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

Thermal Protection System Technologies for Enabling Future Venus Exploration

by

Ethiraj Venkatapathy* (Lead), Helen H. Hwang*, Bernard Laub*, Joseph L. Conley*, James Arnold**, Christine E. Szalai***, and 90 Co-authors

* NASA ARC, ** UC Santa Cruz, *** JPL.

Co-Authors (90 individuals representing 18 organizations)

Jim Tibaudo, Robert Knudsen (Textron); Andrew Chambers (Space X); David Atkinson (U. of Idaho); Sushil K. Atreva (U. of Michigan); Joseph M. Vellinga, William H. Willcockson, Janine M. Thornton, Nicholas G. Smith, Richard A. Hund (Lockheed Martin); John Dec, Max L. Blosser, Michelle M. Munk, Robert Maddock, Prasun N. Desai, Walter Engelund, Stephen Sandford, David A. Gilman, Steven W. Gayle (NASA LaRC); John Kowal, Christopher B. Madden, Stan Bouslog, Brian J. Remark, Donald Curry, Scott Coughlin, Adam J. Amar (NASA JSC); Kevin H. Baines, Tibor Balint, Bernard Bienstock, George T. Chen, James A. Cutts, Jeffery L. Hall, Samad A. Hayati, Pamela J. Hoffman, Linda Spilker, Romasso P. Rivellini, Robert Manning, Eric M. Slimko, Adam D. Steltzner, Thomas Spilker, Jeffrey Umland (JPL); Charles Kiskiras, Duane Baker, Thomas Foster (ITT Corp); Dominic Calamito (HITCO); James B. Garvin, Timothy A. Sauerwein, Sharon Seipel, Lori S. Glaze (NASA Goddard); Spencer Stolis, Mark Lippold (FMI); Francis Schwind, James Thompson, Raj Narayan (C-CAT); Thomas Andrews, Conley Thatcher, Edwin B. Curry, John McKinney, Robert Frampton, Todd Stever (Boeing); Charley Bown (ATK); William Congdon, Jennifer Congdon (ARA); Daniel M. Empey, Joe Hartman (Jacobs Technology); Dinesh Prabhu, Nancy L. Mangini, Kristina A. Skokova, Margaret M. Stackpoole, Tood White, Howard Goldstein, Melmoth Covington (ELORET); Robin A. Beck, Carol W. Carroll, Charles A. Smith, Deepak Bose, Anthony Colaprete, David M. Driver, Edward Martinez, Donald T. Ellerby, Matthew J. Gasch, Aga M. Goodsell, James Reuther, Sylvia M. Johnson, Dean Kontinos, Mary Livingston, Michael J. Wright, Harry Partridge, George A. Raiche, Huy K. Tran, Kerry A. Trumble (NASA ARC)

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[1,3,5]. 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 research, 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, balloons and other instrumented systems. Minimizing the weight and cost of TPS, while insuring the integrity of the vehicle, is the continuing challenge for the TPS 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 shifted its focus to the Space Shuttle program that was designed to be a reusable system, including the TPS. While reusable TPS research, development and testing occurred in the late 1970s and through the 1980s, the ablative TPS community saw a serious decline in capability.

However, NASA continued to require ablative TPS for robotic entry probe missions (e.g., Mars Viking, Pioneer Venus, Galileo). Fortunately, TPS requirements for these missions were satisfied with existing ablative materials. In particular, NASA leveraged the significant investment made by the U.S. military in the 1970s in developing FM5055 carbon phenolic for use as heat shields on ICBM reentry vehicles. Since then, NASA and industry have made modest investments in ablative TPS for specific missions.

CURRENT CAPABILITY: TPS & Venus Missions

Materials

Given the properties of the Venusian atmosphere and the expected entry velocities for Venus probes, the forebody thermal protection systems for Venus entry vehicles will almost certainly consist of ablative materials due to extreme environment encountered during entry[6].

Table 1 illustrates the capabilities of currently available ablative TPS materials in the US with flight heritage or high Technology Readiness Levels (TRL), their potential performance limits, and their potential regions of applicability for a Venus probe mission. 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 1. Candidate ablative TPS materials for Venus probe applications

Density	TPS	Supplier	Flight Qual or TRL	Potential Limit		Venus Mission Design		
				Heat flux, W/cm^2	Pressure, atm	Direct	Aerocap	From Orbit
FOREBODY HEAT SHIELD								
High	Heritage Carbon phenolic (CMCP) & (TWCP)	Several	Venus, Jupiter	10,000-30,000	>> 1	●	■	■
	3DQP	Textron	DoD TRL 3	~ 5000	> 1	✖	◡	◡
Low-Mid	PhenCarb family	ARA	TRL 4-5	2000-4000	> 1	✖	◡	◡
	ACC	LMA/C-Cat	Genesis	> 2000	> 1	✖	◡	■
	PICA	FMI	Stardust	~ 1200	< 1	✖	●	●
	Avcoat	Textron	Apollo	~ 1000	~ 1	✖	◡	◡
	BPA	Boeing	TRL 3-4	~1000	~1	✖	◡	◡
BACKSHELL TPS								
Low-Mid	PICA	FMI	Stardust	~ 1200	< 1	●	■	■
	Avcoat	Textron	Apollo	~ 1000	~ 1	●	■	■
	PhenCarb family	ARA	TRL 5-6	2000-4000	> 1	◡	◡	◡
	BPA	Boeing	TRL 3-4	~1000	~1	◡	◡	◡
	SRAM Family	ARA	TRL 5-6	~ 300*	~ 1	◡	◡	◡
	SLA-561V	LMA	Mars	~ 300*	< 1	◡	●	●
	SIRCA†	Ames	Mars	~ 150	> 1	◡	◡	◡
	Acusil II†	ITT	DoD	100	< 1	◡	◡	◡
High	Teflon†	Several	Various	> 500	> 1	■	■	■

● Fully capable ◡ Potentially capable (qual needed) ■ Capable but heavy ✖ Not capable

*For low shear environments †RF transparent

Table 1 illustrates applicability for three Venus Probe mission scenarios: direct entry, aerocapture and entry from orbit. 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 but significantly larger heat loads. Entry from orbit results in the mildest forebody environments due to the 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.

Carbon phenolic is the only flight-qualified material capable of providing reliable performance when subjected to the severe forebody heating environment typical for direct entry to Venus. While the ability to re-manufacture heritage carbon phenolic has been acknowledged as a concern, attention must also be paid to the afterbody TPS. In general, a TPS design incorporates several materials, each selected based on the environment they will be exposed to while striving to minimize TPS mass. As an example, the heating environment over the afterbody of a blunt cone aeroshell similar to any of the Pioneer Venus probes is an order of magnitude less severe than the forebody environment. Lower density materials are available, but only 2 have been demonstrated to provide reliable performance at such conditions. Table 1 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 a number of 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 2 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.

Table 2. 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, and none of the existing facilities have a separate radiative simulation capability

Ground Test Facilities

A mainstay of TPS development for the past several decades has been the high-enthalpy arc jet facilities at ARC, JSC, 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.

Although existing arc jet facilities are not capable of simulating the high combined heat flux associated with hyperbolic direct entry to Venus, candidate TPS materials can be tested with high-energy lasers to estimate the level of heat flux required to initiate char spallation, a potential material failure mode. A high-energy carbon dioxide continuous wave (CW) laser would be best as the absorption length to 10.6μm laser radiation is extremely small for almost all materials and would eliminate the potential for in-depth deposition. 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 'flat top' characteristic of the LHMEL lasers refers to the energy distribution in the beam, which is essentially uniform or flat, subjecting the test article to a very uniform radiant heat flux. LHMEL II, with a delivered power of 100 kW, can produce a maximum heating of ~7,000 W/cm^2 on a reasonable size test article of about 43 mm in diameter. By matching the peak heat flux condition but not the peak pressure, performance of a carbon phenolic manufactured from heritage rayon may be confirmed by comparison to the known database. However, because of limitations at these facility limitations in achieving a variety of high pressure and heat flux conditions, it is currently not possible to qualify new heat shield materials for a direct entry Venus mission.

ISSUES & CHALLENGES

Materials

Fully dense carbon phenolic, developed in the 1960s, was the only material from that era with the demonstrated capability to handle heat fluxes in the range from 1-5 kW/cm^2 at pressures in the range from 1-10 atmospheres. Because neither the U.S. military nor NASA has made any significant investment in ablative TPS materials development over the past 30 years, heritage carbon phenolic remains the only material proven to be capable for these extreme environments. This version of carbon phenolic, FM5055, was used for both Pioneer Venus and Galileo missions. While other forms of the carbon phenolic family of materials are still being fabricated today using different precursors (e.g., for shuttle SRB nozzles), the performance database on these modern materials for conditions relevant to Venus missions is lacking.

Carbon phenolic composites are fabricated from carbon cloth held together with phenolic resin and processed either using autoclaves or heated hydraulic presses. The 30+-year-old heritage carbon phenolic composite uses a carbon cloth derived from high temperature processing of aerospace-grade rayon, which is no longer manufactured. This rayon requires a quality control system to produce a uniform, consistent product, which is not a requirement for other applications. Domestic companies that formerly manufactured this heritage rayon have gone out of business. Ames Research Center acquired a modest supply of 1970s vintage rayon from the limited stockpile held by the Navy's Strategic Systems Program Office, enabling NASA to fabricate only a few heritage carbon phenolic heat shields of modest size for upcoming space missions requiring a high performance heat shield.

The advantage of using heritage material lies in the extent and maturity of the database and design models. But of equal importance is the capability to process and manufacture high quality Tape Wrapped Carbon Phenolic (TWCP) and Chop Molded Carbon Phenolic (CMCP) composites. There are several vendors that routinely manufacture TWCP to the original FM5055 specifications, but CMCP has rarely been made since the Galileo program. (CMCP is necessary for an entry probe, as TWCP cannot be manufactured to cover the nosecap.) The critical processing parameters are temperature, pressure, time and the direction of heating during cure. Significant resources were devoted in the '70s to develop these specifications and they need to be followed rigorously to produce reliable composites. However, 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. **One *very* important lesson learned by the Orion TPS team was that even with a detailed specification in place, manufacturing a heritage material requires several years of intense and expensive effort due to the mothballed industrial capability and the lack of key personnel.**

Another significant gap in materials development for reentry technology is the need for mid-density ablative TPS. Whereas carbon phenolic is a high-density material, most of the other available materials are low density. There are missions where a mid-density ablative TPS would be the best choice, such as a shallow, low-g entry trajectory to Venus to protect an onboard radioisotope power system (RPS). Heating rate and/or pressures may be beyond the capabilities of low-density TPS materials but use of high-density materials would impose a significant weight penalty. There are a few ablative materials (e.g., Avcoat, PhenCarb) that represent the lower end of the medium density category, but their region of applicability is limited. Thus, there is a need for materials of higher density than Avcoat but lower density than carbon phenolic to provide weight-efficient TPS options for a range of mission scenarios.

Technical Engineering Development

Current ablative TPS designs are still using methodologies and tools based on those developed in the '60s and '70s. One of the major problems has been the impossibility of validating the models with flight data because flight instrumentation on reentry probes has been the exception. Pathfinder did have limited in-depth thermocouple data but several of the sensors failed. Galileo incorporated ablation sensors in the carbon phenolic TPS, but the severity and uncertainty in the heating environment made interpretation of those data very difficult. Consequently, to minimize risk in the light of existing uncertainties, TPS designs are necessarily conservative, i.e., heavy. Were more effort to be invested in material response modeling and aerothermal heating analysis, any TPS mass savings that resulted could be applied to additional scientific instrumentation (payload). Recent efforts in 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. These efforts have come to a natural termination due to either completion or the project phase has shifted and no more funding is deemed necessary to continue exploring alternate TPS or significant design tool improvement. These analysis efforts should be continued as they enhance material development and are relatively inexpensive compared to materials testing.

Another area where improved understanding could result in TPS mass savings is coupling of the aerothermal environment analysis with the TPS response analysis. For example, the AFOSR/NASA/SNL ablator working group, in collaboration with academia, has initiated an effort focused on developing advanced flow-materials coupling codes. However, the lack of fundamental data, albeit difficult to acquire, remains an obstacle to validating these efforts. There are many other possible improvements for analysis and modeling, such as multi-scale physics models for predicting char structure and thermal properties, better gas surface interaction models, and coupled Computational Fluid Dynamic (CFD) solvers with high-fidelity radiation solvers. All of these could aid in the further understanding of material response and eventually reduce the amount of testing required for qualification. In addition, these advances could lead to increased performance reliability to avoid the type of mis-predictions that occurred for the flank and nose recession on Galileo.

Ground Test Facilities

Arc jet facilities continue to provide the best simulation of TPS flight environment, with certain limitations. For the foreseeable future, it is impossible to simulate in a ground facility all environmental parameters (heating rate, enthalpy, pressure, shear stress) simultaneously. Also, all of the US facilities currently available operate only with air, which may be problematic for certain combinations of planetary atmospheres and TPS materials. Most importantly, the maximum heating on a reasonable size test model in an arc jet is limited to about 2.5 kW/cm^2; far short of the peak fluxes predicted for missions currently in the planning phase. Although high power lasers can achieve high heat fluxes, the other entry conditions, such as pressures near 10 atm, cannot be met simultaneously. MSL and Orion TPS development demonstrated that testing to peak heat flux/load conditions is insufficient for finding material failure modes. Test facilities must be upgraded in order to increase the range and combination of conditions of heat flux, enthalpy, pressure, and shear stress that are within the expected flight regime.

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. While there is a need to obtain material performance data with correct thermochemistry, there are very few test facilities currently operating in gases other than air. Furthermore, the non-air facilities have limitations (test sample size, heat flux, pressure) that can limit their usefulness in planetary mission applications. For example, the LaRC Hypersonic Materials Environmental Test System (HyMETS) Facility is a 400 kW facility capable of running on CO_2 for planetary atmosphere entry simulation. The current test gases are nitrogen and oxygen with argon shield gas, with plans to be operational on carbon dioxide in the near future. A new facility, the Development Arc jet Facility (DAF) will operate up to a maximum of 5 MW, with the possibility of operating on a wide variety of gases and gas mixtures. In addition, the arc heater could be configured with a 'supersonic-anode' that produces very high stream-centerline enthalpy and thus high heat flux, albeit on relatively small test articles. Also, because the DAF will operate at only a fraction of the power levels of the larger facilities, long duration exposures (four hours or longer) and repetitive sample exposures are possible. Nearly all of the components required to assemble the DAF are in place, but assembly has been delayed due to a lack of adequate financial resources. Both Ames and JSC are evaluating adding the CO_2 capability to their existing arc jets, as well as DAF, so that both workhorse test facilities together with developmental test facilities could cover the existing gap in material development and flight qualification.

Limitations of the current TPS material test facilities will dictate a 'piece-wise certification' strategy for certain planetary missions[2]. Qualification for Venus direct entry, for example, could use arc jet facilities to simulate a wide range of heat flux and pressure, but will likely require an alternate approach such as a laser facility to attain the complete range up to the maximum predicted heat flux. Large arc jet facilities such as those at ARC, JSC, AEDC, and Boeing will continue to play a primary role in development and qualification of TPS, but other testing approaches/facilities (laser, solar) may be used for extreme or unique environments**. Currently, due to test facility limitations, any new heat shield material for direct Venus entry missions (including replacements for heritage carbon phenolic) cannot be qualified.**

RECOMMENDATIONS

A limited number of science missions to Venus can be accomplished in the near term using existing materials and 1960s era design methodologies. However, replacement materials need to be developed to ensure that future Venus probes and landers have adequate TPS. New TPS materials are likely to significantly increase the science return of Venus missions with probes / landers by reducing the weight of the required TPS. Improved design analysis tools and ground test facilities will significantly reduce the risk of TPS failure while also reducing the weight of the required TPS.

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. Re-certify industry's capability to manufacture heritage carbon phenolic every few years until an alternate material can be qualified.
2. Develop an alternate to heritage carbon phenolic using currently available precursors.

3. In parallel to recommendation (2), develop new mid-to-high density TPS materials.
4. Sustain current manufacturing capabilities and expertise to ensure that at least two proven backshell materials are available for future Venus missions.

Test facilities:

1. Upgrade existing facilities (such as arc jets at ARC and JSC) to operate at very high heat fluxes (7-8 kW/cm^2).
2. Provide the capability for testing in CO_2.

Technical Engineering Development:

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 include TPS instrumentation to build a database of relevant flight data which will aid in the planning of all future Venus missions.

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 and can be deployed to support different missions, the Decadal committee should consider not only the specific recommendations made above for destinations of interest to this sub-panel, but also the needs of other Science destinations (addressed in other white papers) and the needs of other NASA stakeholders to ensure that scarce dollars provide the maximum return on investment.

Finally, it is requested that during the course of the development of recommendations by the new decadal planning team, the TPS community be given feedback on those missions that appear to be emerging as high priority, and that involve atmospheric flight. If helpful, estimates for cost and schedules could be provided upon request.

REFERENCES

1. T. Balint et. al., "Technologies for Future Venus Exploration," White paper submitted to the NRC Decadal Survey Inner Planets Sub-Panel, Sept. 2009.
2. E. Venkatapathy, et. al., "Selection and Certification of TPS: Constraints and Considerations for Venus Missions," 6th International Planetary Probe Workshop, June 2008.
3. VEXAG (Ed.) 2007. "Venus scientific goals, objectives, investigations, and priorities", Venus Exploration Analysis Group. http://www.lpi.usra.edu/vexag/
4. NASA SMD PSD, 2006. "Solar System Exploration Roadmap for NASA's Science Mission Directorate", NASA SMD PSD , Report Number: JPL–D–35618
5. Hall, J.L., et. al. , 2009. "Venus Flagship Mission Study: Report of the Venus Science and Technology Definition Team", Jet Propulsion Laboratory, California Institute of Technology, Task Order NM0710851, April 17
6. Kolawa et al., "Extreme Environment Technologies for Future Space Science Missions", Technical Report JP D–32832, Sept 19, 2007