Updated TPS Requirements for Missions to Titan

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ABSTRACT

In 2002, NASA conducted a systems analysis study of a potential aerocapture mission to Titan. Predictions of the aerothermal environment during Titan aerocapture demonstrated that shock layer radiation dominated the convective heating. Furthermore, almost all of the radiation was from the CN molecule at UV wavelengths (350-420 nm). Given modified modeling assumptions and recent conclusions from shock tube data taken in the EAST facility at Ames, an updated estimate of the radiant heating at Titan was made. With an updated aeroheating environment, TPS requirements for aerocapture at Titan were updated. The paper will compare updated requirements with earlier TPS thickness and weight requirements for aerocapture at Titan, on the basis of analytical studies of existing low-density ablative materials.

1. INTRODUCTION

During 2002 a study [1] to develop a conceptual design for an aerocapture mission at Titan was conducted by a NASA systems analysis team comprised of technical experts from several of the NASA centers. Multidisciplinary analyses demonstrated that aerocapture could be accomplished at Titan with a blunt rigid aeroshell. Through detailed trade studies, the mission analysis team further specified a rigid aeroshell configured as a 70-degree half-angle blunt cone forebody with a lift-to-drag (L/D) ratio of 0.25 and a ballistic coefficient (M/C_DA) of ≈ 90 kg/m^2. The configuration is illustrated in Figure 1. Extensive mission analysis studies [2] determined that a viable Titan mission, delivering an orbiter with a mass of 590 kg, could be launched around December 2010 and, with use of an Earth Gravity Assist (EGA) and Solar Electric Propulsion (SEP), flight time to Titan could be reduced to 5.9 years with an inertial entry velocity of ≈ 6.5 km/s at an altitude of 1000 km.

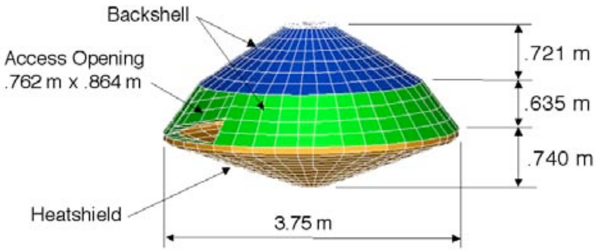

Fig. 1. Aeroshell configuration for Titan aerocapture

1.1 Titan Atmosphere

The atmosphere around Titan is composed primarily of nitrogen with some argon and methane. There is some uncertainty about the concentrations of argon and methane, which leads to uncertainties in the density distribution through the atmosphere. Yelle [3] developed engineering models for atmospheric density shown in Figure 2.

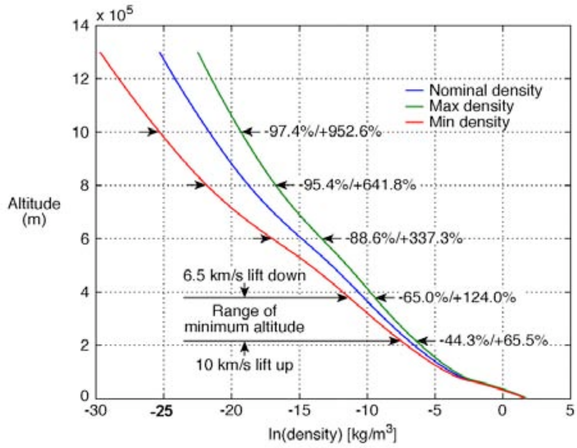

Fig. 2 Yelle engineering models for the density of the Titan atmosphere[†]

The variations in predicted atmospheric density are attributed to different models for methane concentration. The figure indicates the range of density variation of the minimum and maximum density models relative to the nominal model at selected altitudes. The figure also shows the minimum altitude range for candidate aerocapture trajectories. In these models the methane concentration is inversely proportional to mean atmospheric density. As shown in Figure 3, the molar percent CH_4 is nearly constant over the altitude range where the energy of 6.5 km/s and 10 km/s aerocapture entries would be dissipated. Furthermore, the composition does not vary with density perturbations. There is a drop of 50% in the methane content of the minimum density atmosphere between the surface and 6 km, due to CH_4 condensation. However, CH_4 concentrations in the nominal and maximum density

[†]The term "lift down" employed in the figure is associated with the overshoot trajectory and indicates that the lift vector is in the trajectory plane and is always pointing downward throughout the entire aerocapture trajectory. Conversely, "lift up" is associated with the undershoot trajectory and indicates that the lift vector is always pointing up.

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atmospheres are below the saturation level and thus remain constant to the surface.

These models were used in the 2002 aerocapture systems analysis study and eventually will be revised using data from the successful Huygens probe. At present, however, the Huygens data is still being evaluated; no model updates are possible at this time.

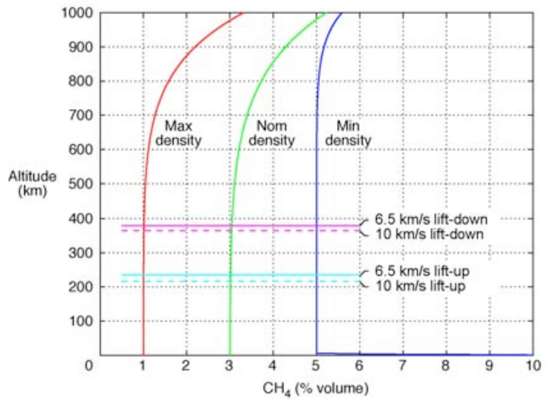

Fig 3. Models for methane concentration in Titan atmosphere

1.2 Aerocapture Trajectories

Way et al [4] evaluated potential aerocapture trajectories at Titan with consideration of a range of ballistic coefficients and the uncertainties in atmospheric density. Guidance, navigation and control (GN&C) were limited to controlling the lift vector through bank angle modulation. The limiting cases are undershoot trajectories, where the lift vector is always pointing up, and overshoot trajectories, where the lift vector is always pointing down. Four trajectories, which bound the limits of peak heating rate and maximum total heat load, were selected and are shown in Figure 4.

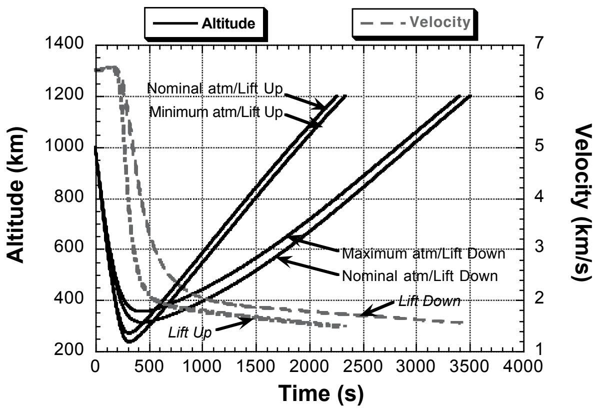

Fig. 4. Limiting aerocapture flight trajectories

The Titan atmosphere models described in Section 1.1 were used to define these trajectories. It is hoped that the data from the Huygens probe will allow the uncertainties in the atmosphere models to be reduced, and may provide grounds for a re-evaluation of the aerocapture trajectories.

1.3 Convective and Radiative Heating

Convective and radiative heating rates[‡] at the stagnation point were calculated [5] for the aeroshell configuration described previously and the four limiting trajectories presented in Figure 4. Calculation of the stagnation point convective heating employed the Fay-Riddell correlation [6] and was later confirmed with axisymmetric Computational Fluid Dynamics (CFD) solutions performed with the DPLR code. [7] Non-equilibrium radiation calculations were performed with the NEQAIR code. [8] As shown in Figure 5, the peak stagnation point convective heating rates are less than 50 W/cm^2 and the undershoot trajectories (lift up) result in higher peak heating rates in comparison to the overshoot (lift down) trajectories. However, the peak stagnation point radiative heating rates were substantially larger. For the undershoot trajectories (lift up), peak stagnation point radiative heating rates were in the 120-150 W/cm^2 range. For the overshoot trajectories (lift down), peak stagnation point radiative heating rates were in the 45-85 W/cm^2 range.

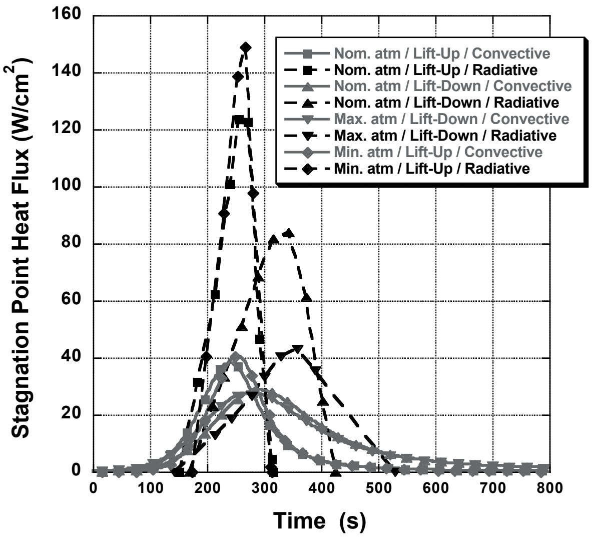

Fig. 5. Stag point heating for limiting trajectories

It is worth noting that while the convective heating is rather insensitive to the concentration of methane assumed in the atmosphere, the opposite is true for the radiative heating, all of which comes from CN formed in the shock layer from the interaction of dissociated methane with nitrogen. Consequently, the higher the methane concentration in the atmospheric model (see Fig. 3), the higher the radiative heating rates. While the non-equilibrium radiation environment was calculated with the most up-to-date chemistry and radiation

[‡] Without consideration of the effects of ablation

models available, it was recognized that there is significant uncertainty associated with these predictions. Shock tube tests at NASA Ames were conducted during 2004 to measure CN radiation at relevant conditions to enable validation and/or update of existing radiation heating models for Titan entry. The impact of these data on predicted radiative heating will be discussed later.

It must also be noted that the overshoot trajectories involve a longer time spent in the atmosphere than the undershoot trajectories. Consequently, the total convective heat load is typically larger for the overshoot trajectories than for the undershoot trajectories. That is not necessarily true for the radiative heating, because there are significant differences in the heat flux levels predicted for the range of trajectories and atmospheric models considered. This is demonstrated in Table 1, which summarizes the total convective and radiative heat loads for the four limiting trajectories considered. Note the similarities in the convective heat loads for the two overshoot and two undershoot trajectories, illustrating their relative insensitivity to methane concentration. The radiative heat loads, on the other hand, exhibit the dependence on methane concentration discussed above. The minimum density atmosphere model has the highest methane concentration, while the

Table 1. Total heat loads for limiting aerocapture trajectories

Atmosphere model/ aerocapture trajectory	**Convective heat load (J/cm^2)**	**Radiative heat load (J/cm^2)**
Nominal atm/Lift up	5,500	10,021
Nominal atm/Lift down	7,500	12,090
Maximum atm/Lift down	7,700	8,393
Minimum atm/Lift up	5,200	15,769

.

Table 2 Candidate forebody TPS materials for Titan aerocapture

Material	**Density (g/cm^3)**	**Description**
Shuttle tiles (NASA)	0.192-0.352	Low-density glass-based ceramic tile with glass-based coating
SLA-561V (LMA)	0.256	Low-density cork silicone composite in Flexcore honeycomb (forebody TPS on Mars Viking, Mars Pathfinder and Mars Exploration Rover landers)
SRAM14 (ARA)	0.224	Low-density cork silicone composite fabricated with strip-collar bonding technique
SRAM17 (ARA)	0.272	Low-density cork silicone composite fabricated with strip-collar bonding technique
SRAM20 (ARA)	0.320	Low-moderate density cork silicone composite fabricated with strip-collar bonding technique
SIRCA (NASA)	0.192-0.352	Low-density ceramic tile impregnated with silicone resin
PICA (NASA)	0.256	Low-density carbon fiberform partially filled with phenolic resin (forebody TPS on Stardust spacecraft)
PhenCarb20 (ARA)	0.320	Low-moderate density phenolic composite fabricated with strip-collar bonding technique
Acusil I (ITT)	0.480	Moderate density filled silicone in Flexcore honeycomb
TUFROC (NASA)	Varies with layer sizing	Multilayer composite: carbon fiberform/AETB tile with high temperature, high emissivity surface treatment
Genesis Concept (LMA)	Varies with layer sizing	Carbon-carbon facesheet over carbon fiberform insulator (forebody TPS on Genesis spacecraft)
Carbon phenolic	1.45	Fully dense tape-wrapped or chopped molded heritage material (forebody TPS on Galileo and Pioneer Venus entry probes)

maximum density atmosphere model has the lowest methane concentration (see Fig.3). The values for the lift up and lift down trajectories for the nominal density atmosphere in Table 1 suggest that the total radiative heat load has some dependence on time in the atmosphere. Its stronger dependence on the atmospheric model, however, is suggested by comparing the values for the maximum atmosphere on a lift up (undershoot) trajectory with the values for the minimum atmosphere on a lift down (overshoot) trajectory.

1.4 Candidate TPS Materials

Given the range of convective and radiative heating described above, a range of candidate thermal protection materials for Titan aerocapture applications was identified [9]. The candidate TPS materials are summarized in Table 2

Most of these materials are organic resin-based composites that will pyrolyze when heated, leaving a carbonaceous char at the surface. Because total heat loads for aerocapture are typically much larger than for direct entry, the lowest mass TPS solutions will be good insulators, a characteristic usually associated with low-density materials. Insulation performance, however, is not the only factor to be considered. It must be balanced with ablation performance. Too much surface recession, for example, can lead to alterations in shape that can affect aerodynamic performance, and high-density materials are usually employed to minimize surface recession. Nevertheless, several of the low-density candidate materials would be considered the most attractive candidate materials from the standpoint of minimizing TPS mass. They are capable of the peak heating rates predicted for Titan and they can provide good insulation performance with minimal surface recession.

1.5 TPS Mass Estimates

To provide an estimate of TPS mass, preliminary forebody TPS sizing analyses [9] were performed for many (but not all) of the candidate materials listed in Table 2, for the four limiting aerocapture trajectories shown in Figure 4. The analyses were limited to the stagnation point heating shown in Figure 5 and, for purposes of estimating TPS mass, it was assumed that the nominal (zero margin) stagnation point TPS thickness is applied uniformly on the forebody. It was also assumed that the TPS is adhesively bonded to a rigid substructure consisting of 0.0376 mm thick graphite polyimide facesheets (front and back) on a 31.75 mm thick aluminum honeycomb; the density for the honeycomb and graphite polyimide facesheets is 0.069 g/cm^3 and 1.0 g/cm^3, respectively. It was further assumed that all materials are at a uniform temperature of –74.8°C at atmospheric interface, and that all candidate materials absorb CN radiation at the surface and perform as thermochemical ablators, without spall or melt runoff. Analyses were performed to determine the thickness required for each candidate material, in order to limit the maximum bondline temperature to 250°C. Although different individuals performed the analyses for different materials, all used comparable analysis tools, which address the fundamental physical and chemical mechanisms associated with the thermal/ablation performance of these materials in the Titan atmosphere. Some of the materials models are very mature and have been validated with extensive laboratory and arc jet test data; other materials are relatively new and their models are based on limited laboratory and arc jet test data. †

The results of the analyses demonstrated that, for the four trajectories considered, the TPS thickness is significantly larger for the overshoot trajectories (lift down) than for the undershoot trajectories (lift up). This was the case for all of the candidate materials considered. Furthermore, maximum bondline temperature is attained during heat soak, that is, after the end of aerodynamic heating. Table 3 summarizes the zero margin TPS thickness for the overshoot trajectory assuming different atmosphere models since the overshoot trajectories, with their larger heat loads, dictate the TPS requirements. The heating was shown previously in Fig. 5.

1.6 TPS Performance Uncertainties

At the time that this study was performed, there was considerable concern that the low density, porous TPS materials might be semi-transparent to the CN radiation, with the potential for in-depth absorption resulting in spallation. This was of particular concern as there had not been any tests of this class of materials at the heat fluxes and wavelengths of the anticipated radiative environment at Titan. Consequently, the use of a low-density ablative material was identified as an unacceptable risk and a heavier TPS solution, TUFROC, was selected as the forebody TPS for the baseline design.

2. HUYGENS SUPPORT

At the Huygens Delta Flight Acceptance Review (FAR) held in Cannes in February 2004, NASA Ames offered to test AQ60, the probe's forebody TPS material, for the Huygens project. Ames was in process of acquiring a mercury-xenon lamp to test low-density ablative materials at UV wavelengths and heat flux conditions relevant to Titan aerocapture and/or entry. ESA accepted the offer and under the Huygens contract with Alcatel as prime contractor, EADS supplied samples of

† The fidelity of many of these material models has not been adequately validated.

Table 3. Preliminary forebody TPS sizing for Titan aerocapture

	Maximum atmosphere - Lift Down Convective Heat Load = 7,700 J/cm^2 Radiative Heat Load = 8,393 J/cm^2		**Nominal atmosphere – Lift Down Convective Heat Load = 7,500 J/cm^2 Radiative Heat Load = 12,090 J/cm^2**	
Candidate TPS Material	**<u>Thickness</u> (cm)**	**Areal weight (g/cm^2)**	**<u>Thickness</u> (cm)**	**Areal weight (g/cm^2)**
SLA-561V	2.44	0.626	2.43	0.622
SRAM 14	1.57	0.353	1.55	0.348
SRAM 17	1.93	0.526	1.93	0.526
SRAM 20	2.08	0.667	2.08	0.667
PhenCarb-20	2.29	0.696	2.34	0.711
TUFROC	4.88	1.117	5.13	1.181
Genesis	---	---	5.51	1.298
PICA	5.94	1.591	5.82	1.557
Carbon phenolic	8.70	13.084	8.76	13.167

AQ60 for the tests. NASA Ames instrumented the samples with (sometimes multiple) in-depth thermocouples and conducted the tests with the mercury-xenon lamp.

The UV test data [10] demonstrated that all of the low-density ablative materials absorbed the radiative energy at the surface and not in-depth, and eliminated the uncertainty considered during the 2002 Titan aerocapture systems analysis study. The importance of that result is that it allows consideration of the low-density ablators as viable TPS materials for Titan missions.

There were significant differences between the NASA Ames predictions for radiative heating during Huygens entry and those employed by the ESA for the Huygens TPS design. With radiative heating predicted to be the dominant heating mode during flight through the Titan atmosphere, NASA Ames collaborated with ESA in reviewing the models. After nine months of interchanges in which the fundamental assumptions were reviewed, NASA and ESA reached agreement on what assumptions were justifiable in modeling radiative heating during Titan entry. In parallel with that effort, NASA Ames conducted shock tube tests in the Electric Arc Shock Tube (EAST) facility at Ames to study radiative eating in a simulated Titan atmosphere. These data were finally evaluated in December 2004 [11] and demonstrated that the actual shock layer heating rates were *significantly lower* than those being predicted with any of the available models.

3. UPDATED AEROCAPTURE ANALYSIS

3.1 Revised Stagnation Point Heating

On the basis of the modified modeling assumptions and the EAST shock tube data Wright [12] made fresh estimates of the convective and radiative heating during Titan aerocapture for the same overshoot and undershoot trajectories shown previously in Fig. 4, but limited to the minimum density (maximum methane concentration) atmosphere model. These latest heating predictions should be considered only as estimates since an update to NASA's fundamental radiation models to enable prediction of the radiative heating levels indicated by the EAST shock tube data has not yet been completed. Consequently, significant uncertainties associated with the heating persist. Wright suggests adding 30 percent to the estimated convective heating and 200 percent to the estimated radiative heating to account for existing uncertainties. The updated estimate of stagnation point convective and radiative heating (with margin) for the overshoot and undershoot aerocapture trajectories is shown in Fig. 6.

The updated heating estimate for convective stagnation point heating is not very different from the heating prediction employed in the 2002 aerocapture systems analysis study. The radiative heating, however, even with the addition of a 200 percent margin, is a factor of 2-3 lower than earlier predictions. The convective and radiative heating were calculated separately; Wright et al [13] demonstrated that the predicted radiative heating would be significantly reduced if the convective and radiative heating were treated in a loosely coupled manner.

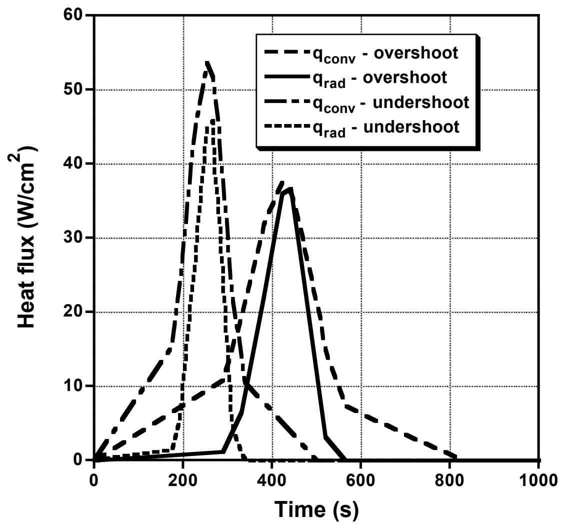

Fig. 6 Updated estimate of stagnation point heating (including margin) during Titan aerocapture for the minimum density atmosphere model

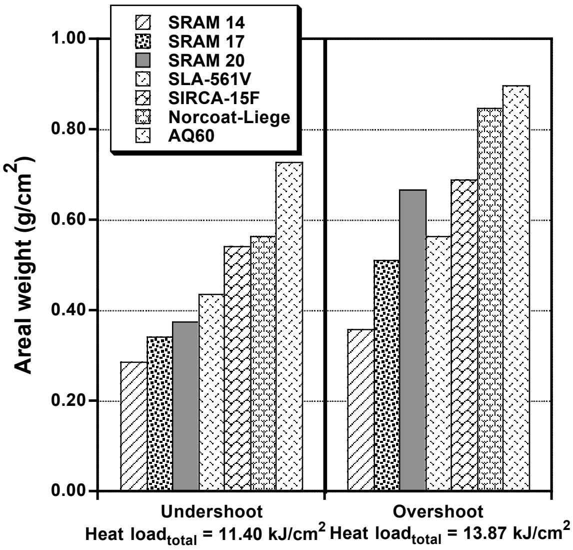

Fig. 7 Updated stagnation point TPS requirements for a Titan aerocapture mission

3.2 Revised Stagnation Point TPS Requirements

The updated heating shown in Fig. 6 was used to re-evaluate the zero margin stagnation point TPS requirements. The initial conditions, substructure and TPS design criteria remain unchanged from those employed in the 2002 aerocapture systems analysis study. The UV material tests demonstrated that the low-density ablators performed as surface absorbers. As a result, they were considered as the primary materials of interest, and the heavier materials evaluated in the 2002 aerocapture systems analysis study were not considered here.

In addition to the low-density ablators considered in the original systems analysis study, two low-density European materials were added for this updated study. AQ60, a proprietary material developed by EADS Space, referred to above as the forebody TPS on the successful Huygens probe, is a felt made of short silica fibers reinforced by impregnation of phenolic resin (30% by mass). The density of the virgin material is ≈ 0.280 g/cm^3 and the density of the char (after pyrolysis of the phenolic resin) is ≈ 0.240 g/cm^3. Norcoat-Liège, also developed by EADS, was employed as the afterbody TPS on the successful ARD capsule. It is a cork phenolic composite with a virgin density of 0.470 g/cm^3.

The zero margin stagnation point TPS requirements for the blunt aeroshell design (Fig. 1) for a Titan aerocapture mission are illustrated in Fig. 7.

As seen, the areal weight requirements for the overshoot trajectory exceed those for the undershoot trajectory, consistent with prior results and the larger total heat loads predicted for overshoot trajectories. The results also suggest that for the modest heat fluxes involved here (little, if any, surface recession was predicted for any of these materials), silicone-based materials would be lighter than phenolic-based materials, because silicones typically have lower thermal conductivity than phenolics. The phenolics are typically better suited to environments with higher heat fluxes. Their higher char densities (in comparison to silicones) make them more robust ablators.

These results also demonstrate that the zero margin forebody TPS areal weight for a Titan aerocapture mission would be in the range of 0.40-0.60 g/cm^2, significantly lower than the ≈ 1.20 g/cm^2 for TUFROC adopted in the original Titan aerocapture systems analysis study.

4. SUMMARY AND CONCLUSIONS

The results of a detailed systems analysis study of a Titan aerocapture mission conducted by NASA in 2002 were reviewed, with emphasis on the TPS requirements for such a mission. The selection of a heavier TPS for the baseline design was due to uncertainties about the performance of low-density porous TPS materials when exposed to short-wavelength UV radiation.

More recent studies conducted by NASA Ames Research Center in support of the In-Space Propulsion Aerocapture project and the Huygens probe to Titan demonstrated that the concern about the interaction of low-density materials with UV radiation was unfounded. Of even more significance was the demonstration, through shock tube tests to study CN radiation in a simulated Titan atmosphere, that radiative heating levels were substantially lower than previous estimates.

With updated estimates of the convective and radiative heating for an aerocapture mission, stagnation point TPS requirements were re-evaluated. As expected, the low-density ablators are the most attractive materials from the standpoint of minimizing TPS mass. Nevertheless, the TPS mass requirements for these low-density materials are not markedly different from the results for low-density ablators in the earlier aerocapture study, where the predicted peak radiative heating rates were substantially higher. Ablative materials are less efficient at low heating rates, where there is little if any surface recession, than at higher heating rates, where energy absorption due to ablation makes them more efficient.

The ability, afforded by the findings of the UV study, to consider employing a low-density ablator for a Titan aerocapture mission, rather than the heavier TUFROC TPS solution adopted in the 2002 systems analysis study, makes possible significant mass savings, on the order of 73-98 kg for updated forebody TPS areal weights in the range of 0.40-0.60 g/cm^2. Such mass savings have the potential to be converted to additional scientific payload.

5. NOMENCLATURE

ARD	Atmospheric Reentry Demonstrator
CFD	Computational Fluid Dynamics
CH_4	Methane
CN	Cyanogen (gas phase chemical species)
EADS	European Aeronautic Defence & Space
EAST	Electric Arc Shock Tube
EGA	Earth Gravity Assist
ESA	European Space Agency
FAR	Flight Acceptance Review
GN&C	Guidance, Navigation & Control
L/D	Lift-to-drag ratio
M/C_DA	Ballistic coefficient
NASA	National Aeronautics & Space Administration
SEP	Solar Electric Propulsion
TPS	Thermal Protection System
UV	Ultraviolet

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