WHITE PAPER TO THE NRC DECADAL SURVEY
INNER PLANETS SUB-PANEL

Technologies for Future Venus Exploration

by
Matthew Gasch – NASA Ames Research Center
650-604-5377 Matthew.J.Gasch@nasa.gov

Co-Authors: Helen Hwang, Don Ellerby, Mairead Stackpoole, Ethiraj Venkatapathy, Alan Cassell, Jay Feldman, Suman Muppidi, Robin Beck, Todd White (NASA Ames Research Center) and Michele Chaffey (Boeing Research and Technology)

Co-Signers (45 individuals from 18 organizations): Aaron Brandis, David Driver, Kristina Skokova (Analytical Mechanics Associates, Inc.); Douglas Adams, Kenneth Hibbard (Johns Hopkins Applied Physics Laboratory); Amanda Brecht, David Hash, Dean Kontinos, Milad Mahzari, Mary Kathleen McGuire, Harry Partridge, Michael J. Wright, Kerry Zarchi (NASA Ames Research Center); Mary Litwinski (Boeing Research and Technology); Mark Lippold, Steven Violette (Fiber Materials, Inc.); Michael J. Way (NASA Goddard Institute of Space Studies); Natasha Johnson, Conor Nixon, Melissa Trainer (NASA Goddard Space Flight Center); David Atkinson, Kevin Baines, Tibor Balint, Bernard Bienstock, James Cutts, Jeffery L. Hall, Siddharth Krishnamoorthy, Kim Reh, Eric Slimko, Linda Spilker (NASA Jet Propulsion Laboratory); Adam Amar, Stan Bouslog, Gerald Lebeau, Steven Rickman (NASA Johnson Space Center); Ye Lu (Kent State University); Alicia Dwyer-Cianciolo, N. Ronald Merski, Michelle Munk (NASA Langley Research Center); Jarvis Songer (Lockheed Martin Space); Manish Mehta (NASA Marshall Space Flight Center); Paul Byrne (North Carolina State University); Matthew Kelly (Peraton); Kandis-Lea Jessup (Southwest Research Institute); Sushil Atreya (University of Michigan); Martha Gilmore (Wesleyan University)

ABSTRACT

The purpose of this white paper is to provide an overview to the NRC Decadal Survey Inner Planets Sub-Panel on thermal protection system (TPS) technologies required for future Venus exploration missions. It considers the capability of heritage TPS technology used by the Pioneer Venus and Galileo probe missions and identifies new technologies that could enable greater science value and more ambitious missions in the future. A prime conclusion is that there are important advances regarding the availability of forebody TPS required for Venus entry probes. Specifically, the carbon phenolic flown on the Pioneer Venus probes has been deemphasized and a new 3D woven material system, Heatshield for Extreme Entry Environment Technology (HEEET) has replaced carbon phenolic. Along with the development of HEEET, there have been test facility upgrades and design tool improvements. These new material and test methods are enabling for Venus missions. However, without a mission scheduled in the near future, even these new developments are at risk of becoming unavailable. Therefore, we recommend that NASA invest in a cross-cutting technology program that focuses on 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 Venus as well as anticipated TPS requirements in support of future Venus missions. The paper begins with a brief history of thermal protection systems relevant to the exploration of Venus, presents a discussion of current TPS capabilities and technology issues, and concludes with recommendations for establishing a TPS Technology Program that includes development, testing and manufacturing capabilities needed to support future Venus missions.

BACKGROUND: Historical 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 re-entry. In addition, for the science community, it enables the safe deployment of *in situ* science instruments using probes, landers, and other instrumented systems. Minimizing the weight and cost of TPS materials, while ensuring the integrity of the vehicle, is the continuing challenge for the entry systems community.

During the 1960s and into the mid-70s, the ablative TPS community in the U.S. was very active supporting both NASA and U.S. military programs. New facilities to test TPS materials were created, including hypersonic ground test facilities such as arc jets, shock tubes, and ballistic ranges. Analytical models and codes that predicted the aerothermal environment during entry (both convective and radiative) and the thermal and ablation response of candidate TPS materials were also developed. However, by the late 1970s, the research, development, and testing of ablative TPS materials significantly declined as the military's nuclear missile program was completed and the Apollo program was terminated.

NASA continues to require TPS materials and entry system design capabilities for robotic entry probe missions. These capabilities require specialized expertise, unique testing facilities and tools including aerothermal environment prediction, TPS material selection and sizing, thermo-structural analysis of complex integrated elements, and arc jet testing of TPS from development to flight qualification.

Once developed, this expertise in areas of system design and integration, including system engineering and manufacturing integration of components (from sub-systems to system) is essential to maintain. Such expertise and capabilities reside within NASA and with select vendors. Key outside vendors include raw materials suppliers, and in many instances, this translates to foreign owned suppliers and processing groups. We assume that when a NASA critical capability starts to atrophy the NASA Center responsible for such capability will act to maintain it. The same scenario is not true for external vendors. Many segments that feed into a TPS, from raw material vendors to prime aerospace integrators, have no obligation or incentive to maintain such technologies. In this regard, we need to ensure the critical capabilities and expertise are maintained both within and external to NASA.

Materials and Entry Systems for Science Missions in the Next Decade

Prior to the last Planetary Science Decadal Survey, *Vision and Voyages*, there was a limited number of existing materials and 1960s era design methodologies capable of enabling science probe and lander missions to Venus and the outer planets. In 2008, we prepared and submitted white papers to the Decadal Study team assessing the state of the art in TPS for Venus/solar system exploration. [1] These white papers were co-authored by a combination of experts from NASA, industry, and academia. 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. A summary of the recommendations from the previous Venus decadal paper [1] and current status is listed in Table 1.

Table 1. Recommendations to the Decadal Survey from 2008 and Current Status.

	Recommendation	Current Status
1	Recertification of industry's capability to manufacture chop molded heritage carbon phenolic (HCP)	Manufacturing technology was not invested in. Chop molded HCP for NASA missions is not available without further development and testing
2	Development of an alternate to heritage carbon phenolic using current commercially available fibers	Developed 3D woven entry systems: HEEET and ADEPT
3	Development of new mid-to-high density TPS materials	Development of 3D woven dual layer materials: HEEET, Phenolic-based ablative materials (BPA)
4	Upgrade of existing facilities (arc jets) to operate at very high heat fluxes (7-8 kW/cm^2)	Built and tested 3-inch nozzle in NASA ARC's IHF arcjet with demonstrated heat flux of ~4000 W/cm^2 @ 5atm
5	Capability for testing in CO_2	Was established at NASA JSC but still awaiting implementation and testing after JSC arcjets were consolidated and moved to ARC
6	Improve design and analysis tools, such as CFD and material response models, needed to verify material response and qualification test conditions	NASA developed engineering and higher-fidelity predictive tools for environments (DPLR and LAURA (convection), NEQAIR and HARA (radiation)) have become the standard. FIAT and CHAR are NASA improved TPS sizing tools that are used both within NASA and by Industry.
7	Development of robust TPS instrumentation to build a database of relevant flight data which will aid in the planning of all future probe and lander missions	TPS instrumentation developed and flown on MSL and Orion EFT-1; now required for all future entry missions

As noted in Table 1, several advancements in TPS materials and entry systems technologies have been made, upgrades to test facilities and test capabilities have been completed, and improvements to design and analysis tools have been implemented and shared with industry.

CURRENT CAPABILITY: TPS & Venus Missions

Materials

Given the properties of the Venusian atmosphere, expected entry velocities for Venus probes, and the lack of a requirement for reusable TPS for any foreseeable Venus mission, the entire aeroshell thermal protection systems for Venus entry vehicles will almost certainly consist of ablative materials.

Table 2 lists the capabilities of currently available flight-proven TPS materials in the US as well as the potential performance limits, and potential regions of applicability new TPS materials and emerging entry systems that have been developed since the last study. There are materials not included in the table that are at lower TRLs, developed outside of the US, developed without widely available performance data, or have not been specifically evaluated for entry applications.

Table 2 illustrates applicability for forebody materials for 3 Venus probe mission scenarios: direct entry, aerocapture, entry from orbit, and also backshell materials. Direct entry on a hyperbolic trajectory, like Pioneer Venus, produces the highest forebody heating rates and pressures. Aerocapture, in which aerodynamic drag rather than retro propulsion is employed to place a vehicle in orbit around a planetary body, produces lower forebody heating rates and pressures with significantly larger heat loads. Entry from orbit results in the mildest forebody environments with lower entry velocity in comparison to direct entry. For aerocapture and entry from orbit applications, lower density materials are better choices from the standpoint of TPS mass.

Table 2. Candidate TPS materials and entry systems for Venus landers or probes.

					Capability		Applicability		
Density	**Forebody Material**	**Supplier**	**Estimated TRL, Heritage, & Notes**	**Integration**	**Heatrate$^+$ (W/cm^2)**	**Pressure (kPa)**	**< 13.5 km/s**	**> 13.5 km/s**	**Back shell**
Low	PICA	Spirit/FMI	Stardust/OSIRIS-Rex (Single Piece) MSL/Mars 2020 (Tiled)	Single Piece (<1.5m), Tiled (>1.5m)	< 1800	< 150	●	◠	○
	C-PICA	NASA Ames/FMI	TRL 4-5	Single Piece (<1.0m), Tiled (>1.0m)	< 700	< 60	◠	✖	◠
	SIRCA	NASA Ames	Mars Pathfinder, MER, requires production re-start. No commercial vendor.	Tiled	< 125	< 50	✖	✖	●
	C-SIRCA	NASA Ames	TRL 3-4, Conformal tiles. No commercial vendor.	Tiled	< 125	< 50	✖	✖	◠
	Avcoat	Textron/LMS	Apollo (H/C), Orion EFT-1(H/C), Orion EM-1 (Tiled)	Honeycomb or Tiled	< 1000	<100	●	◠	○
	ACC	LMS/C-CAT	Genesis	Single Piece	< 800	< 100	●	✖	◠
	MONA	LMS	TRL 4	Honeycomb filled	< 300	< 100	✖	✖	●
	SLA-561V$^\#$		Heatshield: InSight, Phoenix; Backshell: MSL, M2020, Stardust, OSIRIS-REx	Honeycomb filled	< 100	< 50	✖	✖	●
	SLA-561R		TRL 4	Honeycomb filled	< 300	< 100	✖	✖	◠
	SLA-220		InSight, Phoenix Backshell	Moldable or spray-on	< 20	< 20	✖	✖	●
	BPA	Boeing	TRL 4	Honeycomb filled	< 1500	< 100	◠	✖	○
	BLA		CTS-100	Honeycomb filled	< 400	< 50	✖	✖	◠
	Acusil I	Peraton	TRL 5	Moldable Silica	< 100	< 50	✖	✖	●
	Acusil II		MSL, M2020 Backshell	Moldable Silica	< 50	< 50	✖	✖	●
	Acusil IV		DoD	Moldable Silica	< 300	< 100	✖	✖	●
Medium	HEEET - Dual Layer	NASA Ames	TRL 6	Tiled	< 3800	< 550	○	●	○
	HEEET- Insulation Layer Only	NASA Ames	TRL 5	Single Piece (<1.3m), Tiled (>1.3m)	< 3800	< 550	◡	◠	○
High	Carbon Phenolic	Multiple	Pioneer Venus, Galileio, requires production re-start.	Nose Cap (CM)/ Flank (TW)**	10000 - 30000	> 600	◡	◡	◡

[#] Heat flux limit is lower at high shear

[**] CM = Chop Molded, TW = Tape Wrapped

[+] Combined total heating at hot-wall conditions

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

Although chop molded HCP was critical to PV and Galileo, it has not been produced or used in flight since the 1980s. NASA Ames held two workshops (FY10 and FY11) concerning the supply chain issues with respect to HCP and proposed the development work required to qualify a new rayon-based carbon fiber as well as a proposed alternate, more sustainable, material to CP. Ultimately NASA deemed the restart of HCP ineffective and not sustainable and instead efforts were invested in the Heatshield for Extreme Entry Environment Technology Project (HEEET) that led to the development of an alternate to CP for NASA's missions with extreme entry environments. The HEEET system, shown in Figure 1, replaced the capability once provided by HCP for Venus and most outer planet missions except for Jupiter. HEEET's dual layer design is more mass efficient than HCP for missions that use high speed entry to deliver landers, probes, aerial platforms, *higher speed* skimmers and aerocapture.

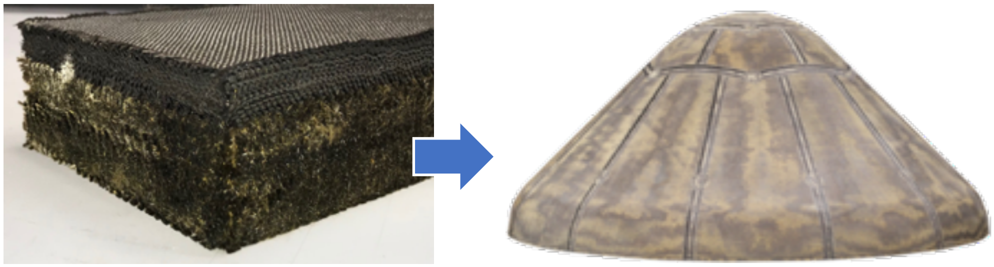


Figure 1. HEEET dual layer dry weave (left) and 1-meter Engineering Test Unit (right).

Boeing has developed two families of ablative materials, Boeing Lightweight Ablator (BLA) and Boeing Phenolic Ablator (BPA), as low-cost solutions for heat shield TPS in low to mid-range heat flux applications. BLA is radio frequency (RF) transparent and available in a range of densities from 20-33 lb/ft³, offering cost and mass efficiency for vehicle backshells. This material is used on the base heat shield of Boeing's CST-100 LEO return vehicle. The suite of BPA materials with densities of 27-34 lb/ft³, offer higher heat flux capability for probe, lander, and sample return missions. A graded density configuration (BPA-G) is under development that decreases mass while providing increased insulation capabilities.

a) b) c)

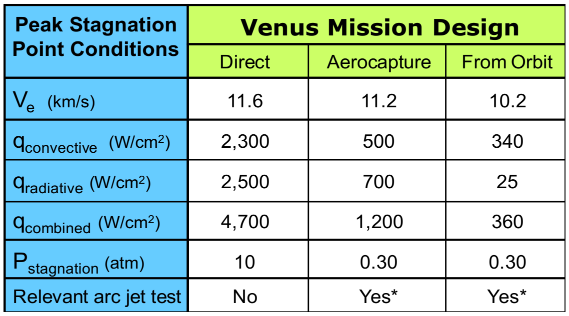
Figure 2. BPA Curved Section (a), Full Sized Panel (b) and Graded Density (c)

Testing of these materials at relevant planetary entry environments is required to determine applicability to specific mission requirements, such as the high heating and high shear levels due to Venus ballistic entry. Further development of the graded-density BPA configuration and sizing of layers to specific requirements could potentially lower both mass and cost, making it a suitable candidate for cost capped missions for New Frontiers and Discovery missions. Support from NASA in providing and updating requirements and testing of the material would be required to establish, maintain, and expand the property database, model robustness, and selectability of the material for future missions.

Table 2 reflects material capabilities for usage over the entire afterbody, even in regions of reattaching flow (moderate heat fluxes and shear forces). It is possible to use several materials, particularly low-density materials, in lower heating areas. There may also be regions on the backshell where RF transparent TPS materials will be required to allow communications, and several candidate materials are available to meet this requirement, as well. Other system-level engineering decisions, such as designing aeroshell shapes and weights, orbits and trajectories, entry speeds and angles, as well as vehicle system optimization will affect the actual entry heating conditions for each mission.

Table 3 presents a comparison of stagnation point environments for these three mission scenarios for probe geometries similar to the Pioneer Venus large probe. Although not shown in the table, it should be noted that due to Venus's slow rotation, prograde and retrograde entry trajectories have nearly the same heating profiles. There are a broad range of potential entry environments depending on factors such as: entry velocity, entry flight path angle, probe ballistic coefficient (size, shape, mass), target latitude and prograde or retrograde entry. This table should not be interpreted as encompassing all potential environments. One of the key lessons learned from previous mission concepts was that the stagnation point may not result in the highest heat fluxes. Roughness-augmented turbulent heating was often found to create the highest entry heating conditions on the flank of the vehicle.

Table 3. Stagnation point environments for three Venus mission scenarios



Peak Stagnation Point Conditions	Venus Mission Design		
	Direct	Aerocapture	From Orbit
V_e (km/s)	11.6	11.2	10.2
$q_{convective}$ (W/cm^2)	2,300	500	340
$q_{radiative}$ (W/cm^2)	2,500	700	25
$q_{combined}$ (W/cm^2)	4,700	1,200	360
$P_{stagnation}$ (atm)	10	0.30	0.30
Relevant arc jet test	No	Yes*	Yes*

*Existing facilities capable of simulating combined peak heat flux in air, not CO_2. Current max combined conditions available are in the IHF 3-inch nozzle P_{Stag} 5-6 atm @ 4000 W/cm^2.

Ground Test Facilities

A mainstay of TPS development for the past several decades has been the high-enthalpy arc jet facilities at ARC, Arnold Engineering and Development Center (AEDC), and Boeing (LCAT). These facilities with power capabilities from 10 to 60 MW provide the largest test article or the highest heating capability possible and have proven to be indispensable for TPS development work as well as qualification of flight hardware. The test facilities at ARC were upgraded with the addition of a new 3-inch diameter nozzle capable of achieving ~4,000 W/cm^2 at 5 atmospheres. As shown in Figure 3, relevant test facility capabilities compare well with Venus entry environments.

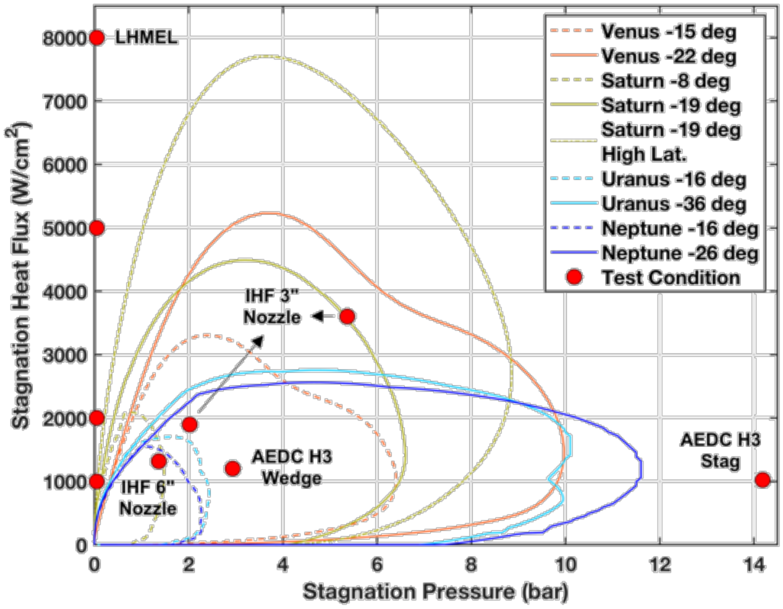


Figure 3. Arcjet envelopes for Venus and other planetary destinations and relevant test facility capabilities (red circles).

With the addition of the 3-inch nozzle in IHF, arc jet facilities are now capable of simulating the high combined heat flux and pressure associated with hyperbolic direct entry to Venus. The Laser Hardened Materials Evaluation Laboratory (LHMEL) facility at the Air Force Research Laboratory at Wright Patterson Air Force Base has supported the aerospace community for several decades. LHMEL has both a 10-kW and 100-kW carbon dioxide (10.6-µm), continuous wave, flat top laser. The LHMEL facility allows candidate TPS materials to be tested in air to estimate the level of heat flux required to initiate char spallation at ambient pressure. The HEEET system was tested at LHMEL to 8000 W/cm^2 without any issues, whereas traditional tape wrapped and chop molded CP samples cracked and demonstrated ply separation.

Although the Venusian atmosphere is more than 90% CO_2, none of the existing high-power arc jet facilities in the US can operate with CO_2. Material performance using the correct thermochemistry has been calculated using high fidelity response models with validation from tests using varying ratios of O_2/N_2. Very few test facilities currently operate in gases other than air. The non-air facilities have limitations (test sample size, heat flux, pressure) that can limit their usefulness in planetary mission applications. For example, the NASA Langley Hypersonic Materials Environmental Test System (HyMETS) facility is capable of running in CO_2 but only at 400kW (350-400 W/cm^2 on a 1-inch model). All other arc jet facilities run nitrogen and oxygen with argon shield gas. The arc jets at JSC briefly added the ability to test in a partial CO_2 environment. However, that capability ended when the JSC arc jets were shut down and relocated to ARC. Although there is a plan to resurrect that capability, to date it has not been accomplished.

ISSUES & CHALLENGES

Materials and Ground Test Facilities

Recent history (e.g., resurrecting Apollo's Avcoat TPS for the Orion CEV) has shown that just having written specifications does not guarantee that manufacturers can deliver consistent, quality products. Over time, the people involved in fabrication change and there is no substitute for direct experience. The development of HEEET and the test facilities for evaluating materials in extreme environments is enabling for Venus missions but must be sustained until an actual Venus mission is selected. The 3-inch nozzle capability has expanded the test envelope but still a piece-wise qualification strategy must be used to encompass the full range of gas composition (CO_2), heat flux, pressure, shear, enthalpy, etc. Without specific investment from NASA, these technologies may atrophy.

Analytic and Model Development

In the past decade, the support of TPS design for Mars Science Laboratory (MSL) and the CEV TPS Advanced Development Project (ADP) led to significant expansion of capabilities within NASA, particularly in the areas of TPS testing and aerothermal environment definition. In the few years preceding these efforts, the In-Space Propulsion program sponsored important work in analytical tools development and ablative materials development, with specific emphasis on aerocapture. Recently, the Entry Systems Modeling project has focused on advanced modeling techniques for material performance, however the budget is limited, and the topics covered span a broad range. These analysis efforts should be continued as they enhance material development and are relatively inexpensive compared to materials testing.

RECOMMENDATIONS

With the development of HEEET and test capabilities for extreme environments, science missions to Venus can be accomplished in the near term using existing materials. However, these materials need to be sustained until a Venus mission is selected, in order to retain knowledge and skills. Improved design analysis tools and ground test facilities will significantly reduce the risk of TPS failure and to the mission.

Specifically, it is recommended that NASA establish a cross-cutting TPS Technology program with elements focused on enabling both near- and longer-term Venus Entry Missions. The program will need to focus on the following:

Materials:

1. Ensure the fabrication of TPS materials for extreme environments is maintained by conducting annual or semi-annual manufacturing assessments

2. Sustain current manufacturing capabilities for existing and heritage TPS materials for at least two proven backshell materials to be available for future Venus missions

Test facilities:

1. Ensure the ability to test in extreme environments at existing facilities (such as arc jets at ARC and AEDC) is maintained at very high heat fluxes (≥ 5 kW/cm^2)
2. Endeavour to provide the capability for testing in CO_2, and potentially H/He

Analytic and Model Development:

Continue to improve design and analysis tools, such as CFD and material response models, needed to verify material response and qualification test conditions. These improvements will also aid in analyzing material reliability concerns.

Flight Instrumentation:

Any future Venus entry mission should be required to include TPS instrumentation to build a database of relevant flight data which will aid in the planning of all future Venus missions. [See Ref. 8] This flight instrumentation will be especially important to verify the performance of HEEET, which has not been flown.

In conclusion, it is worth noting that each of these recommendations, if implemented, have direct benefit to other planetary missions, such as Sample Return missions, entry probes to the Outer Planets, and even Mars. Given that TPS is a cross-cutting technology requiring specialized resources in terms of expertise, facilities, and capabilities across NASA and industry, the specific recommendations made above are applicable for all solar system destinations to an atmospheric body. These investments will thus provide maximum return to NASA's future missions.

Finally, 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.

REFERENCES

1. E. Venkatapathy, et.al. "Technologies for Enabling Future Venus Exploration" Decadal Whitepaper: Sept 2009.
2. Venus Technology Plan, 2019, Venus Exploration and Analysis Group.
3. D. Ellerby, E. Venkatapathy, M. Stackpoole, et.al., "Woven Thermal Protection System Based Heatshield for Extreme Entry Environments Technology (HEEET)," presented at National Space and Missile Materials Symposium, Bellevue, WA, June 24-27, 2013.
4. E. Venkatapathy, D. Ellerby, P. Gage, "Heatshield for Extreme Entry Environment Technology (HEEET) Development Status," presented at the 13th International Planetary Probe Workshop, June 13-17, 2016.
5. E. Venkatapathy, "Ablators - From Apollo to Future Missions to Moon, Mars and Beyond," presented at the 70th International Astronautical Congress (IAC), Washington D.C., United States, 21-25 October 2019, IAC Paper # IAC-19,C2,4,1,x55164
6. D. Ellerby, M. Gasch, "Heatshield for Extreme Entry Environment Technology (HEEET) Thermal Protection System (TPS)", presented at Materials Science and Technology (MS&T), Portland, OR, Sep. 29 – Oct. 3, 2019.
7. J. Feldman, J. Arnold, "Current Capabilities, Gaps and Development Pathways Required to Enable Future Planetary Missions that need Carbon Phenolic Heatshields: Mars Sample Return, Venus and the Outer Planets; Summary Report to NASA's Office of the Chief Engineer and Office of the Chief Technologist ISPT Program Office SMD," July 26, 2010.
8. J. Santos, et.al. "Entry, Descent, and Landing Instrumentation," Decadal Whitepaper: Aug 2020.