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MARS, OCEAN WORLDS, AND TECHNOLOGY DEVELOPMENT TOPIC AREAS

TPS and Entry System Technologies for Future Mars and Titan Exploration

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ABSTRACT

The purpose of this white paper is to provide an overview to the NRC Decadal Survey Mars and Ocean Worlds Sub-Panels on thermal protection system (TPS) technologies required for future Mars and Titan exploration missions. It considers the capability of heritage TPS technology used by previous Mars and Titan missions. A prime conclusion is that there are important advances regarding the availability of forebody TPS therefore, we recommend that NASA invest in a cross-cutting technology program that focuses on development and sustainment of relevant TPS materials, entry systems, test facilities, design tools, and flight instrumentation.

INTRODUCTION

This NRC Decadal Survey white paper, provided by the thermal protection technology community, is a general assessment of the current capability of thermal protection systems (TPS) with respect to the scientific exploration of Mars and Titan as well as anticipated TPS requirements in support of future Mars and Titan missions. The paper begins with a brief overview and update of thermal protection systems relevant to the recent exploration of Mars, presents a discussion of current TPS capabilities, limitations, technology issues, and concludes with recommendations for establishing a TPS Technology Program that includes further development, testing and manufacturing capabilities needed to support future Mars and Titan missions.

BACKGROUND: Overview of TPS Development

For vehicles traveling at hypersonic speeds in an atmospheric environment, TPS is a single-point-failure system. TPS is essential to shield the vehicle (sub)systems and other onboard assets such as payloads, crew, and passengers against the high heating loads encountered during atmospheric entry. In addition, for the science community, it enables the safe deployment of *in situ* science instruments using probes, landers, and other instrumented systems such as rovers and helicopters. Minimizing the weight and cost of TPS materials, while ensuring the integrity of the vehicle, is the continuing challenge for the entry systems community.

In 2008, the TPS community prepared and submitted a series of white papers to the Decadal Study team assessing the state of the art in TPS for solar system exploration. These white papers were co-authored by a combination of experts from NASA, industry, and academia [1-5]. Recognizing the need to significantly increase the *in situ* science return of missions with probes and landers by reducing the weight of the required TPS, NASA previously made several recommendations for the entry systems community to consider. Improvements in materials, testing techniques and facilities, modeling methodologies and instrumentation were all recommended to the panels in those white papers.

UPDATES: Progress Since the Last Decadal Survey

Since the submittal of those papers, many of the recommended improvements were realized. NASA and industry have created newly improved materials that could be applicable for use on spacecraft entering at Mars and/or Titan and brought them to differing TRL levels. These materials may reduce mass, increase workmanship quality, or reduce installation costs on future missions.

In addition, NASA has developed new test article designs for arc jet testing in shear that are improvements over traditional wedge shapes. One design is a small sphere cone, which allows for five instrumented test sections with two heating regimes. Two others are a small sphere-cone-cone and a sphere-cone-sphere that will allow for up to nine instrumented test sections and three heating regimes. These arc jet coupon designs are shown in Figure 1.

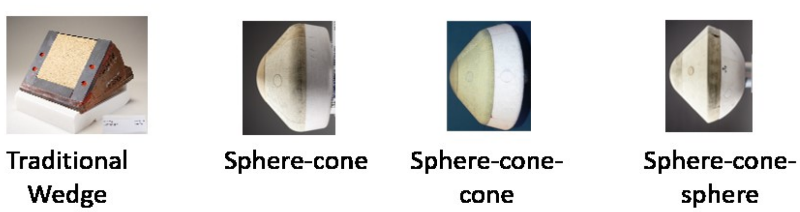

Figure 1. Various arc jet coupon shapes used for TPS testing.

These new test articles remove the adverse test model design influences on the behavior of the materials found when testing in water-cooled copper wedges [6]. In addition, conditions achievable on these articles (pressure, heat flux and shear) align well with Mars and Titan environments. These new test articles also can accommodate an internal data acquisition system greatly increasing the amount of data acquired during a test.

One of the most notable improvements in this past decade was the design and installation of a suite of instruments on the heat shield of the Mars Science Laboratory (MSL) heat shield, MSL Entry Descent and Landing Instrumentation (MEDLI) [7]. Both pressure and temperature distributions were measured allowing for a much more accurate determination of the actual flight trajectory. Based on this success, the NASA science community has required that all future mission proposals for vehicles entering a planetary atmosphere must also include an accompanying Entry, Descent and Landing (EDL) Instrumentation Engineering Science Investigation (ESI) proposal. The Mars 2020 vehicle contains both heat shield and aftbody instrumentation (MEDLI2) [8] and Dragonfly, the New Frontiers 4 mission to Titan, will contain the DrEAM (Dragonfly Entry Atmospheric Measurement) instrumentation suite [9].

Using data collected from the MEDLI and Schiarparelli [10], it was determined that the radiative heating on entry vehicle aft sections from CO_2 is non-negligible. All previous NASA missions had ignored this phenomenon and had solely calculated aft-body aerothermal heating based on convection. Since the design of the InSight spacecraft, all Mars missions now include the effects of the radiant energy from CO_2 in the wake on the aft-body components using validation with ground testing and thermal models. These radiative heating terms are similar in magnitude or even larger than the convective heating terms on some locations of the aft-body, and also extend the time of the heating pulse. DrEAM will fly a similar aftbody radiation sensor to Schiarparelli to inform and further refine the understanding of radiative heating for future Titan entry vehicles.

CURRENT CAPABILITIES: TPS for Mars and Titan Missions

Since the last decadal survey, NASA has delivered two large landers and one large rover successfully to Mars. The Phoenix (2008) and InSight (2018) landers were sent to the arctic region to look for water/ice and to the near equatorial region to measure seismic and in-depth thermal variations, respectively. The Curiosity Rover (2012), weighing nearly a metric ton, was delivered to the Gale Crater to characterize the climate and geology of Mars to determine if it could have supported life in the past. Curiosity, powered by a multi-mission radioisotope thermoelectric generator (MMRTG), is still operational. This year (2020), a similar, slightly heavier rover, Perseverance, was launched for a 2021 landing at the Jezero Crater, where it will study the history and geology of Mars, attempt to produce oxygen from the CO_2 atmosphere, explore other resources such as subsurface ice and cache samples for the next mission to retrieve and return. These missions were, or will be, successfully protected by a set of thermal protection materials developed by industry and by NASA.

The spacecraft designs, each with 70^{o} sphere-cone forebodies and conical or multi-conic aftbodies continued the NASA design philosophy that started with Viking for successful entries at Mars [11]. The entry, descent and landing systems grew more sophisticated through the years as the payload masses increased. The current design approach, used by MSL and Mars 2020, is sufficient for landing approximately one metric ton.

A mission currently in the design stage is Dragonfly, which will deliver an octocopter to explore the surface of Titan, the largest moon of Saturn. The entry heating conditions are similar to the MSL design conditions and the vehicle design will employ the same TPS materials used on MSL and M2020.

Approximate peak aerothermal conditions expected for the heat shields of current and future missions to Mars and Titan are shown in Table 1.

Table 1. Conditions for Mars and Titan Missions

Heat Shield Peak Conditions	Mars Missions				Titan Missions	
	Viking-Like (Orb. Entry)	Ballistic (MPF-Phoenix)	Lifting (MSL Class)	Aerocapture	Ballistic (Dragonfly)	Aerocapture
V_∞ (km/s)	4.42	5.5-7.2	5.7-5.9	~7.2	6	6
$\dot{q}_{radiative}$ (W/cm^2)	0	0-5	~0	~0	150	~40
$\dot{q}_{convective}$ (W/cm^2)	21	44-105	~200	57-112	145	~60
$\dot{q}_{combined}$ (W/cm^2)	21	44-110	~200	57-112	290	100
$Q_{combined}$ (kJ/cm2)	~1	~4	~6	5.5-12.0	13	20
$p_{stagnation}$ (atm)	0.06	<0.2	<0.4	<0.2	0.25	0.1

The entry heating conditions for Mars and Titan mission dictate that TPS materials are necessarily ablative in order to protect the vehicle. Mars missions, since the last decadal survey, have used materials including the NASA-invented Phenolic Impregnated Carbon Ablator (PICA), manufactured by Fiber Materials Inc. (now Spirit AeroSystems), various Super Lightweight Ablators from Lockheed Martin Space systems (SLA-561V, SLA-561S, and SLA-220), and Acusil II from Peraton Inc. These materials are fully capable of withstanding the predicted heating for Mars missions and for the upcoming Dragonfly mission to Titan, from small vehicles (Pathfinder-sized) to large vehicles (MSL). Although the TPS will experience similar heating rates, it is important to note that the atmospheres at the two locations are quite different and will result in different surface responses. The Mars atmosphere is primarily carbon dioxide, CO_2, with about 4% nitrogen, N_2 and the atmosphere at Titan is primarily N_2, with methane, CH_4, amounts varying from ~1.4% above 30km (the peak deceleration altitudes) to ~5% near the surface [12]. The oxygen in the CO_2 at Mars will react with the carbon in the PICA char via oxidation and will cause the PICA to recede (get thinner) during entry. The N_2 at Titan should not react with the PICA char, so there should be no recession on the Dragonfly TPS. Surviving the entry conditions expected for current and even future missions is not the issue. However, as vehicle sizes grow, manufacturing and assembly issues will arise with these materials, as explained in the following section.

ISSSUES AND CHALLENGES: Improving TPS for Mars and Titan Missions

The previous decadal study paper for Mars and Titan listed many developmental materials which, unfortunately, have not been under further formal development in the past decade. Those materials have been dropped from consideration for this white paper. In addition, the European materials have not been included because of the difficulties of including them on NASA funded, US built spacecraft. This section will describe the US materials that are considered either state-of-the-art, or have undergone development in the past decade.

Although PICA is a capable TPS material, it has limitations due to how it is manufactured and its inherent material properties. PICA heat shields can be cast in a single piece for small vehicles (<1.5m diameter), such as for Stardust and OSIRIS-REx. However, for large aeroshells, PICA is applied in a tile format with filled gaps. PICA is manufactured from ~0.5m by 1.0m Fiberform (carbon reinforcement) rectangular blocks that are either 0.15m or 0.20m thick, which limits the net tile size. In addition, these blocks have an inherent fiber direction that is perpendicular to the through-the-thickness direction, resulting in double the thermal conductivity in the fiber direction compared to the through-the-thickness direction. In order to retain the low thermal conductivity in the through-the-tile direction (toward the structure), the tile surface angle to the fiber is limited to 20^o. This constraint further limits the achievable PICA tile size. To add even more complexity, PICA has a very low strain-to-failure, making it very brittle. Tile size, thickness, and attachment to structure method are all limited by this brittleness. Improving these properties is paramount to extending PICA's usefulness.

Past missions have bonded PICA to the vehicle structure using a high temperature epoxy that requires an oven cure. For the MSL and Mars 2020 spacecraft, the tiles were bonded on row-by-row, with oven curing occurring after each row's installation, due to the limited out-time of the adhesive. The oven was large enough to accommodate the 4.5m diameter heat shield. For larger spacecraft, much larger ovens would be required with more trips into the ovens if the same attachment adhesives are used. A new technique may need to be developed for larger vehicles, involving room temperature, atmospheric pressure cured adhesives for bonding PICA.

The application of SLA-561V also becomes more and more challenging as the entry vehicle structures become larger with each mission to accommodate larger payloads. SLA-561V is attractive as a TPS material due to its monolithic nature. It is comprised of a honeycomb material bonded to the structure and then filled with a silicone, cork, phenolic, and glass mixture. A monolithic heat shield eliminates the need for bonding tiles with gaps and developing and installing gap filler. The time limitations driving the filling of the honeycomb and processing of the SLA-561V material make it a questionable choice for much larger structures, however. The filling of the back shell for Mars 2020 was precisely choreographed with 21 participants and still had issues with out-time exceedances, indicating that the time required to install and fill the material may not be possible for larger vehicles. The material may need to transition from monolithic to a block-tile format, or to longer out-time polymers and primers to be successfully used on larger structures.

The need for larger vehicles is becoming evident in the planning of future missions, such as the Mars Sample Return missions. System designers for the Mars Sample Retrieval Lander (MSRL) mission are finding that their heavier payload weight (~1.75 metric tonnes) and higher volume requirement is resulting a larger diameter forebody and a much larger conical aftbody than the MSL-class vehicle. Even so, slowing the expected entry mass is becoming more and more difficult due to the higher mass and lower atmospheric density expected during entry [13]. This is pushing the design toward the need for lower TPS weight. To conserve weight, the project is evaluating moving away from a constant TPS thickness toward tapered sizing for local heating or moving to lighter weight materials. Currently, the ablative TPS materials under consideration that might reduce heat shield mass are at TRL 5 or less and would require further development.

One such material that could potentially be beneficial in reducing mass would be a material similar to PICA but with material properties that lead to mass efficiency for Mars entry conditions. In 2010, NASA started the development of a higher strain-to-failure and less brittle conformal PICA (C-PICA) that uses a flexible needled carbon felt as the reinforcement, instead of the rigid Fiberform [14]. The use of the flexible felt resulted in a similar density material with a higher strain-to-failure. Although the felt has high thermal conductivity in the fiber direction like Fiberform, it can be formed before impregnation to a near net shape, allowing for the through-the-thickness thermal conductivity to be constant across the entire tile. In addition, felt is processed as broad goods, in ~1.5-m wide by several meters in length, like textiles, which could allow C-PICA formed tiles to be much larger than machined PICA tiles. Early estimates showed that converting from PICA to C-PICA on the MSL heat shield could have reduced the tile count by well over 50%. In addition C-PICA's lower thermal conductivity would require thinner tiles resulting in 20% less mass. Unfortunately, the development of the C-PICA stopped as it achieved TRL 5 for small vehicles and there are no future plans for NASA to continue its development. For test articles and small vehicles, the TPS tiles were installed using butt-joints, without gaps (which are not required due to the higher strain-to-failure). Assembly difficulties will arise when designing and installing larger tiles on larger vehicles, requiring the evaluation of allowable gap sizes and development of appropriate gap filler materials and techniques. Additional development in the felt white goods manufacturing process and its subsequent carbonization is also needed to assure consistency. A mid-fidelity thermal response model has been developed for C-PICA, however for further development to TRL 6, additional ground testing and analysis would be required to produce a high-fidelity model.

NASA has also developed (to TRL 4) a conformal, RF-transparent aft-body material, Conformal Silicone Impregnated Reusable Ceramic Ablator (C-SIRCA), as an improvement over rigid SIRCA. SIRCA flew as the Transverse Impulse Rocket System (TIRS) covers on the back shells of the 2003 Mars Exploration Rovers (MER) entry vehicles. The conformal material is based on broad-goods silica felt, can be processed into much larger tiles than SIRCA, and easily bonded to a structure due to its high strain-to-failure. At TRL 4, only a low-fidelity thermal response model has been developed for C-SIRCA. To further the readiness level, additional manufacturing and assembly development, ground testing, thermal response model advancement and qualification is required. Again, there are no plans for NASA to continue C-SIRCA's development.

Another material under development is a new carbon-phenolic TPS, Boeing Phenolic Ablator (BPA). BPA is a medium-density phenolic syntactic foam ablative material that can be fabricated in a formable glass/phenolic reinforcement core for high shear environments. It can also be used without the reinforcement and fabricated into panels. Boeing can also reduce the weight and conductivity of the filler material and grade the density through the reinforcing core. The development level of BPA is TRL 4 as a material, requiring further development, testing, thermal response model development and qualification to result in a material system at TRL 6.

Finally, Lockheed Martin Space (LMS) is developing a low-density monolithic ablator (MONA) with similarities to PICA. The material begins with honeycomb bonded to the structure and is injected with a phenolic and carbon fiber slurry, eliminating the need for gaps and gap fillers. In addition, LMS is investing in an improved version of SLA-561V, called SLA-561R, which is slightly higher density and can withstand higher shear rates and thus increases the allowable heating environments. Both MONA and SLA-561R are monolithic TPS materials that could be considered for Mars and Titan missions, without the complications of gaps and gap fillers. These materials are at TRL 4 and require further development, testing, thermal response model development and qualification.

The current and developmental materials and their suitability for missions to Mars and Titan are shown in Tables 2 and 3.

Table 2. Potential Heat Shield TPS Materials

			Potential Limit		Mars Entry			Titan Entry	
Forebody Material	Supplier	Flight Qual or TRL	Heatrate^{+} (W/cm^2)	Pressure (atm)	MPF Class	MSL Class	Aero-capture	Direct	Aero-capture
SLA-561V	LMS	MPF, MER, PHX, etc.	< 100*	< 0.5	●	✖	◠	✖	●
PICA	Spirit/FMI	MSL, Stardust	< 1800	< 1	○	●	●	●	●
BLA	Boeing	Boeing CTS-100	< 400	< 0.5	○	●	●	●	●
Avcoat	Textron/LMS	Apollo, EFT-1	< 1000	< 1	○	●	●	●	●
Acusil I	Peraton	TRL 5-6	< 100	< 0.5	◠	✖	◠	✖	◠
C-PICA	NASA Ames/FMI	TRL 5-6	< 700	< 60	◡	◠	◠	◠	◠
BPA	Boeing	TRL 3-4	< 1500	< 1	◡	◠	◠	◠	◠
SLA-561R	LMS	TRL 4	< 300	< 1	◠	◠	◠	◠	◠
MONA	LMS	TRL 4	< 1000	< 1	◡	◠	◠	◠	◠

*Heat flux limit is lower at high shear

● Fully capable ○ Capable, but heavy ◠ Potentially capable, further dev. req ◡ Potentially capable and heavy, further dev. req ✖ Not capable

Table 3. Potential Aft-Body TPS Materials

Aftbody Material	Supplier	Flight Qual or TRL	Potential Limit Heatrate[+] (W/cm^2)	Potential Limit Pressure (atm)	Mars Entry MPF Class	Mars Entry MSL Class	Mars Entry Aero-capture	Titan Entry Direct	Titan Entry Aero-capture
SLA-561V	LMS	MPF, MER, PHX, MSL, etc.	< 100*	< 0.5	●	●	●	●	●
SLA-561S	LMS	PHX, InSight, etc.	< 1800	< 1	●	✖	✖	◓	✖
BLA	Boeing	Boeing CTS-100	< 400	< 0.5	○	●	●	◓	◓
SLA-220[t]	LMS	Apollo, EFT-1	< 20	< 0.2	●	●	●	●	●
SIRCA[t]	NASA	MER	< 125	< 0.5	●	◓	◓	◓	◓
C-SIRCA[t]	NASA	TRL 4	< 125	< 60	◓	◓	◓	◓	◓
Acusil II[t]	Peraton	DoD, MSL	< 50	< 0.5	●	●	●	●	●

[t]RF transparent *Heat flux limit is lower at high shear

● Fully capable ○ Capable, but heavy ◓ Potentially capable, further dev. req ◒ Potentially capable and heavy, further dev. req ✖ Not capable

RECOMMENDATIONS: TPS for Future Mars and Titan Missions

Going forward, future missions to Mars and Titan will likely have larger and heavier payloads which will lead to larger spacecraft. For vehicles beyond what has been previously manufactured for robotic missions (4.5m in diameter, ~1 metric tonne), challenges will arise if designers are limited to the current menu of TPS materials. NASA and its vendors have materials in the pipeline that should help alleviate the challenges, however, NASA should invest in sustaining their current technologies [15] for the near term and expanding their new technologies to ready them for future missions. Previous mission spent significant resources and time re-creating heritage TPS materials, such as with Mars Pathfinder in redeveloping SLA-561V from the Viking era. Losing expertise and experience in this area can result in lengthy and expensive delays for future missions.

Specifically, we recommend that NASA invest in TPS material development which will benefit Mars and Titan missions, such as re-establishing the C-PICA project and complete its development to TRL 6. The C-PICA material provides substantial manufacturing improvements over PICA and should allow for both lighter weight and larger heat shields. This could enable future growth from robotic to human missions at Mars. NASA should also continue with its Collaborative Opportunities program and support TPS vendors in the advancement of their materials.

In addition, we recommend that NASA continue to expand its capabilities in instrumenting TPS for every atmospheric entry, to allow for accuracy in trajectory reconstruction, aerothermal modeling and TPS response model improvements [16], which could reduce uncertainties and margins used in sizing TPS. Both InSight and Mars 2020 have used flight data collected from MEDLI that altered the overall analytic methods used and margins employed [17].

In conclusion, it is worth noting that each of these recommendations, if implemented, have direct benefit to other planetary missions. Many of the heat shield materials developed for Mars and Titan could be used as back shell materials for more extreme entry destinations. TPS is a cross-cutting technology that requires specialized resources in terms of expertise, facilities, and capabilities across NASA and industry and can be deployed to support different missions. Therefore, the Decadal committee should consider not only the specific recommendations made above for destinations of interest to these sub-panels, but also the needs of other destinations (addressed in other white papers [18-20]) and the needs of other NASA stakeholders to ensure that scarce dollars provide the maximum return on investment. The TPS community requests participation in future atmospheric entry mission studies commissioned by the Decadal panels, in order to advise about material feasibility and performance, and potential mission constraints.

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