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Background

Venus probes and landers, Saturn and Uranus probes, and some high speed sample return missions have been highly ranked for their scientific value by the National Research Council (NRC) Planetary Science Decadal Survey (PSDS) committee. Due to their extreme entry environments, thermal protection system (TPS) options for these missions have been limited to a single heritage material, Carbon Phenolic (CP), except for a subset of sample return missions that fall within the capability of Phenolic Impregnated Carbon Ablator (PICA). The HEEET project is developing a woven TPS technology that will provide an efficient and readily-manufacturable heat shield material for entries with heating rates between 1500 w/cm^2 and 8,000 W/cm^2 and stagnation pressure between 1.0 atm and 10 atm.

Studies have been conducted to evaluate the impact of the HEEET technology on the mission design for three destinations. Several trajectories are evaluated for each destination, to support trades between TPS mass and peak deceleration and heating levels. The required TPS thickness has been calculated for CP and HEEET's woven TPS, so that the merits of each solution can be compared. It is possible to compare TPS areal mass for the same trajectory, or to find a more benign trajectory with the same TPS areal mass.

Here we provide a brief overview of the analysis methodology, including trajectory, heating analysis, and thermal response for TPS sizing. We then concentrate on studies for three mission opportunities:

Mission	Entry Mass (kg)	Diameter (m)	Shape	Relative Entry Velocity (km/s)	Entry Angle (º)
Venus Lander	2000	3.5	45º sphere-cone	10.8-11.6	-30 to skip-out
Saturn Probe	200	1.0	45º sphere-cone	26-28	-30 to skip-out
Sample Return	50	0.8	60º sphere-cone	15	-12 to -8

In each case, the entry mass is governed by the science need, and a range of entry conditions is considered to identify a reasonable range of peak deceleration for the science instruments and structure, reasonable heating rates for the material response and heat loads that can be accommodated with reasonable TPS thickness.

For all missions, the TPS thickness and mass for HEEET woven material are compared with those for carbon phenolic.

Overview of Sizing Methodology

The standard procedure for TPS preliminary design includes the following steps:

Definition of inputs

- An entry mass and vehicle size and shape are assumed (based on desired science payload mass and volume). A range of vehicles may be defined for a parametric survey of the design space.
- A target end state, or acceptable range of end states, is defined for the entry trajectory
- A range of initial conditions, or entry interface states, is defined.
- A model of the target body's gravitational field and atmosphere is selected.

Trajectory calculation

A three degree-of-freedom trajectory code is used to calculate the entry path for each instance of vehicle and entry condition defined for the study. The software marches in small time steps, calculating aerodynamic pressure, which is included in the force balance to update the velocity vector for the next time step. For parametric studies involving blunt vehicle shapes, the pressure is commonly estimated with a Newtonian approximation.

$$p_{stag} \approx \rho_\infty V_\infty^2$$

Aerothermal heating

At each step, the heating on the vehicle is also calculated. For parametric studies, the convective heat-flux at the nose is commonly estimated with a Fay-Riddell correlation, or a variant there-of. Similarly, the radiative heat-flux is estimated with a correlation. The constants C_{conv}, C_{rad} and b in the following expressions are tailored for each destination, to account for the effects of the atmospheric gas composition.

$$q_{stag,conv} = C_{conv} \frac{\sqrt{\rho_\infty}}{\sqrt{R_n}} V_\infty^{3.04}$$

$$q_{stag,rad} = C_{rad} \sqrt{R_n} \rho_\infty^{1.2} V_\infty^{b}$$

Later in the design process, a database of CFD solutions might be provided for a selected vehicle configuration, to support more accurate heating estimates at the stagnation point and to provide heating elsewhere on the vehicle, but such fidelity is typically not necessary to support comparison of design alternatives in a conceptual trade.

In the studies presented here, no attempt has been made to assess margined environments that account for uncertainties in entry state, atmosphere and estimated heating. Nominal values have been used in all cases. Hence, the results are suitable for comparison of options but not for detailed definition of flight hardware.

Material response

For extreme entry environments, thermal protection systems cannot rely entirely on re-radiation from an insulative material to accommodate the atmospheric heating, because the resulting surface temperatures exceed the mechanical capability of available materials. Ablative materials sacrifice mass through pyrolysis (release of gas due to chemical decomposition within the material) and ablation (conversion of solid material through sublimation, vaporization and oxidation) to manage extreme heating rates. Specialized analysis codes that account for all of these mechanisms are needed to predict in-depth heating of the thermal protection system. They should also account for mechanical loss of material through mechanisms such as melt flow, spallation and erosion. Important quantities to be considered in the analysis are summarized in Figure 1. Further details of the chemical analysis are beyond the scope of this summary, but can be found in Ref [3].

The variation in heating parallel to the surface is generally much smaller than the variation through the thickness of the thermal protection system, so a 1-dimensional model is sufficient for conceptual trade studies. Later in the design process, a multi-dimensional response model may be used in regions of high curvature or where the structure has high thermal mass to better account for lateral heat flow.

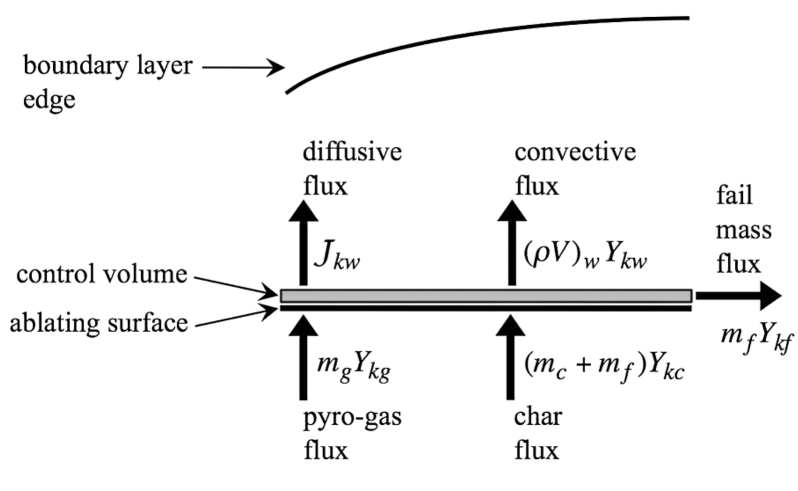

Figure 1. Mass fluxes at an ablating surface, from Ref [3]

The mass loss and the interior heating of the thermal protection system depend on the material constituents throughout the thickness of the system. The constituents affect the composition and quantity of the pyrolysis gas and the conduction of heat to the underlying structure. It is advantageous to have dense material close to the ablating surface, and less dense material, with lower conductivity, below the surface. However structural attachment at the interface between layers can be challenging. The three-dimensional weaving that is central to HEEET technology permits the use of different fibers and different weave densities at different locations through the thickness of the material, while the weaving still binds the layers together to provide the necessary mechanical integrity at the interface. Since the distinct layers have different material properties, they are handled separately in the material response model. Figure 2 shows the stacks used for Carbon Phenolic and for Woven TPS in the studies summarized in this report. To calculate the required thickness of thermal protection material, a temperature constraint is imposed at the interface between thermal protection material and the substructure, to maintain the integrity of the attachment, typically an adhesive bond, that secures the TPS to the substructure. The thickness is adjusted to satisfy this constraint, and to assure that virgin (unpyrolyzed) material remains at the interface. For the two-layer woven material, the recession layer is first sized to assure that it is thicker than the calculated recession depth, and then the insulative layer is sized to satisfy the substructure interface constraint.

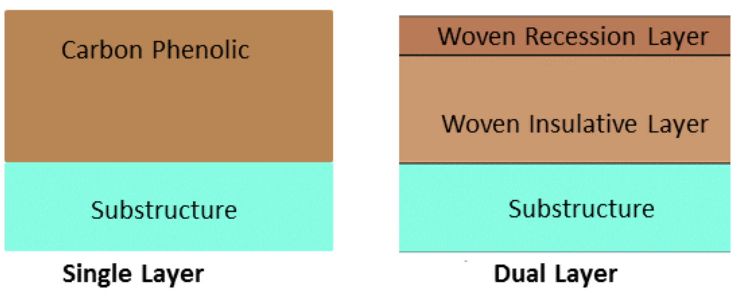

Figure 2. Material stacks in 1-dimensional model of Carbon Phenolic and Woven TPS

Material properties are required for all constituents of the system. A summary of properties relevant to thermal response, normalized to those of Carbon Phenolic, is provided in Table 1. A comprehensive database is available for heritage carbon phenolic, but properties for the new HEEET materials are based on a few measurements or derived by analogy with carbon phenolic. Conductivity for the insulative layer was measured with Comparative Rod Apparatus (CRA), and for the recession layer with laser flash. At each temperature, just 3 or 4 measurements are averaged. For temperatures above the range at which measurements have been made, the offset between CP properties and recession/insulating layer properties is extrapolated. Specific heat is calculated from Differential Scanning Calorimetry (DSC). Density is measured for multiple samples. Other quantities are adopted from the Carbon Phenolic database.

A more comprehensive set of material properties for woven TPS is expected to be released in the final Discovery AO bidders' library. Since the current set is immature, the values included here should not be over-interpreted.

	HEEET		Carbon Phenolic
	Recession	Insulative	
Heat of Formation	0.43	1.77	1.00
Virgin			
Density	0.72	0.54	1.00
Conductivity	0.89	0.41	1.00
Specific Heat	0.72	0.88	1.00
Char			
Density	0.79	0.34	1.00
Conductivity	0.75	0.71	1.00
Specific Heat	1.00	1.00	1.00

Table 1. Material Properties used in Sizing Studies normalized to the properties of Carbon Phenolic

Since the uncertainty in properties is relatively high at this point in the HEEET material development, this study included a sensitivity assessment for required thickness based on variations in assumed properties. Figure 3 summarizes results for a typical Saturn entry case. Even when all thermal conductivities (both virgin and char for both the insulating layer and the recession layer) are doubled (which is a much larger increase than current uncertainties), the areal mass for woven TPS only increases by about 30%, and remains 10% lower than the Carbon Phenolic sizing for the same mission. The benefit in areal mass is a strong function of the lower densities of both the recession layer and, more importantly, the insulating layer.

Despite the uncertainty in individual properties, a model developed with the material response program *FIAT* has been used to predict recession in a few arc-jet tests. Current manufacturing constraints limit the current woven material to a maximum recession layer thickness of only 0.2". Thus, the total amount of recession observed in the tests to date is small. Measurement of final thickness is complicated by swelling of the remaining material (which is also seen in CP and complicates recession measurements for CP too). Nevertheless, comparison of predicted and measured recession shows agreement within 50%. The predictive accuracy should increase as property measurements become available and modeling is refined by the HEEET project.

All of the results presented in the following section do not include any margin to account for analysis uncertainty. Hence the **reported masses are definitely not suitable for mission mass estimation**. No specific margin policy is recommended here, but it is common for the total thickness to be increased by around 50% to provide margin for ablator applications. It is not expected that the thickness increments for woven TPS will be larger than those for Carbon Phenolic (and it is plausible that the increment for the insulative layer may be smaller), so the relative sizing for the alternate ablator systems presented here should be indicative of ratios for mission implementation.

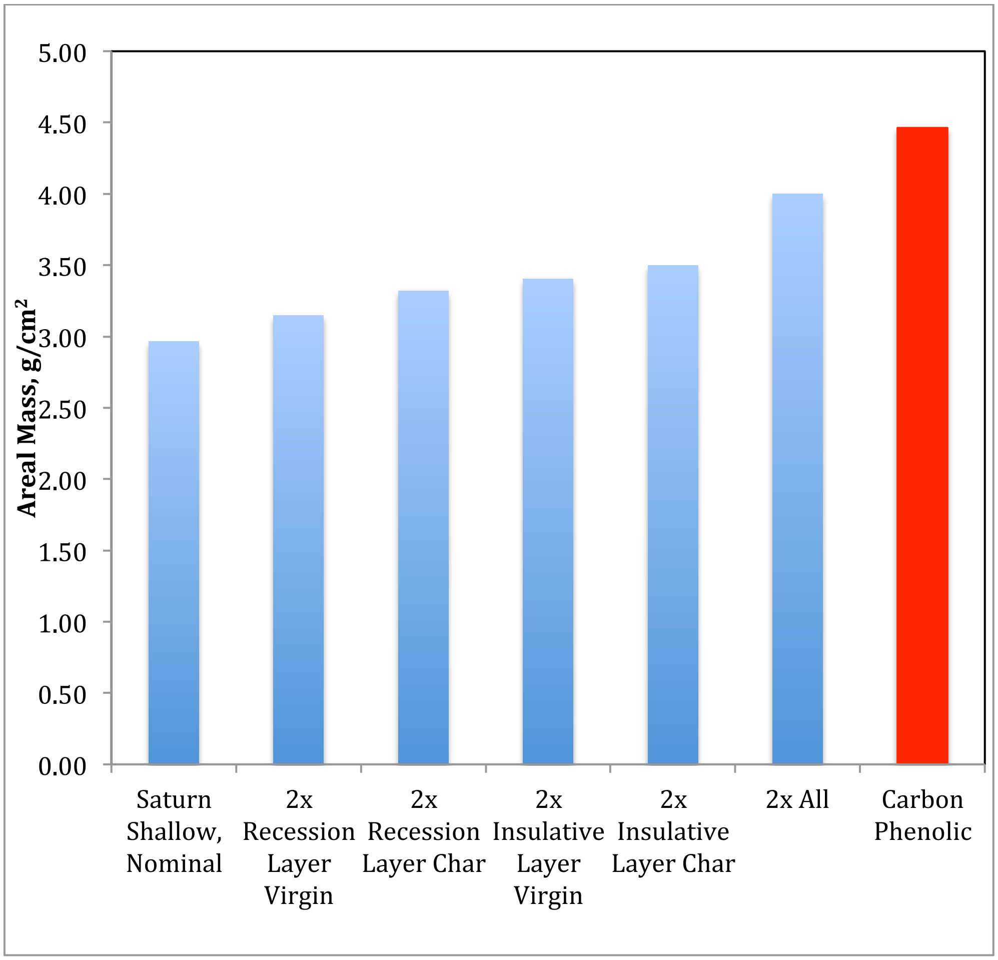

Figure 3. Sensitivity of required thickness for variation in thermal conductivity. Equatorial entry, 26 km/s relative velocity, 1 m diameter 45 ° sphere-cone, 250 kg entry mass.

A more detailed discussion of methodology can be found in Prabhu's investigation of Venus entry [1]. In the studies discussed in the next section, *Traj* [2] was used for steps 2 and 3, and *FIAT* [3] was used for Step 4.

Mission Summaries

Venus Lander

Mission concepts that are currently prioritized for Venus require entry mass at least three times greater than Pioneer Venus Large Probe. It is proposed to land up to 1000 kg at the surface, with an instrument suite for atmospheric and surface science [4]. For this study, we concentrate on a 45 º sphere-cone, photographically scaled from the Pioneer probes. A diameter of 3.5 m and entry mass of 2000 kg is assumed, corresponding to a ballistic coefficient just under 200 kg/m^2. Entry angle is varied between skip-out (about – 8 º) and -30 º, and inertial entry velocity between 10.8 and 11.6 km/s.

Figure 4 shows the strong sensitivity of peak deceleration to entry angle: an entry angle of 13 º or lower can keep peak loads below 100 g's, which can facilitate design and ground testing of instruments.

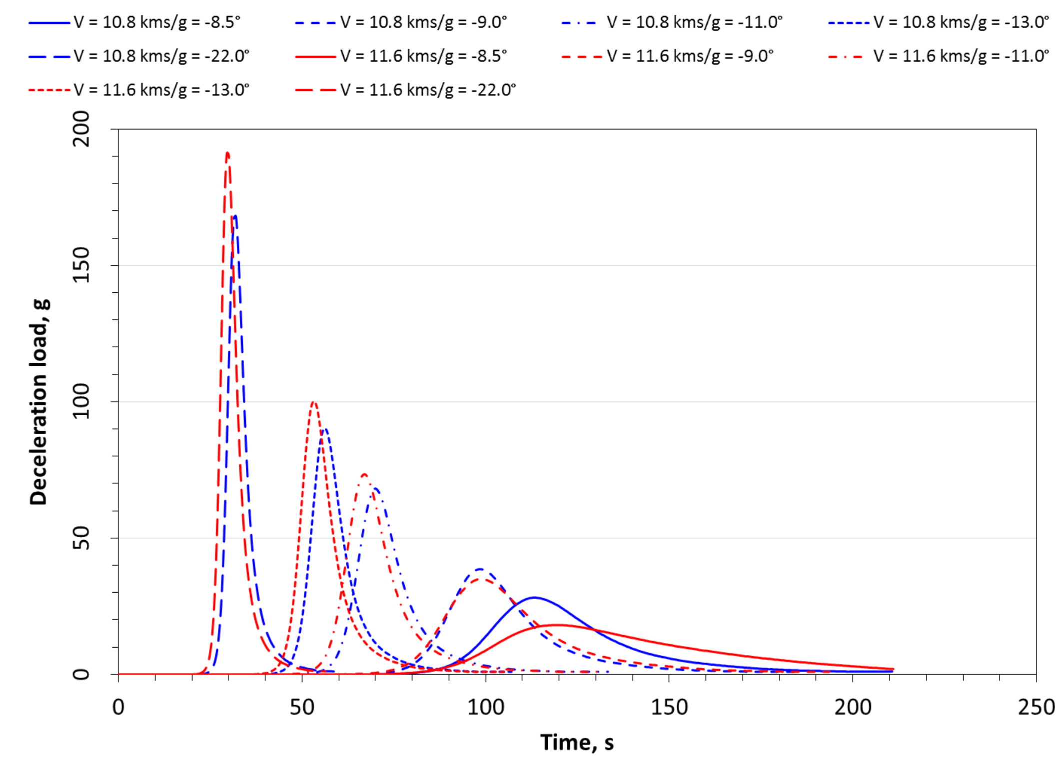

Figure 4. Peak deceleration for a range of entry velocities and entry angles

Figure 5 shows that for low entry angles, the heating rate is at or below 2000 W/cm^2, where a dense ablator is not highly efficient. Figure 6 shows that total heat load is strongly dependent on entry velocity, and increases substantially for shallow long-duration entries.

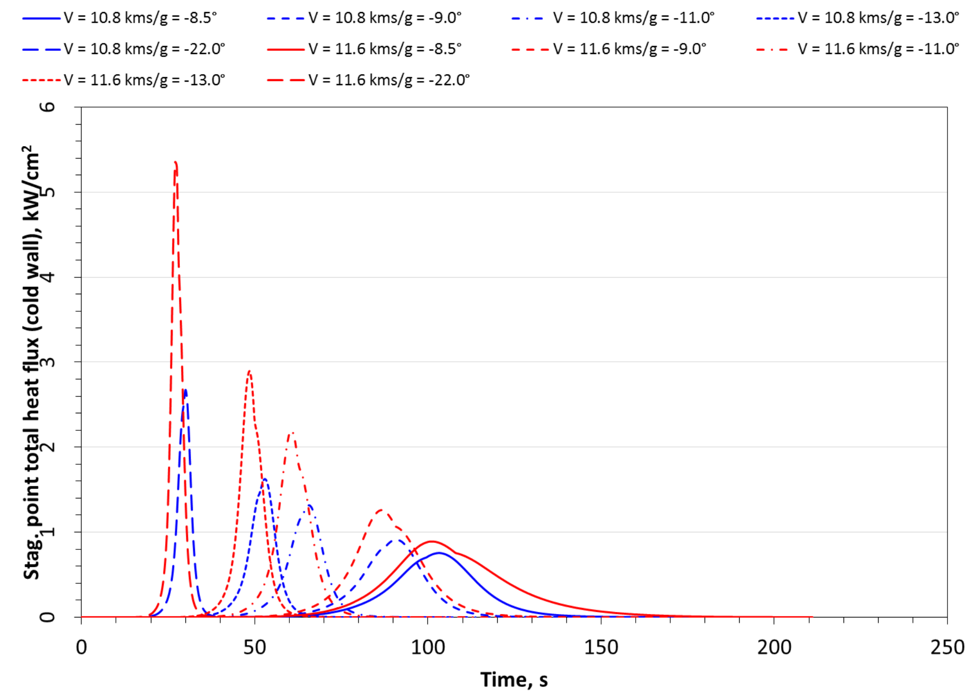

Figure 5. Heating rates for a range of entry velocities and entry angles

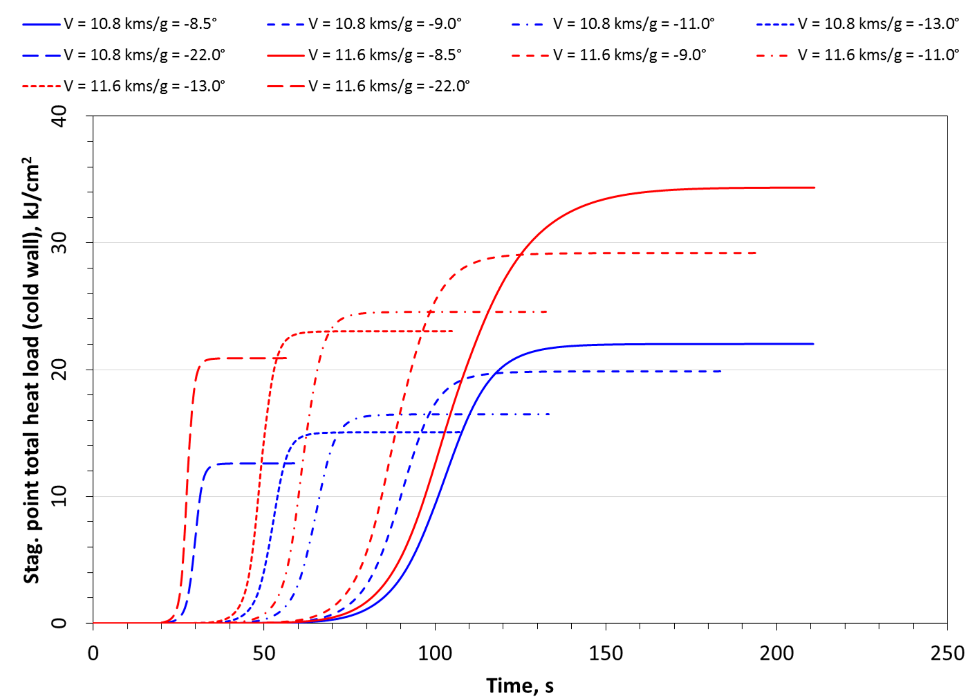

Figure 6. Heat load for a range of entry velocities and entry angles

Material sizing results are shown in Figures 7 and 8. The total thickness for the HEEET material is similar to Carbon Phenolic, although the amount of recession for both ablators is very small. Since the bulk of the thickness is functioning as an insulator, the lower density of the woven sub-layer provides a much lower areal mass for the HEEET system. Note that the HEEET system for -8.5 º entry angle has about the same mass as a CP system for a -30 º entry.

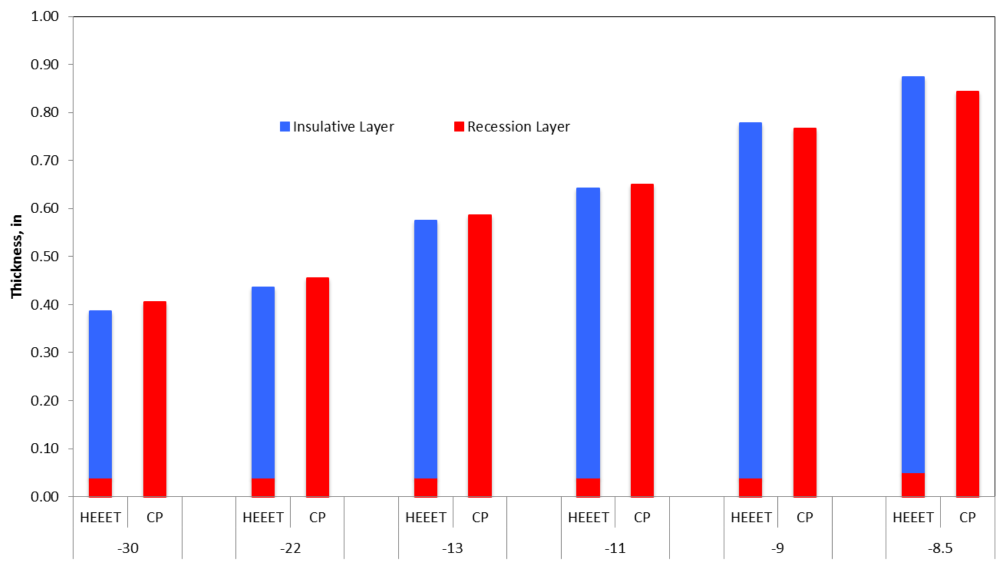

Figure 7. Thickness for 10.8 km/s entry velocity and a range of entry angles

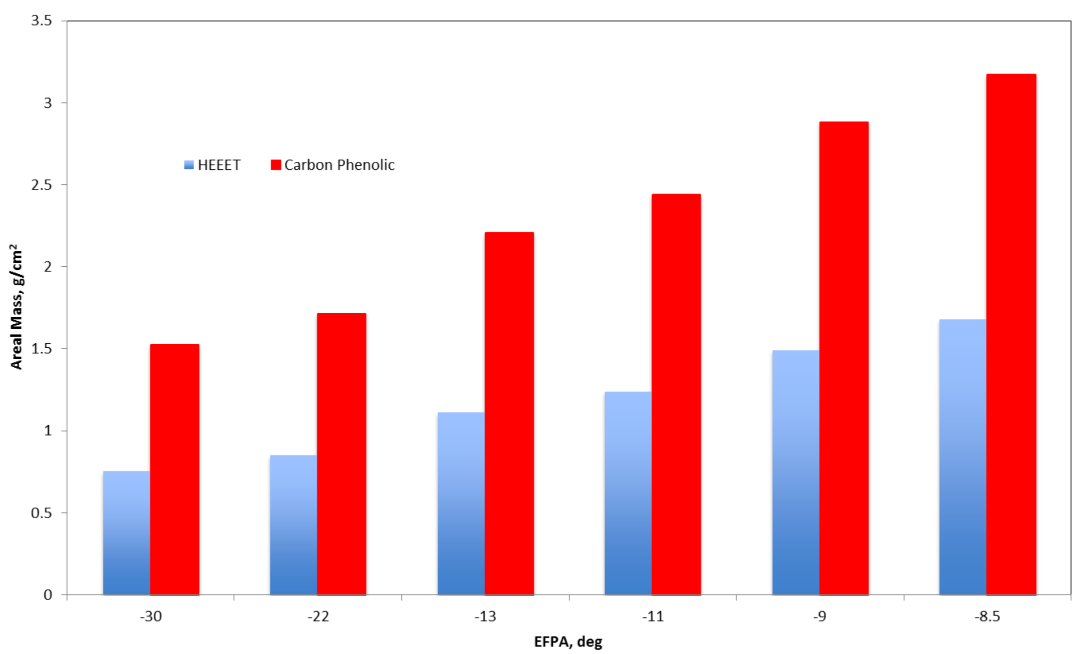

Figure 8. Areal Mass for 10.8 km/s entry velocity and a range of entry angles

Saturn Probe

Mission concepts that are currently considered for Saturn indicate that a small number of instruments concentrating on atmospheric structure and composition is the highest near-term priority, with a larger vehicle carrying an instrument suite similar to Galileo's viewed as a lower priority. This study concentrates on a probe with the same shape as Galileo, but scaled down to 1.0 m (from 1.26 m) and 200 kg (from 335 kg). The ballistic coefficient is almost the same as Galileo (243 kg/m^2 vs 256 kg/m^2). An equatorial entry is known to be less demanding than an entry to high latitude (which has higher relative velocity), but we consider heading angles of 90 º (equatorial) and 30 º (high latitude) to quantify the impact on TPS at entry angles of -8 º and -19 º.

Figure 9 shows that entry angle has a strong influence on peak deceleration, but heading angle does not. On the other hand, Figure 10 shows that peak heat flux at a fixed entry angle is almost doubled for the high latitude entry.

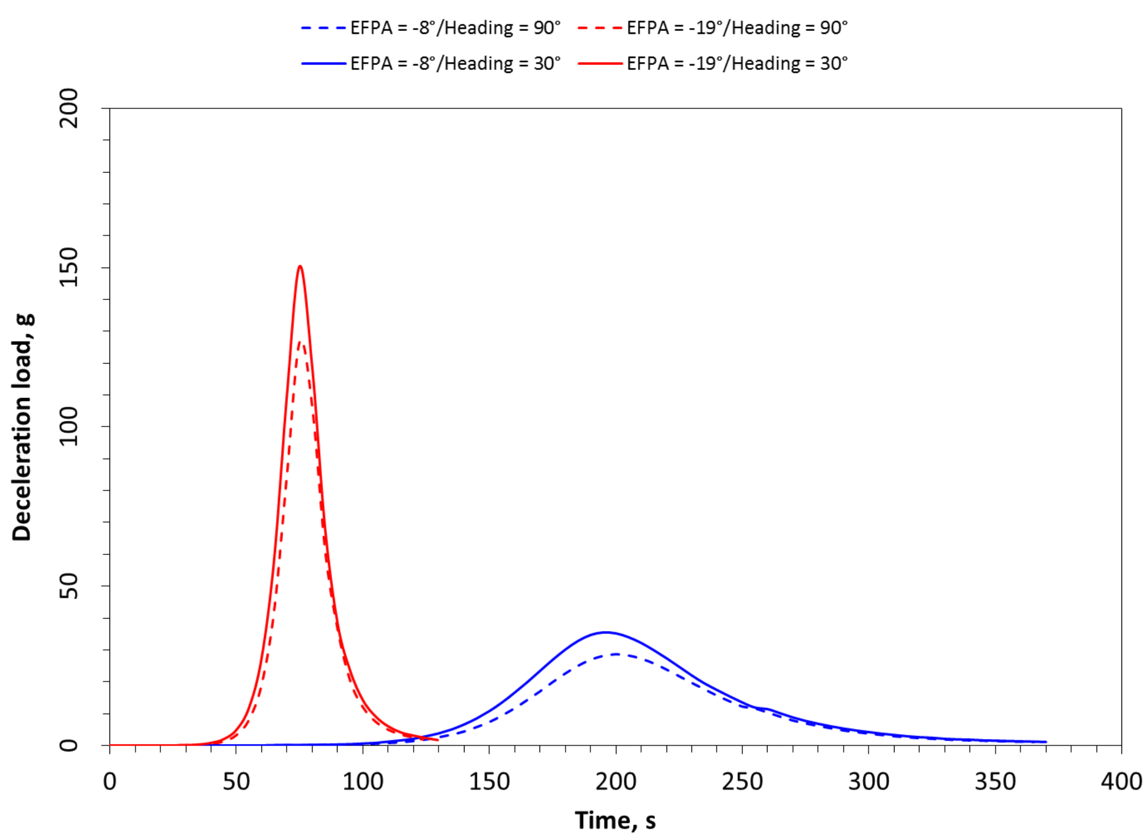

Figure 9. Deceleration for different heading and entry angles

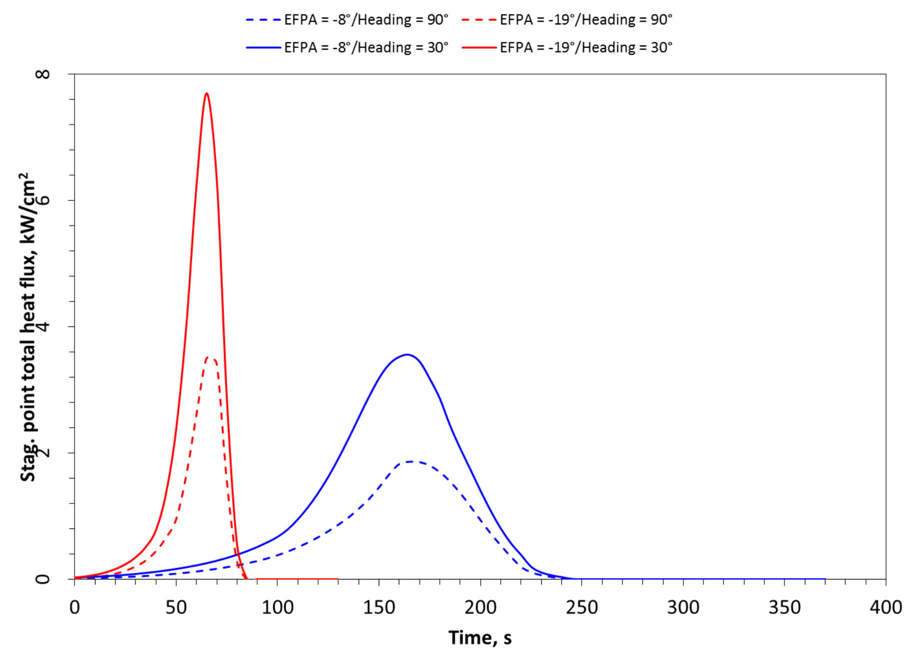

Figure 10. Heat flux for different heading and entry angles

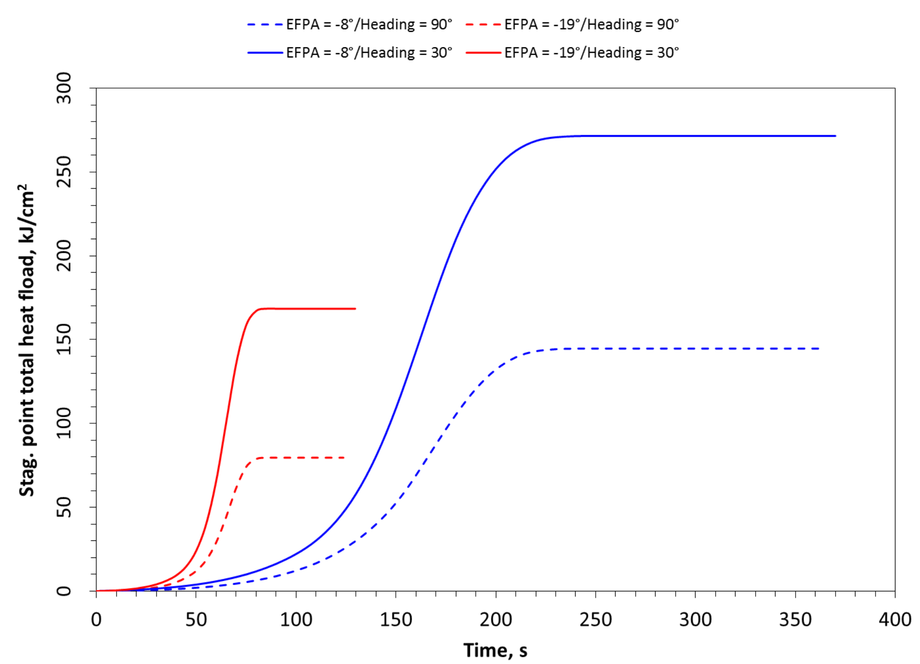

Figure 11. Heat load for different heading and entry angles

Both the heating rate and heat load are much higher for the Saturn mission than for Venus. Consequently the total thickness is much higher and the recession layer is a much larger fraction of total thickness. Equatorial or low latitude entries should be comfortably achievable even when reasonable margins on design thickness are applied (recall that current results are for nominal environments and nominal material properties). However, it could be challenging to support a high latitude, shallow entry mission concept, not due to performance limitations, but due to weaving constraints. The loom that is currently in development can produce a maximum weave thickness of 3” but the maximum thickness of the recession layer may be a more severe constraint. Significant forward work with CFD modeling is required to characterize the uncertainty in heating predictions for the high latitude destination, since sizing with the current simplified method indicates that its requirements may exceed capability.

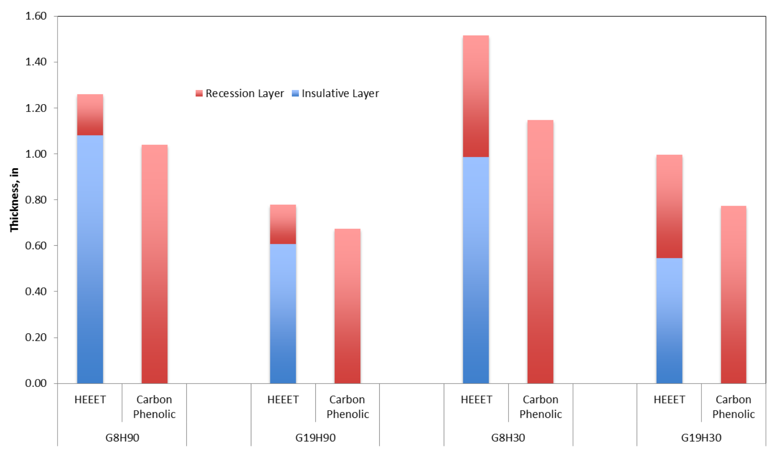

Figure 12. Thickness sizing for HEEET and Carbon Phenolic

With the recession layer contributing more to the total mass of the woven TPS (due to its greater thickness fraction) the mass benefits shown in Figure 13 are less dramatic than for Venus, but still very significant.

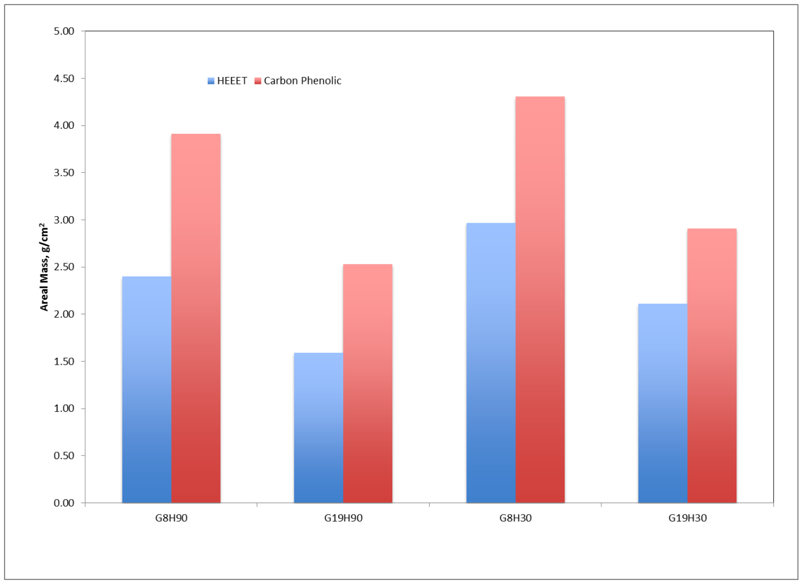

Figure 13. Areal Mass for HEEET and Carbon Phenolic

Sample Return from Enceladus

Missions are currently being considered for sample return from several locations in the solar system. Enceladus is one interesting possibility because the Earth entry velocity would likely be between 15 and 18 km/s, which is significantly higher than the 12.8 km/s for Stardust and 12.0 km/s for Hayabusa. In this study we consider a sample return capsule of similar size to those previous vehicles, and concentrate on a 15 km/s entry velocity. Entry angles between -8 º (similar to Stardust) and -12 º (similar to Hayabusa) are considered.

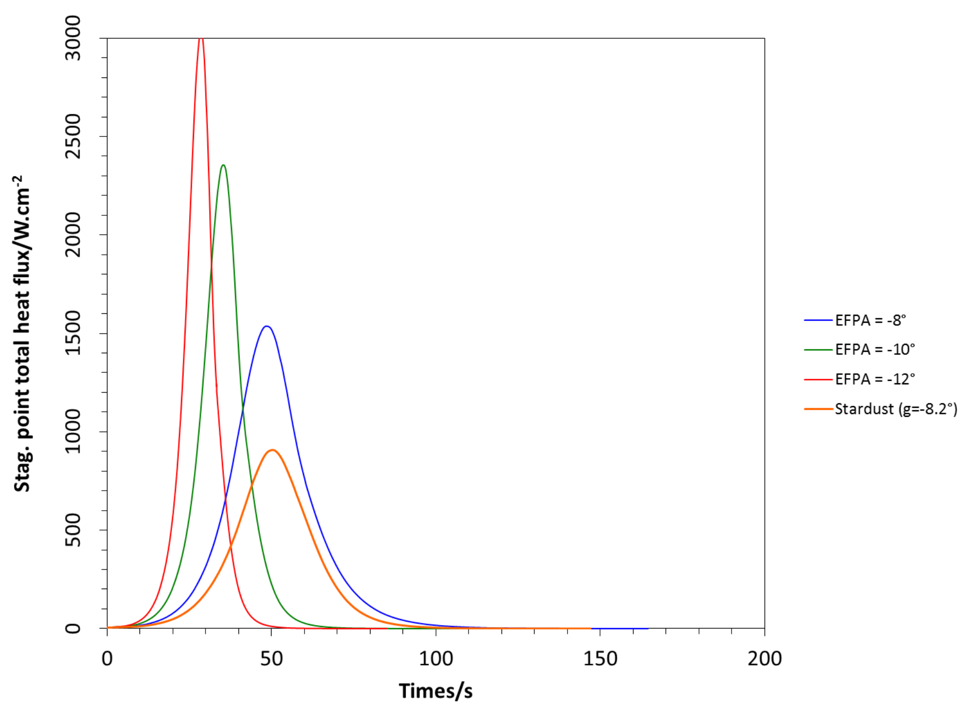

Figure 14. Heat flux for sample return at 15 km/s for range of entry angles

Heat flux, shown in Figure 14, is modest relative to the requirements for Saturn. The duration of the heating pulse is short, so heat load is also modest. Thicknesses are much smaller than required for Saturn, even for small entry angles.

Since the heating requirements are not extreme, the differentiator between TPS material options may become peak pressure, therefore the pressure history is also plotted in Figure 15, along with the pressure history flown by Stardust. This comparison indicates that the environment for an entry angle of -8 ° is within the capability of a PICA system, although that would need to be confirmed when the uncertainties in entry interface conditions and in aerothermal modeling are included.

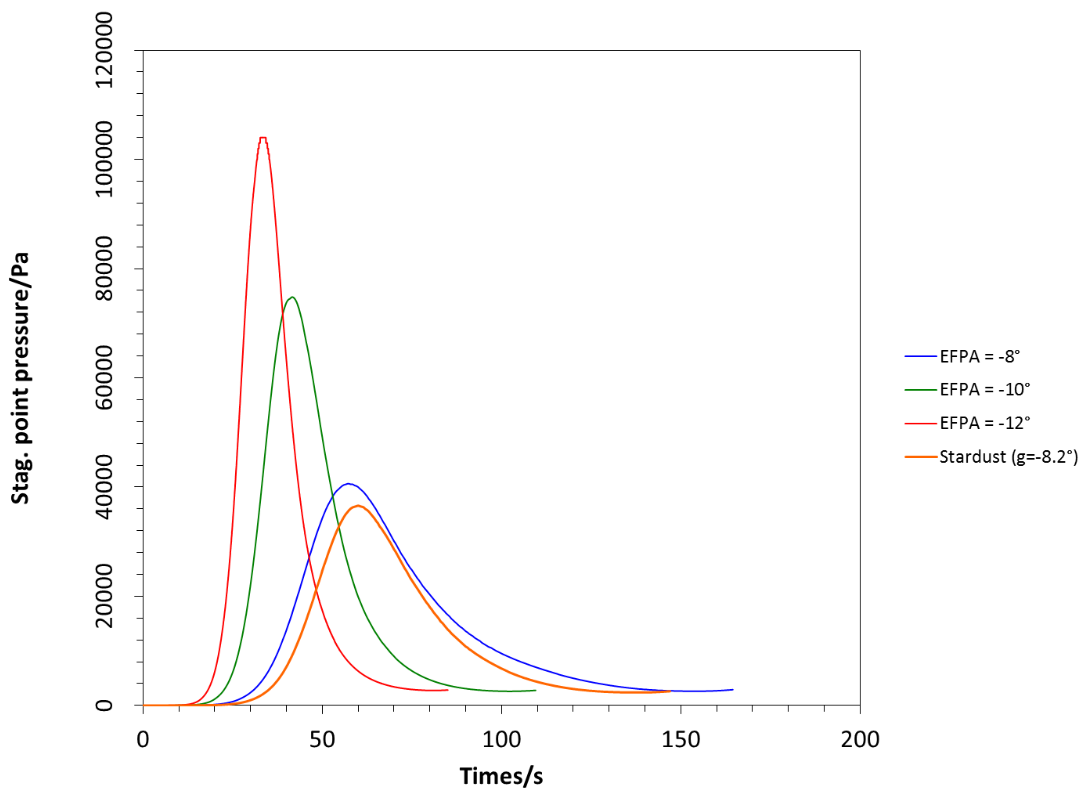

Figure 15. Pressure for sample return at 15 km/s for range of entry angles

Figure 16 shows the areal mass comparison for woven TPS and Carbon Phenolic, for all entry angles considered. Once again, the HEEET technology provides a substantial mass benefit. Also shown is the mass estimate for PICA, for the shallowest entry angle. The diamond-shaped symbols for each material indicate the sizing for the Stardust mission. PICA clearly has a significant mass benefit, provided that the mission can be completed reliably at this entry angle, as was the case for Stardust. If a steeper entry angle, which will reduce the landing dispersion, is preferred, the woven TPS can provide robust performance with a smaller mass penalty relative to the mass of PICA sized for the shallower entry angle. If a higher entry velocity is contemplated, the robustness of woven TPS becomes an increasingly important consideration.

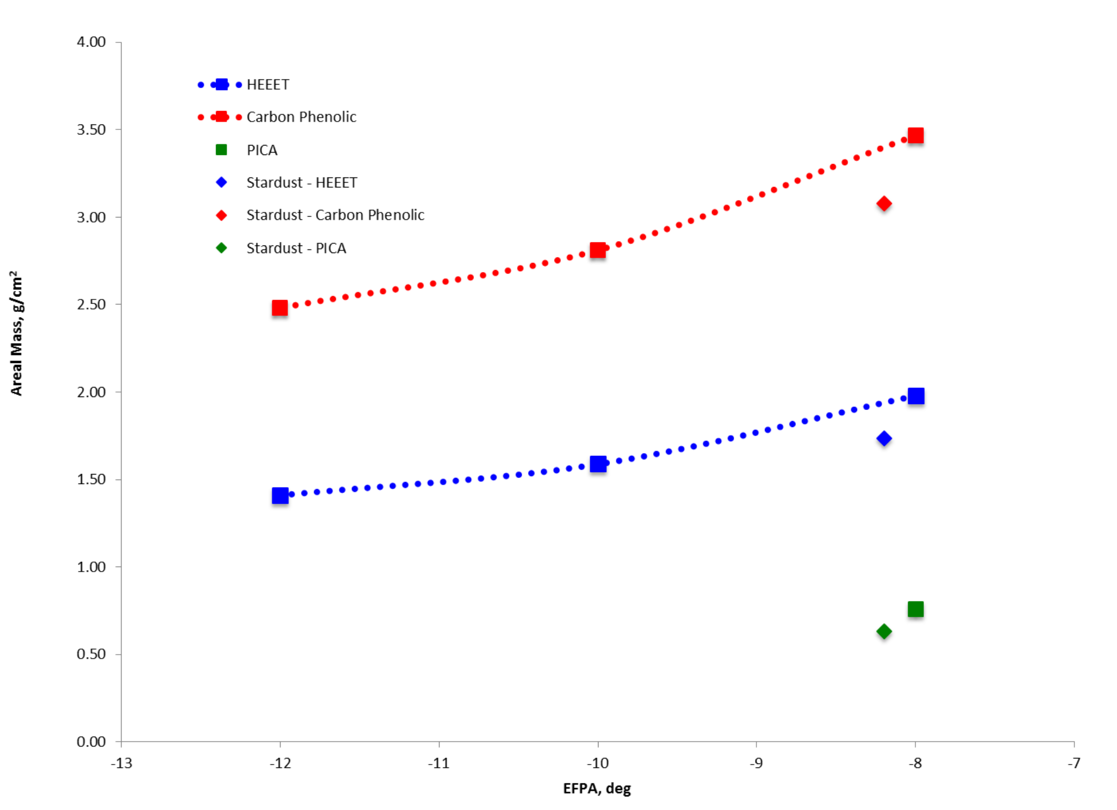

Figure 16. Areal mass for sample return at 15 km/s for range of entry angles. Diamond symbols indicate sizing for the Stardust mission (12.6 km/s entry velocity). The relative masses for different materials are similar at both entry speeds.

General Observations from Sizing Studies

For all missions considered here, woven TPS has a significant mass advantage over Carbon Phenolic. It is particularly pronounced where the amount of recession is relatively small, and mass benefit of the lower density insulative layer is relatively high.

It appears feasible to use woven TPS for all opportunities considered, except perhaps for a high latitude entry at Saturn. The constraint at high latitude is not material performance, but a manufacturing limit on total thickness of the woven material, which could be alleviated by further investment in weaving infrastructure.

The sample return mission studied here could potentially be flown with a PICA system, if the entry angle is kept very low. However, woven TPS can support a broader mission design space, with respect to both entry angle and velocity, and provides superior robustness at a modest penalty in mass.

Acknowledgements

The work that is summarized in this document was performed primarily by Dinesh Prabhu, Gary Allen, and Adam Beerman. The content here is largely extracted from reports and presentations by them.

References

1. Dinesh K. Prabhu, Gary A. Allen, Helen H. Hwang, Gelsomina Cappuccio, Thomas R. Spilker, Robert W. Moses, "Ballistic Entries at Venus" NASA/TM-2014-218310, 2014
2. Gary A. Allen, Jr., Michael J. Wright, and Peter Gage, "The Trajectory Program (Traj): Reference Manual and User's Guide," NASA/TM-2004-212847, 2005.
3. Milos, Frank S and.Chen, Y.K., "Ablation, Thermal Response, and Chemistry Program for Analysis of Thermal Protection Systems," Journal of Spacecraft and Rockets, Vol. 50, No. 1, Jan-Feb 2013.
4. Adams, M. L., and Baker, C. L., "Venus Intrepid Tessera Lander," a Mission Concept Study in support of the NRC Planetary Science Decadal Survey, April 2010.