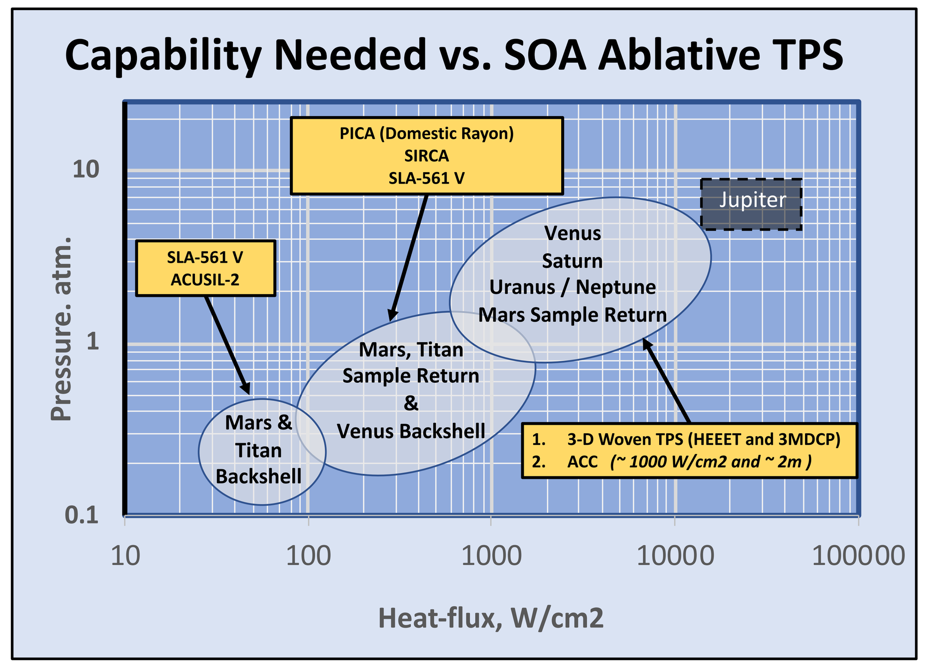
Robust and Mass Efficient Thermal Protection Systems for Future Venus Missions

E. Venkatapathy[1], M. Gasch[1], M. Stackpoole[1], S.Muppidi[1], and J. Morgan[1]

[1] NASA Ames Research Center, Moffett Field, CA 94035

Introduction

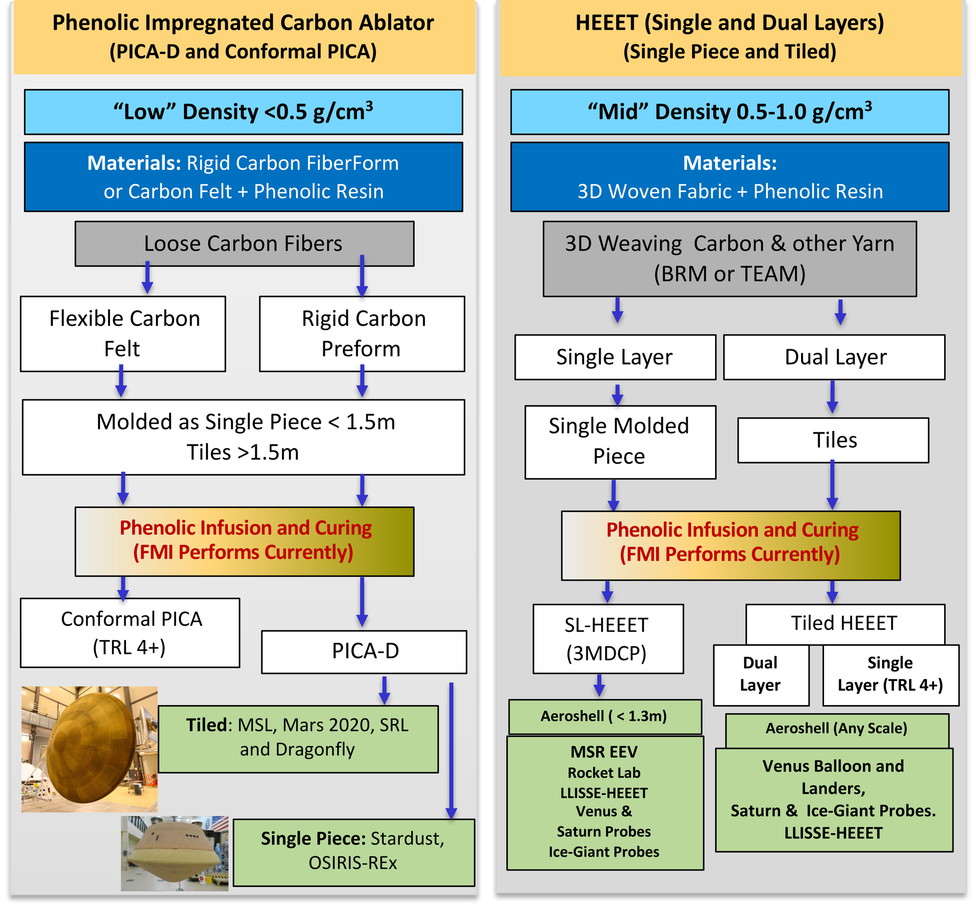
- Two cardinal requirements govern the selection and use of thermal protection systems (TPS):
  - Robustness to assure mission safety during entry
  - Mass efficiency to ensure science is maximized
- Available ablative TPS options are few but capable for many destinations.
- 3-D Woven and PICA-D are unique TPS materials, scalable in both aeroshell size and entry environment and have broad applicability. These two TPS materials are needed for future Venus *in-situ* missions.
- Current Missions and TPS needs in this decade:
  - MSR and Dragonfly have baselined 3-D Woven single-layer system and PICA-D respectively for their heatshield, and their TPS needs will be met by 2023 – 2025.
  - Rocket Lab is studying 3-D Woven TPS for a small probe mission to Venus in 2023.
  - Davinci+ baselined Advanced Carbon-Carbon (ACC), a derivative of Genesis (2001) TPS. 3-D Woven TPS could be a backup if needed. ACC is limited in demonstrated heat-flux capability and scalability.
- The longer-term need for 3-D Woven and PICA-D is unknown until the next set of missions are selected under New Frontiers and Discovery and the missions will likely not launch until early 2030.



High-TRL TPS options available today

Future Venus missions: Dual- and Single-Layer 3-D Woven TPS

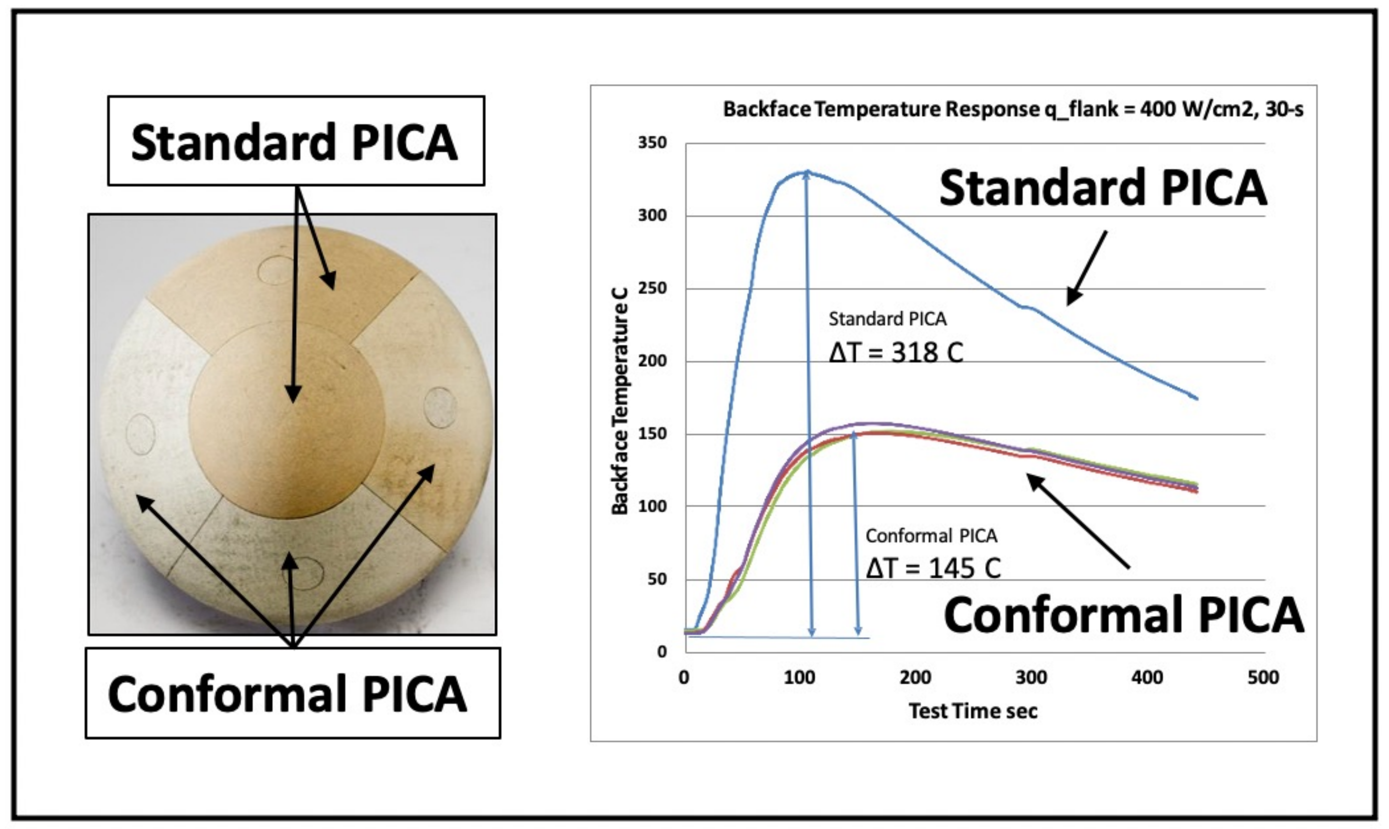
- HEEET, a TRL 6 material, was developed as a 3-D Woven dual-layer system (DL-HEEET)
  - Only viable replacement for heritage Carbon-Phenolic and a substantially more mass efficient (~ 50%) TPS than heritage Carbon-Phenolic
  - HEEET enables precision science instruments that require lower G-load limits; for the same TPS mass as Carbon Phenolic, HEEET withstands larger heat-loads as aa result of trajectory tailoring to achieve lower G-load entries.
  - *Sustainment is a core need for 3-D Woven.*
  - While DL-HEEET is mature, an even more mass efficient option of 3-D Woven is a single-layer HEEET (SL-HEEET) version.
- NASA demonstrated (TRL 5) that the insulating layer of HEEET (SL-HEEET) is very capable and can save significant mass compared to DL-HEEET owing to its lower density.
  - Baselined for Mars Sample Return Earth Entry System, the single-layer 3-D woven system, called 3DMCP, is a single piece heat-shield with no seams at 1.3m diameter.
  - For missions with larger aeroshells, (>1.3m), use of SL-HEEET as a tiled system will require seams. This is not yet demonstrated
  - Rocket Lab planned to fly a small private mission probe (1/8th volume of Pioneer-Venus small probe) to Venus in 2023 and lowering entry system mass is key to accommodating science instruments. ARC analysis indicated that the SL-HEEET system will save 30% mass compared to DL-HEEET.
  - ***Maturation, scaling, and sustainment are core needs to this system.***



Future Venus missions: PICA and Conformal PICA

- PICA has undergone rayon supply chain problems and the commercial preform, a rigid Carbon Fiberform, is no longer made by FMI. Driven by near-term missions including MSR and Dragonfly NASA's Science Mission Directorate Planetary Science Division ensured PICA manufacturing is in place for NASA missions. PICA-D (domestic) uses lyocell as a rayon replacement precursor and PICA-D is proven to be a drop-in replacement for PICA.
  - PICA is a flight-proven material, both as single-piece (Stardust, OSIRIS-REx) and tiled systems (MSL, Mars2020).
  - ***Sustainment is a core need for PICA-D.***

- Conformal PICA (C-PICA) is very similar to PICA in terms of manufacturing
  - PICA uses rigid FiberForm™ and C-PICA uses compliant carbon felt - as a result, is easier to design and integrate. C-PICA is ~ 50% more mass efficient that PICA and less expensive.
  - C-PICA is currently at TRL 5, completion of C-PICA maturation for large scale applications, will provide a mass efficient (~ 50%) and reduced cost alternate. When C-PICA is matured, PICA can serve as a backup.
  - Skimmer missions like Cupid's Arrow do not require 3-D Woven capability. Such missions can benefit from completion of the development of C-PICA.
  - ***Maturation for all scales is the core need for C-PICA.***



C-PICA, when arc jet tested side-by-side with PICA, showed is very efficient. The peak bond-line temperature of C-PICA is half that of PICA.

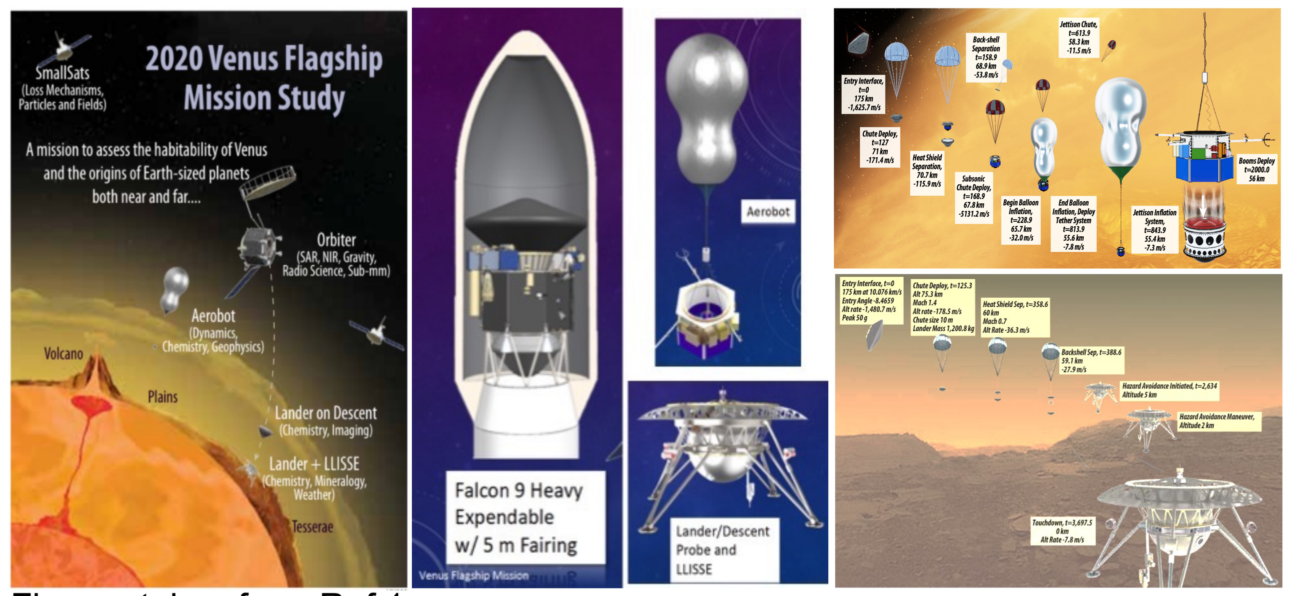
2020 Venus Flagship Mission Study - TPS Highlights

The recently completed VFM[1] study to assess the habitability of Venus baselined two aeroshells with a requirement of limiting entry g-load to < 50g in order to maximize the use of state-of-the-art instruments. A 70^0 half-angle sphere cone was chosen for the large lander aeroshell in part to minimize TPS surface area and mass, and a 45^0 half-angle cone was chosen for the aerobot due to its superior aerodynamic stability despite the TPS mass penalty.

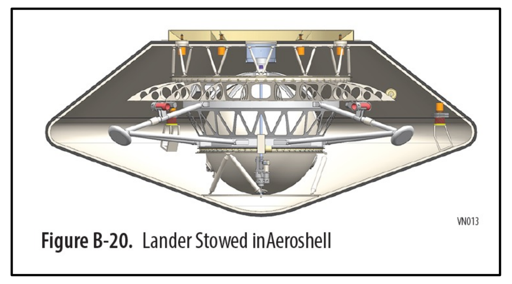
Heatshield TPS:

- Preliminary TPS trades and detailed aerothermal analysis indicated both SL-HEEET and DL-HEEET are viable TPS options.
- SL-HEEET, offering 30% mass savings, was baselined for both aeroshells.
- For heatshields larger than 1.3m diameter, a tiled heatshield with seams is necessary for both DL-HEEET and SL-HEEET. While not-yet demonstrated, extending SL-HEEET capability to larger than 1.3m diameter can be done following the DL-HEEET seam approach.
- It should be noted that ACC, currently the baseline for DAVINCI+, is a derivative of the Genesis TPS and will be heavier than SL-HEEET. Its applicability beyond ~ 1000 W/cm2 and at scales > 2 m is not yet established.

Backshell TPS: The VFM study baselined PICA-D for the backshell and did not perform trades. Based on our evaluation, C-PICA would provide an additional mass savings compared to PICA.



Figures taken from Ref 1.



Aeroshell for the Lander (Ref 1.)

4.6 m Dia., 70 deg. Half-anlge Sphere-Cone Aeroshell for Lander					
	TPS Material	Peak Heatflux W/cm2	Areal Density (kg/m2)	Area (m2)	Mass (kg)
Heatshield	Single-Layer HEEET	1734	12.15	17.7	214.6
	Dual-Layer HEEET	1734	16.5	17.7	291.2
Backshell	PICA	TBD	2.42	19.35	46.9

2.8 m Dia., 45 deg. Half-anlge Sphere-Cone Aeroshell for Aerobot					
	TPS Material	Peak Heatflux W/cm2	Areal Density (kg/m2)	Area (m2)	Mass (kg)
Heatshield	Single-Layer HEEET	4000	27.7	8.52	235.8
Backshell	PICA	TBD	2.74	7.66	21

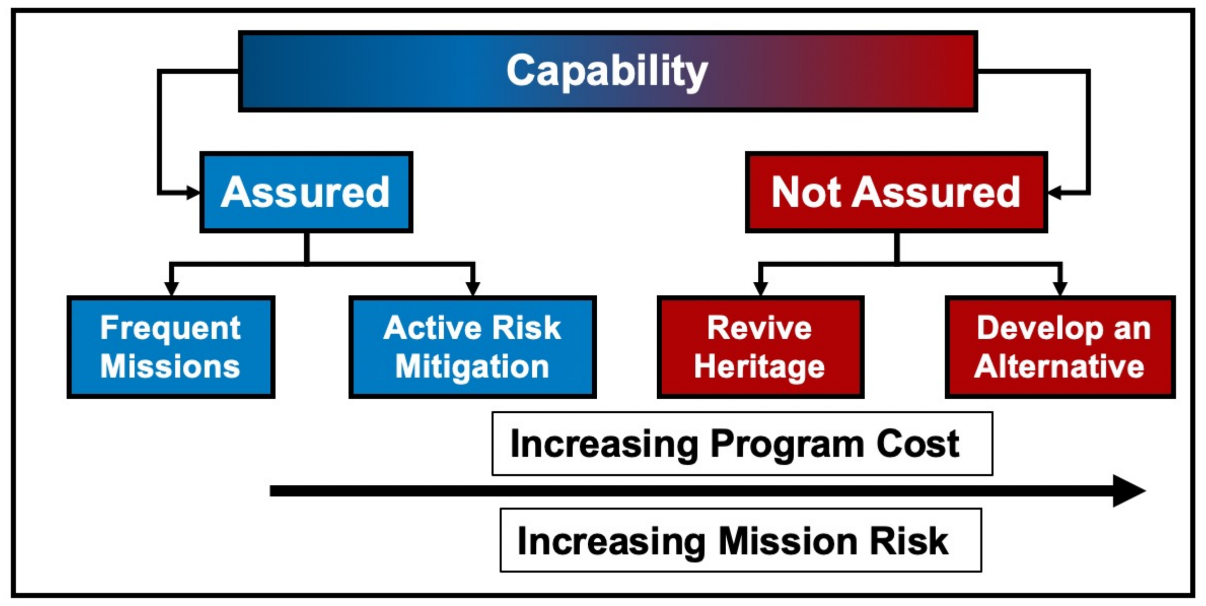
Results from TPS Sizing Studies for Lander and Aerobot

[1] Beauchamp, P., Gilmore, M. S., Lynch, R. J., Sarli, B. V., Nicoletti, A., Jones, A., & Segura, M. E., "Venus Flagship Mission Concept: A Decadal Survey Study," *2021 IEEE Aerospace Conference (50100)* (pp. 1-18), IEEE.

TPS Capability Sustainment – Why Worry?

NASA has dealt with TPS atrophy by recovering the capability or by developing new capability when needed. The process of recovery or alternate-development can easily take 5+ years and 10's of M of $'s.

- Under the competed announcement of opportunities (AO), mission proposers that need TPS, especially NASA-developed TPS, have neither the time nor resources to recover atrophied capability. The risks are high if proposers (un)knowingly propose using un-sustained TPS – it is untenable.
- Avoiding atrophy includes all areas necessary to perform missions: tools, facilities, raw material, expertise, and trained personnel available to perform the needed functions. It resides both inside and outside of NASA.
- With the lack of missions between 2025 and early 2030's, the need for NASA-developed TPS, specifically 3-D Woven and PICA, will be non-existent. The (5–7) year gap between uses is significant and the next New Frontiers and Discovery proposal teams should be aware and be concerned.
- NASA, as the steward for unique, NASA developed TPS technologies, needs to sustain the capability readiness of one-of-a-kind NASA-developed TPS capabilities for planetary missions.
- An annual risk assessment followed by targeted risk mitigation steps in the "gap-years" will assure TPS readiness for the next New Frontiers and Discovery mission proposers that are likely to launch missions in the early-to-mid 2030's



Summary and Recommendations

We seek VEXAG / Venus Science community advocacy:

1. **NASA capabilities for Venus in-situ missions need to be maintained through this decade to ensure Venus mission proposers are not unduly burdened or unable to propose due to potential for TPS atrophy.**
   - Without the capability assurance, next New Frontiers and Discovery Venus proposals will face insurmountable challenges to assure Risk Boards of the TPS technology readiness.
2. **NASA gets support to complete the technology development of SL-HEEET and C-PICA so that robust, mass and cost efficient TPS are in place for future missions. Until then, alternates (DL-HEEET and PICA) exist to enable missions.**
   - STMD invested in the development of C-PICA. C-PICA leverages PICA manufacturing and is 50% more mass efficient than PICA. Completing maturation of conformal PICA from TRL 5 to 6 is warranted as PICA has no alternate and C-PICA can also serve as a future replacement.
   - For scales larger than ~ 1m SL-HEEET TPS can save 30% mass but a seam approach needs to be matured. SL-HEEET is also at TRL 5 and timely investment will have significant benefit to future Venus in-situ missions.