shown in Figure 2.

The initial uniform temperature (through thickness) of both concepts was assumed to be 20°C for both aerocapture and entry analysis for both concepts. A sizing analysis for both aerocapture and entry was performed to size the TPS for both designs. The sizing parameters were the thickness of the PICA and thickness of the flexible fibrous insulation for the ablative TPS and HOST designs, respectively.

4.2 Loads and Boundary Conditions

The heat fluxes for aerocapture and entry portions of flight are provided in Figure 6. In the figure, both trajectories were normalized to the maximum aerocapture heat flux and were plotted on the same time scale, but in reality, the trajectories take place at different times. The aerocapture portion had a longer duration heating pulse with maximum heat flux of 86.9 W/cm^2, while entry had a shorter duration heat pulse with a peak heat flux of 23.5 W/cm^2. An adiabatic back wall boundary condition was conservatively assumed.

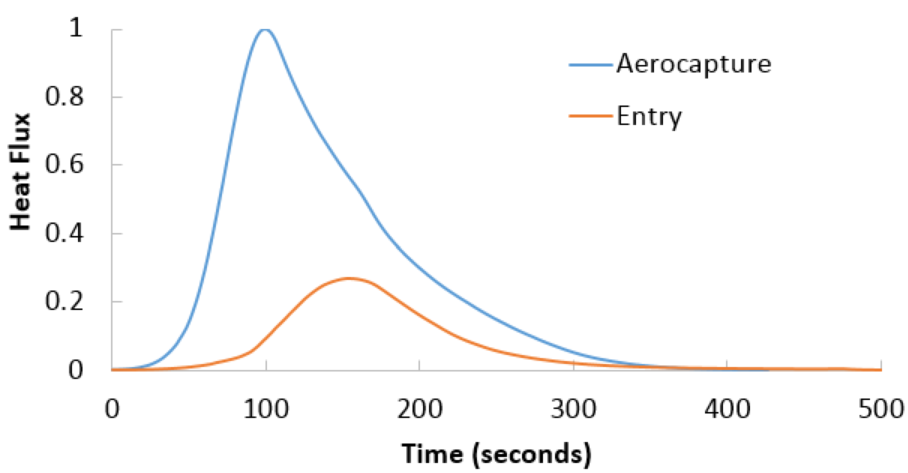


Figure 6: Heating rates for aerocapture and entry

4.3 Design Variables and Constraints

The ablative TPS thermal design consisted of a variable thickness PICA installed over 0.3-mm thick RTV-560 which was bonded to a honeycomb structure. The honeycomb structure consisted of 1.0-mm thick IM7 facesheets and a 20.0-mm thick aluminum honeycomb. The thickness of PICA was sized subject to the constraint that the RTV-560 temperature does not exceed 300°C. This temperature limit was derived from the material temperature constraints of RTV-560. For the HOST design, the thermal analysis layup consisted of 6.35-mm thick ACC-6, OFI with variable thickness, and a 0.5-mm thick Nextel 440 fabric. The thickness of OFI was sized subject to the constraint that the Nextel 440 fabric temperature should not exceed 150°C. This temperature limit was based on an assumption of the temperatures that potential payloads could withstand. The material temperature limit of the Nextel 440 fabric did not set the maximum limit since the Nextel 440 fabric can withstand much higher temperatures. Both the ablative TPS and HOST layups are depicted in Figure 2.

4.4 Model Convergence

The FIAT program utilized its own algorithm to determine an automatic grid spacing. The initial grid spacing was uniform within each material layer, and remained uniform thoughout the analysis with the exception of the outermost layer, which ablates. The outermost grid on the layer adapted to the changing outer mold line as necessary as the material ablated [10]. The number of grid points per material layer utilized in the thermal analysis is shown in Table 4. To confirm that the grid spacing was adequate, an additional analysis was run at each trajectory, aerocapture and entry for both the ablative TPS and HOST designs. In each of the additional analyses the number of grid points in each layer was doubled from that of the original analysis. The results from the doubling of grid points in each layer resulted in less than a 1% difference in total PICA or OFI thickness for both the aerocapture and entry trajectories. The small difference in the results confirmed that the spacing used in this study was adequate.

4.5 Results

The sizing of the PICA thickness for the ablative TPS design significantly depended on both the aerocapture and the entry portions, while the sizing of the OFI insulation for the HOST concept was only significantly affected by the entry trajectory. The PICA was sized according to the heating profile for aerocapture and entry, resulting in a PICA thickness of 28.3 mm. PICA recession during aerocapture was 6.10 mm. The remaining 22.2-mm thick PICA was sufficient to handle the entry temperature constraint. The recession of PICA during entry was 3.30 mm.

Table 4: The number of grid points for the ablative TPS and HOST designs used for the aerocapture and entry trajectories.

Material	Aerocapture Grid Points	Entry Grid Points
PICA	39	40
RTV	2	2
Outer Facesheet	4	4
Aluminum Core	22	14
Inner Facesheet	4	4
ACC-6	21	21
OFI	18	18
Nextel 440	2	2

OFI thickness was sized for aerocapture and it was found that 26.7 mm was sufficient to maintain the Nextel 440 fabric temperature below 150°C. The ACC-6 recession during aerocapture was 1.05 mm. However, the remaining ACC-6 and the 26.7-mm thick OFI was not sufficient to withstand the entry heating loads. The OFI thickness required for the entry trajectory was 35.9 mm. Therefore, the required OFI thickness for the vehicle would be 35.9 mm in order to be properly sized for the entry portion of the trajectory. The ACC-6 recession during entry was 1.36 mm.

The thermal analysis resulted in a PICA thickness of 28.3 mm with a non-structural mass of 8.16 kg/m^2 for the ablative TPS design and an OFI thickness of 35.9 mm with a non-structural mass of 5.63 kg/m^2 for the HOST design. The results are summarized in Table 5.

Table 5: Insulation thickness and areal density results from the thermal analysis for both the ablative TPS and HOST designs.

Ablative TPS Design	
Temperature Constraint	300°C at RTV-560/PICA interface
PICA Thickness	28.3 mm
Non-Structural Mass	8.16 kg/m^2
HOST Design	
Temperature Constraint	150°C at Nextel 440 Fabric
OFI Thickness	35.9 mm
Non-Structural Mass	5.63 kg/m^2

5 Comparison of Ablative TPS and HOST Designs

The optimized HOST design was compared with the ablative TPS design using weight as the key metric. The total thickness for each design, which impacts the volume and control of the vehicle, was also included in the comparison.

5.1 Weight

Determining if the hot structure design could lead to a vehicle weight savings was a key goal for this study. This study showed that the HOST concept had a 53.1% weight savings over the ablative TPS design, when considering the mass of the vehicle without the 100 metric ton payload. The weight savings corresponded to a difference of 19,600 kg. A component breakdown of the weights of each design is shown in Table 6. In the table, the non-structural mass represents the TPS required for each design. For the ablative TPS design the non-structural mass accounted for the PICA and RTV-560 and for the HOST design the non-structural mass accounted for the OFI and Nextel 440.

Table 6: Ablative TPS and HOST designs vehicle weight breakdown. (100 metric ton payload is not included.)

Component	Ablative TPS Mass (kg)	HOST Mass (kg)
Longerons	520.	238
Nose Ring	75.6	26.9
Middle Rings	1,670	1,410
Base Ring	840	993
Skin	26,100	9,330
TPS	7,690	5,300
Total	**36,900**	**17,300**

5.2 Thickness

The difference in the aeroshell thicknesses between the two designs was noteworthy, with the ablative TPS design being 1.3 times thicker than the HOST concept. The difference stemmed from not only the thickness of PICA and OFI, but also the difference in the thickness of the ACC-6 and honeycomb sandwich. The component thicknesses are provided in Table 7, and Figure 7 is a visual representation of the differences in composition.

Thickness was an important metric to compare in this study, as it may have favorable effects on the vehicle both in terms of volume savings and center of gravity location. A reduction in skin thickness would lead more internal volume for the payload. A reduced skin thickness would also shift the center of gravity towards the outer mold line of the vehicle which, while outside the scope of this study, is generally favorable for vehicle stability and control.

Table 7: Skin and TPS thicknesses required after completing the structural and thermal optimization of the ablative TPS and HOST designs.

Ablative TPS Design	Thickness
PICA	28.3 mm
IM7 Facesheet	1 mm
Al Honeycomb	20 mm
RTV-560	0.3 mm
Total	**50.6 mm**
HOST Concept	Thickness
OFI	35.9 mm
ACC-6	6.35 mm
Nextel 440	0.5 mm
Total	**39.5 mm**

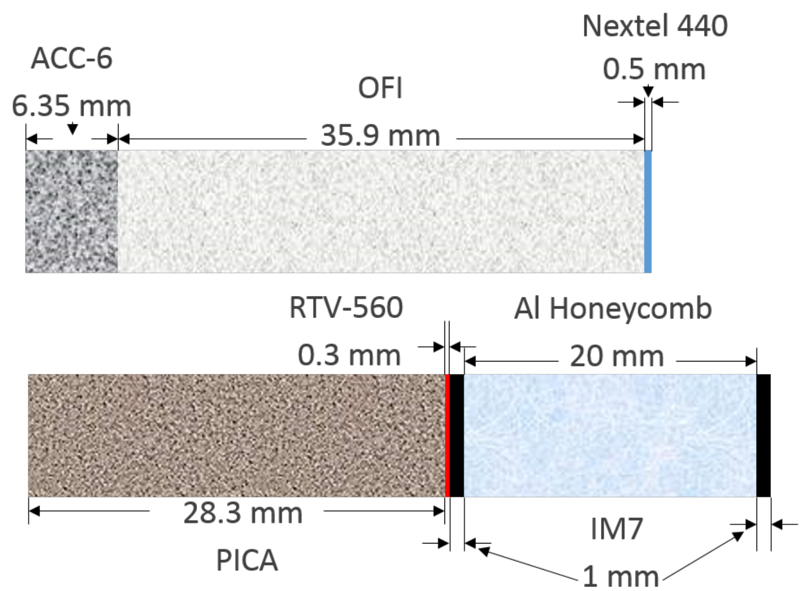


Figure 7: Pictorial representation (to scale) of the thicknesses of the Ablative TPS and HOST designs.

6 Concluding Remarks

A preliminary trade study was performed comparing the current state of the art ablative TPS design to HOST technology on a simple concept vehicle to deliver large payloads to Mars. The Mid L/D vehicle was used for a current technology comparison. Two loading conditions were considered, an approximation of Earth launch loads and Mars entry loads. An ablative TPS design was previously defined and structurally optimized using Nastran solution 200 [7, 8]. A minimum weight HOST design was selected from 24 different stiffener combinations that were each structurally optimized using Nastran solution 200. The thermal analysis was performed to size the TPS for each design: the PICA for the ablative TPS design and the OFI for the HOST design. The vehicle weight and skin thickness were compared for the ablative and HOST designs.

The results of this preliminary trade study indicates both a 53% weight and a 22% skin thickness reduction when using the HOST concept as compared to an ablative TPS design. Higher fidelity design and analyses work is required to obtain more accurate results than the results presented in this paper. A critical next step is to perform the structural and thermal analysis simultaneously, as the thermal loads may affect the mechanical properties of the load carrying components. Structural models will also need to be derived that use a more realistic geometry and take into account factors of safety for the material stress limits and knockdown factors on the buckling loads. Thermal models are also needed that do not assume stagnation point heating over the entire vehicle and can appropriately size the insulation for the leeward surface of the vehicle.

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14. ABSTRACT
Vehicle size and weight are driving cost factors in sending vehicles into space. One area of study for possible vehicle volume or weight reduction is the thermal protection system (TPS) of a vehicle. Hot structures have been proposed as a TPS concept which can carry both primary structural loads and thermal loads. A preliminary trade study was performed on a mid lift-to-drag aeroshell Mars entry concept vehicle; comparing the weight and skin thickness of a vehicle using ablative TPS with a vehicle using hot structures. Independent thermal and structural analyses were performed to determine the minimum mass designs. The goal of this study was to determine if the use of hot structures was feasible and had potential for significant vehicle volume and weight savings over the current state of the art. This trade study found that use of a hot structures leads to a feasible alternative to ablative TPS technology, with potential 53% weight and 22% thickness (volume) saving benefits that could enable future missions.

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