NASA TPS Capability for Astrobiology Missions
Topic 2 Response to 2025 NASA DARES RFI

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Summary
The two kinds of science missions that support Astrobiology are: 1) In-situ investigations at destinations that have the potential for life and 2) technically challenging sample return missions to allow sample analysis with sophisticated hardware on Earth. Both mission types need thermal protection systems (TPS) as they enter the planet's atmosphere, but samples returned to Earth must further obey backward planetary protection requirements to avoid contaminating Earth during atmospheric entry and recovery. In-situ missions benefit from NASA's enduring capability with low-density ablators (missions like Mars2020 and Dragonfly) and the continued efforts in optimizing the technology for improved performance at lower cost. Sample return missions adhering to Category 5 backward planetary protections are made viable by Woven TPS, as with Mars Sample Return – Earth Entry System. For each TPS, however, there are existential threats that originate from commercial supply chain challenges and atrophy in industrial capabilities. Looking to the future missions of interest to Astrobiology (e.g. comet and/or Enceladus sample return), it is imperative that the community advocate for the continuation of NASA's specialized expertise in TPS. Preserving experience base allows NASA, having developed most of the TPS that serve planetary missions, to address supply chain issues, develop alternates, and revive capabilities as needed. NASA experts are the only group with long-term charter that can and will provide end-to-end support to ensure mission success.

Introduction
TPS serves as a mission enabling but also critical single-point-failure system for vehicles traveling at hypersonic speeds through a planet's atmosphere. An update to TPS relevant to astrobiology missions is provided, refining from previous white papers, after giving a history of the development and use of both the low-density family of ablators and the inception of woven, medium-density ablators [1, 2, 3]. This history is punctuated with challenges to commercial supply, atrophy in industrial capability, and changes to NASA's priorities. Even so, NASA's expertise in crafting, implementing, and improving TPS solutions based on these unique events across many years leads us to make a recommendation to the astrobiology community at the end of the paper.

Historical Lessons

Low-Density Ablators

Since the late 1990's, only a couple TPS have found repeated-use for planetary missions: Phenolic Impregnated Carbon Ablator (PICA) and Super Lightweight Ablator SLA-561V. The inception of PICA started first with NASA engineers and technologists that identified the need for a high-performing ablator, when at the time NASA had primarily focused on reusable TPS. A discovery-class mission was proposed to capture samples from a comet, and PICA was the only TPS that was light weight and capable. PICA was derived from a commercial product made by Fiber Materials Inc (FMI), so the technology was quickly matured in partnership with FMI and the sample return mission Stardust was a success as a result. Later, when a failure mode with SLA 561-V was discovered in the Mars Science Laboratory heatshield that could jeopardize the mission, NASA proposed a tiled PICA heatshield replacement and supported the development which led to MSL's success. NASA also supported Space X's adoption of tiled PICA for the success of cargo Dragon missions. PICA performed well yet again on the Mars2020 mission, and more recently on OSIRIS-REx. When it was learned that the commercial supply of the flight-qualified rayon pre-cursor component to PICA would no longer be available, NASA engineers identified a domestic replacement, Lyocell, that could be used. Working with FMI, NASA developed PICA-Domestic (PICA-D) [4]. Around the time Dragonfly was selected, FMI informed NASA that they would no longer manufacture FiberForm™ for the commercial market and as a result, NASA had to work with FMI in establishing a new PICA-D manufacturing capability. NASA procured enough PICA-D for Dragonfly and the Mars Sample Return – Sample Retrieval Lander mission will also potentially use PICA-D.

Thanks again to the insight and expertise from NASA, an alternative to PICA and PICA-D has been under development since 2012 in the form of a Conformal PICA (C-PICA) [5]. While PICA and PICA-D were made from rigid carbon fiber tiles, C-PICA, made from carbon felt, is relatively complaint and is also more mass-efficient while possessing similar performance to PICA-D. SpaceX's PICA-3 is similarly based on carbon felt, and is currently used on Crew and Cargo Dragon. Varda Space Industries obtained C-PICA tiles from NASA for their first two successful flights to return space-manufactured pharmaceutical samples [5]. Even now, while PICA-D and C-PICA are enabling NASA and commercial space missions, NASA TPS experts are developing newer TPS to reduce both the cost and manufacturing time by many factors, to support higher mission cadence expected for exploring Mars as well as commercial missions from Low Earth Orbit and the Moon [6].

Medium Density Ablators

While the PICA family of TPS broadly serves in-situ science destinations like Mars and Titan, there are select destinations and mission formats that demand a more robust system. In the 1970's, NASA launched Pioneer-Venus (P-V) with probes that could withstand heating an order of magnitude higher than Apollo, by adopting a very specific version of DoD's high-density carbon phenolic. NASA dared to explore Jupiter using the Galileo probe in 1989 in which the carbon phenolic TPS was tailored and sized to withstand environments yet another magnitude greater than the Pioneer-Venus probes that could only be survived. Since the successful entry of the Galileo Probe, however, NASA had neither the need nor the material on-hand to produce carbon-phenolic in the same way, and so NASA's capability atrophied. As the Space Shuttle era began to close, NASA expanded its portfolio of planetary missions once more and it was found in the late 1990's that the domestic capability to produce rayon needed, and the know-how to create the specific version of carbon-phenolic, was lost. So, NASA faced two paths to support the burgeoning interest in sample return missions, Venus, and the outer planets: re-establish the carbon-phenolic capability or invest in an alternative. From input based on workshops held with DoD and industry in 2010 and 2012, NASA decided to develop a more mass-efficient alternative and developed the Heatshield for Extreme Entry Environment Technology (HEEET) to Technology Readiness Level 6 from 2014 to 2019 [7]. HEEET leverages 3D-weaving, an innovative approach to create a dual-layer TPS that has a recession layer optimized for ablation integrally woven with an insulative layer sized to keep the vehicle structure cool [8]. Beyond allowing considerable optimization of the TPS for a variety of destinations with a single system, HEEET enables mission designs with lower entry G loads when compared to the use of carbon-phenolic. During the development of HEEET, NASA determined that HEEET's insulation layer (HEEET-IL) performed exceptionally well as a stand-alone TPS. This layer offered a balance of manufacturing and implementation simplicity, robust entry environment performance, and resilience to micrometeoroid and orbital debris (MMOD) strikes. This discovery led to the inception of the 3D woven Mid-Density Carbon Phenolic (3MDCP). Further enhancing robustness, NASA worked with industry to create a loom that is large enough to weave 3MDCP so that it could be implemented as a single-piece TPS. 3MDCP is the baseline forebody TPS for the Mars Sample Return – Earth Entry System (MSR-EES) because of its evaluation as a TPS that can withstand the extreme entry conditions and be robust enough to satisfy backward planetary protection requirements. MSR-EES predicts greater heating during entry than that of Stardust and is also planned to have hard-impact to the Utah desert without the use of a drag chute.

Now, with the completion of all weaving to support current missions, the weaver will enact changes to support other customers. Beyond MSR-EES, the need for 3MDCP as a heatshield for sample return from Titan, Enceladus, and other locations, is decades away, but the Woven TPS family being originally developed for Venus and Outer Planets may be used in the interim period. Probes to Saturn and the flagship-class mission to Uranus will need Woven TPS to withstand the extreme entry environment. Even now, a HEEET-IL preform is being used as the forebody TPS on the privately funded RocketLab & MIT Venus Life Finder mission [9]. Still, these events are low-cadence, and there is no guarantee of support from the manufacturers that are critical to producing the TPS. While the hardware support may change, what remains at NASA is knowledge-set to develop, test, and manufacture Woven TPS remains within the TPS experts that devoted more than a decade to create capability that enables exploration of Venus and beyond. Lastly, it is noted that Advanced Carbon-Carbon (ACC) with FiberForm™, developed by Lockheed Martin and C-CAT for use on Genesis in the early 2000's, is baselined for the DAVINCI mission. While DAVINCI is currently qualifying ACC for use at Venus, the environments are lower than what P-V probes experienced, and the use of ACC for sample return mission was not deemed robust enough for MSR-EES.

Conclusions

White papers written for the previous decadal survey document the capability of TPS both at NASA and across several suppliers in the commercial space, and the figures from each are combined, and adapted here to reflect the mission concepts discussed with updates to the PICA family entries and inclusion of 3MDCP. While it appears there are many options, only the SLA, PICA, ACC, and Woven TPS family have seen regular support. In-situ missions today may be served by the capable PICA, SLA, and ACC families of TPS, but only the PICA family has been regularly used as a forebody TPS, and C-PICA is undergoing Tech Transfer now to multiple commercial partners. In-situ missions with astrobiology objectives in the future may use C-PICA or future improved options within the PICA family as NASA experts continue to refine the technology. For in-situ science missions to Venus, Woven TPS and ACC family technologies may be used, but for sample return missions, Woven TPS family options are the most robust to meet backward planetary protection requirements as with MSR-EES, and Woven TPS are the only materials with demonstrated capability for environments that may result from mission concepts to return samples from Titan and Enceladus, both having interest from the astrobiology community [10, 11]. Behind each of the TPS that serve NASA and the growing commercial space industry are dedicated experts in NASA that have devoted decades since the inception of PICA in the 1990's to advancing and adapting TPS in the face of changing mission's needs, commercial supplies, and industrial capability. It is for this reason that we make the following recommendation to the astrobiology community:

Recommendation

Planetary missions with Astrobiology objectives in the coming decades will need highly capable, qualified Thermal Protection Systems (TPS) to ensure mission success. Given the limited number of viable TPS available today, as well as the challenges associated with sustaining material production, the best way to ensure mission success is to maintain NASA's in-house expertise in TPS development and life-cycle support.

					Capability		Forebody TPS Applicability		
Density	Forebody Material	Supplier	Estimated TRL, Heritage, & Notes	Integration	Heatrate (W/cm^2)	Pressure (kPa)	In-situ to Mars, Titan	Venus	Sample Return from Titan, Enceladus
Low	PICA(-D)	Spirit/FMI	Stardust/OSIRIS-Rex (Single Piece) MSL/Mars 2020 (Tiled) No commerical vendor.	Single Piece (<1.5m), Tiled (>1.5m)	< 1800	< 150	●	◓	✖
	C-PICA	NASA Ames/FMI	TRL 7, Varda W-1 (Tiled)	Single Piece (<1.0m), Tiled (>1.0m)	< 1200	< 150	●	◓	✖
	Avcoat	Textron/LMS	Apollo (H/C), Orion EFT-1(H/C), Orion EM-1 (Tiled)	Honeycomb or Tiled	< 1000	<100	◒	◓	✖
	MONA	LMS	TRL 4	Honeycomb filled	< 300	< 100	◓	✖	✖
	SLA-561V[b]		Heatshield: InSight, Phoenix; Backshell: MSL, M2020, Stardust, OSIRIS-REx	Honeycomb filled	< 100	< 50	●	✖	✖
	SLA-561R		TRL 4	Honeycomb filled	< 300	< 100	◓	✖	✖
	BPA	Boeing	TRL 4	Honeycomb filled	< 1500	<100	◓	✖	✖
	BLA		CTS-100	Honeycomb filled	< 400	< 50	◒	✖	✖
	Acusil IV	Peraton	DoD	Moldable Silica	< 300	< 100	◓	✖	✖
	ACC	LMS/C-CAT	Genesis	Single Piece	< 800	< 100	○	◓	✖
Medium	3MDCP	NASA Ames	TRL 5	Single Piece	< 3700	< 610	○	●	●
	HEEET[d]	NASA Ames	TRL 6	Tiled	< 3800	< 550	○	●	●
High	Carbon Phenolic[c]	Multiple	Pioneer Venus, Galileio, No commercial vendor	Nose Cap (CM)/ Flank (TW)**	10000 - 30000	> 600	◒	◒	◒

[a] Combined total heating at hot-wall conditions
[b] Heat flux limit is lower a high shear
[c] the performance is fully capable of meeting missions but listed as further development required due to lack of manufacturing capability, and lack of certified rayon-based carbon fiber.
[d] the density of the recession layer in dual-layer HEEET is higher than Insulation layer, so although the tested limits are the same for both, the dual-layer HEEET is expected to be capable at more severe environments.

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

Figure 1. Table of Applicable Forebody TPS for Select Applications.

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