

Woven Thermal Protection System (WTPS) a Novel Approach to Meet NASA's Most Demanding Reentry Missions

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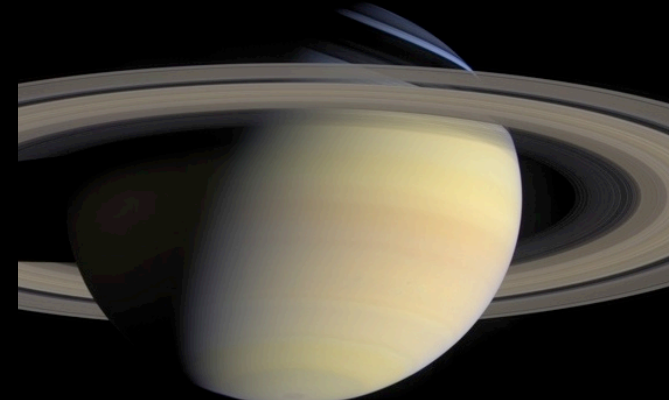
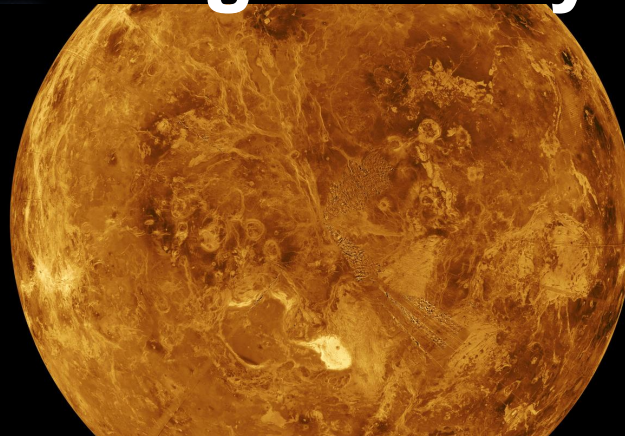
Robert Dillman and Michelle Munk
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NASA's future robotic missions utilizing an entry system into Venus and the outer planets, namely, Saturn, Uranus, Neptune, result in extremely severe entry conditions that exceed the capabilities of state of the art low to mid density ablators such as PICA or Avcoat. Therefore mission planners typically assume the use of a fully dense carbon phenolic heat shield similar to what was flown on Pioneer Venus and Galileo. Carbon phenolic (CP) is a robust TPS material however its high density and relatively high thermal conductivity constrain mission planners to steep entries, with high heat fluxes and pressures and short entry durations, in order for CP to be feasible from a mass perspective. The high entry conditions pose challenges for certification in existing ground based test facilities and the longer-term sustainability of CP will continue to pose challenges.

In 2012 the Game Changing Development Program (GCDP) in NASA's Space Technology Mission Directorate funded NASA ARC to investigate the feasibility of a Woven Thermal Protection System (WTPS) to meet the needs of NASA's most challenging entry missions. This project was highly successful demonstrating that a Woven TPS solution compares favorably to CP in performance in simulated reentry environments and provides the opportunity to manufacture graded materials that should result in overall reduced mass solutions and enable a much broader set of missions than does CP. Building off the success of the WTPS project GCDP has funded a follow on project to further mature and scale up the WTPS concept for insertion into future NASA robotic missions. The matured WTPS will address the CP concerns associated with ground based test limitations and sustainability. This presentation will briefly discuss results from the WTPS Project and the plans for WTPS maturation into a heat-shield for extreme entry environment.



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Introduction and Outline



Woven TPS :

- Woven TPS is an emerging technology in development.
- Woven TPS will result in a robust and certifiable TPS, leading to lower TPS risk, mission cost and higher payload mass fraction.
- Woven TPS technology maturation to TRL 5/6 by 2016 is our target.

Outline of the talk:

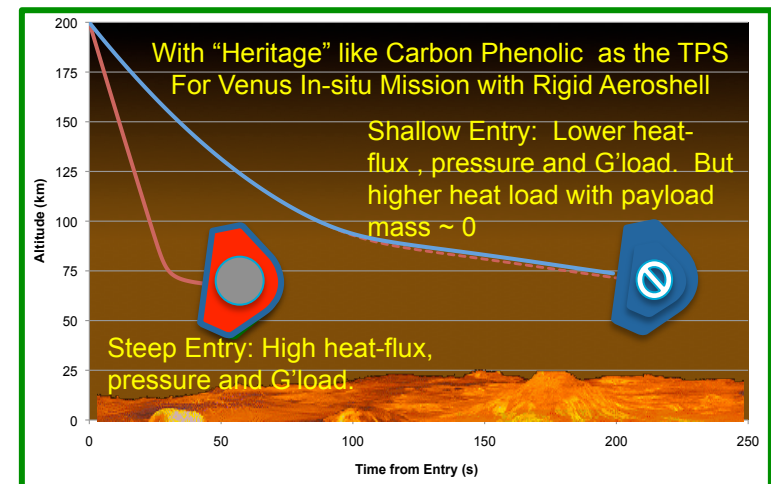
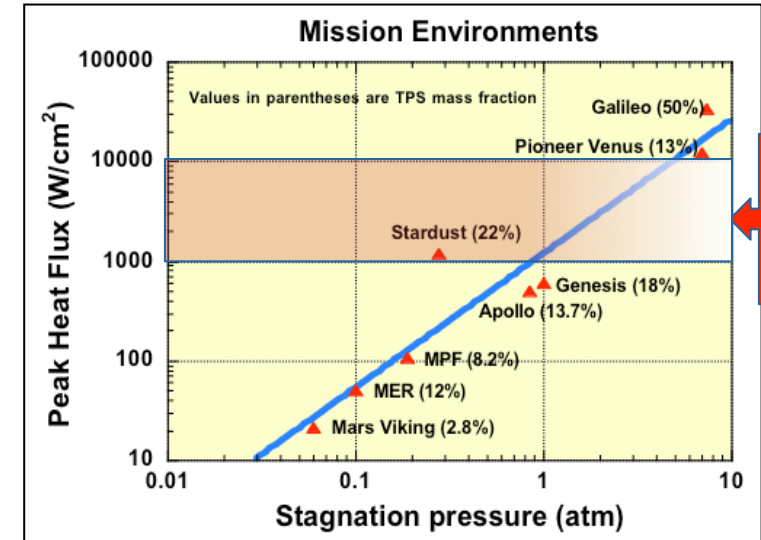
- Ablative TPS past and present
- Venus and Saturn: Extreme entry environment and ground test facility challenges for TPS development.
- Woven TPS project and progress to-date
- Concluding Remarks



SOA: Rigid Aeroshell with Carbon Phenolic Heatshield



- **Mission concepts currently baseline “heritage like” Carbon Phenolic (CP)**
 - CP is very capable and robust
 - CP enabled P-V & Galileo & is flight proven
- **Carbon Phenolic is mission constraining**
 - Mission design with CP and acceptable payload mass leads to:
 - Steeper trajectories result in,
 - Extreme heat-flux and pressure (Testing capability ?)
 - Extreme g’loads
- **Science and Mission Design seek to :**
 - Maximize science payload
 - Minimize mission risk
 - in certification of components and sub-system such as instruments or heat shield
 - Minimize development cost for the technology as well as missions cost that utilize the technology
- **Technology Sustainability:**
 - Alternate rayon based CP carries some technology development risk due to atrophy within the processing and manufacturing capabilities in the U.S.





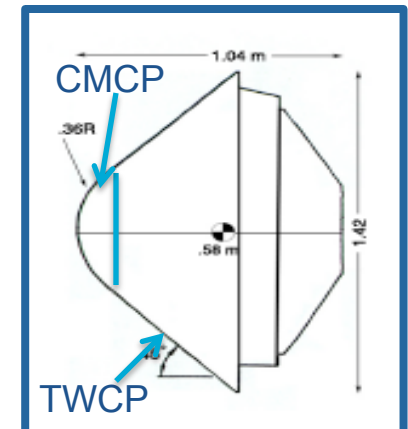
Quick Primer on Carbon Phenolic (CP)



- **Carbon Phenolic (CP) heat-shield is made of two types**
 - Chop Molded and Tape Wrapped CP
 - CP comes in different grades such as reentry grade and nozzle grade, etc - not yet validated that all of them will meet the extreme entry environments
- **Tape wrap technology is needed for applications such as**
 - Rocket nozzles and DoD's slender entry body missiles
- **Chop Molded CP needed only for NASA entry missions**
 - Blunt nose region where tape wrap cannot be used
 - Not been manufactured for reentry in over 4 decades
- **Both CMCP and TWCP use Rayon precursors**
- **NASA held two CP workshops (2010, 2012) to assess the SOA**
 - Heritage rayon based CP no longer viable for Venus (or Saturn)
 - Longer term sustainability of any CP is a ?
 - The industry is shrinking; especially for CMCP.



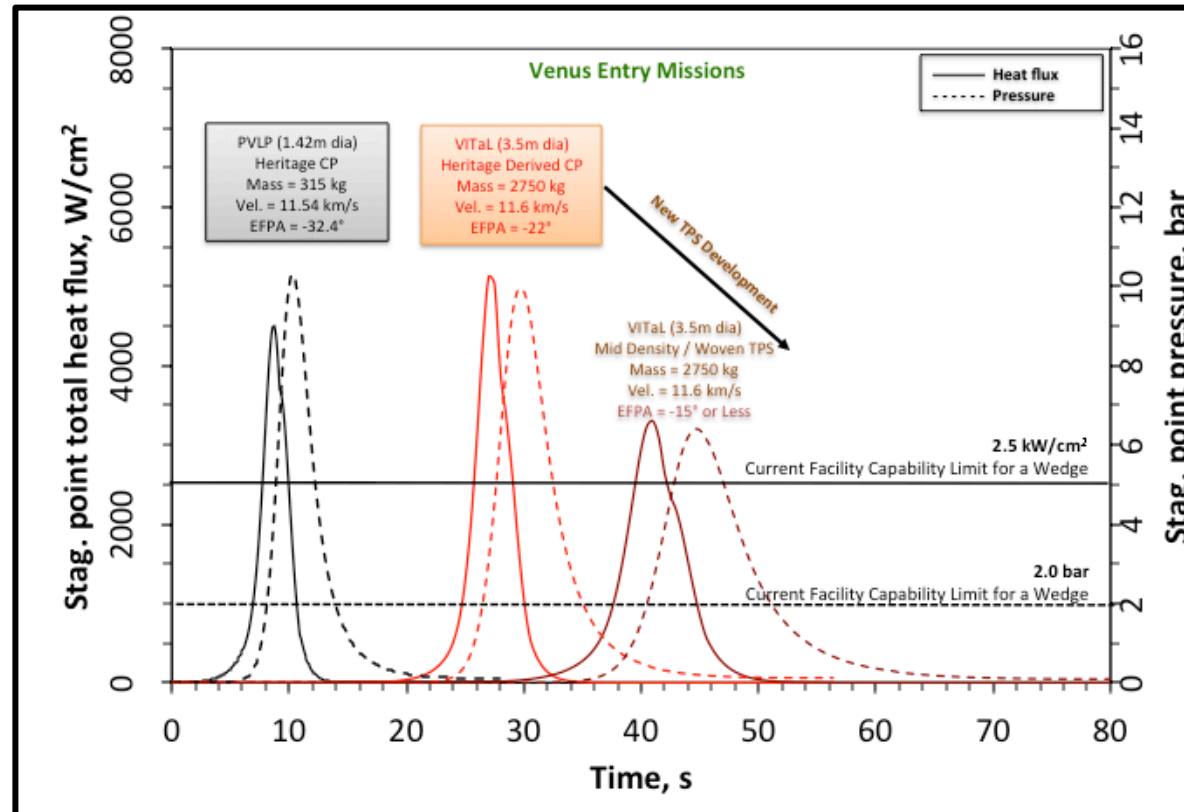
P-V Enabled by CP



**NASA is addressing this challenge through Innovative TPS development
Funded by Game Changing Development Program of STMD and SMD**



Entry Environment for Venus, Current Test Facility Capabilities (limitations) and TPS Development



CP is more mass efficient at steeper entry flight path angle (EFPA) trajectories

- Steeper EFPA results in more severe entry conditions (higher heat flux and pressure) results in certification challenges due to facility limitations
- CP mass fraction increases with shallower EFPA → Decreased payload

Proposal/Mission risk as a result of facility limitation can be reduced with mass efficient TPS allowing:

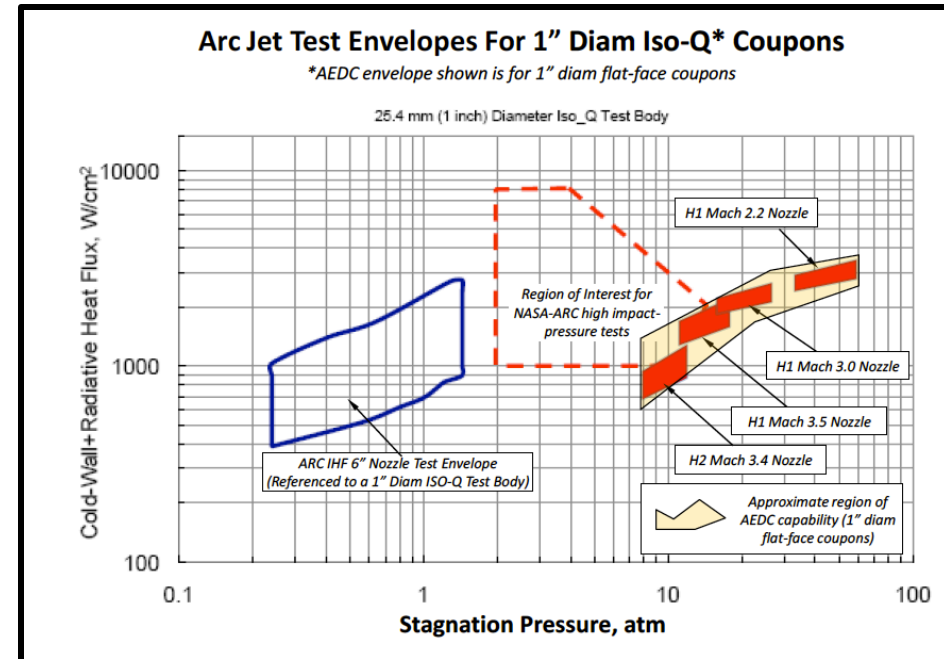
- Lower EFPA resulting in environment that fit within or close to ground testable entry conditions



Material Development Challenges: Arc Jet Facilities Capability Limitations



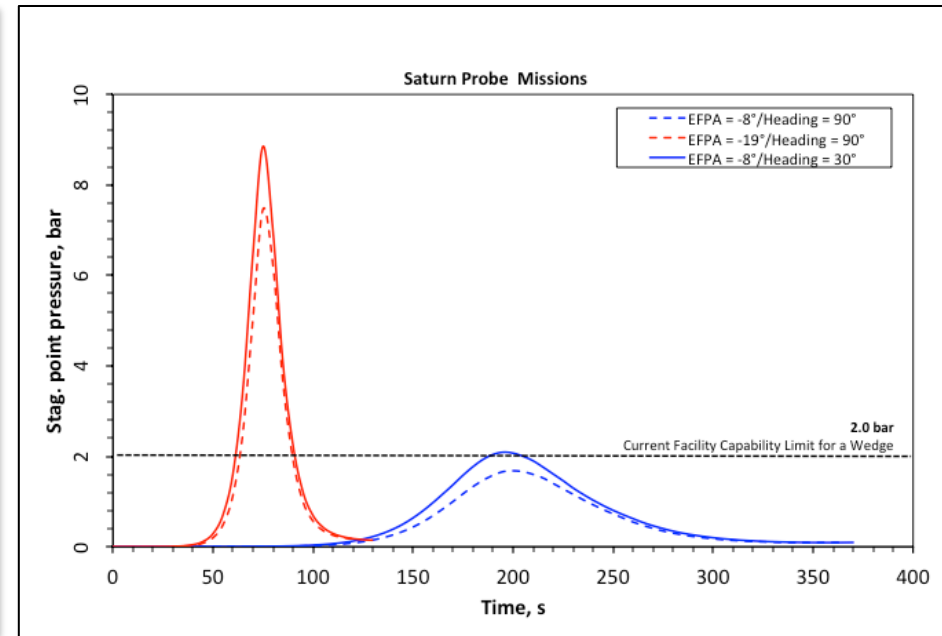
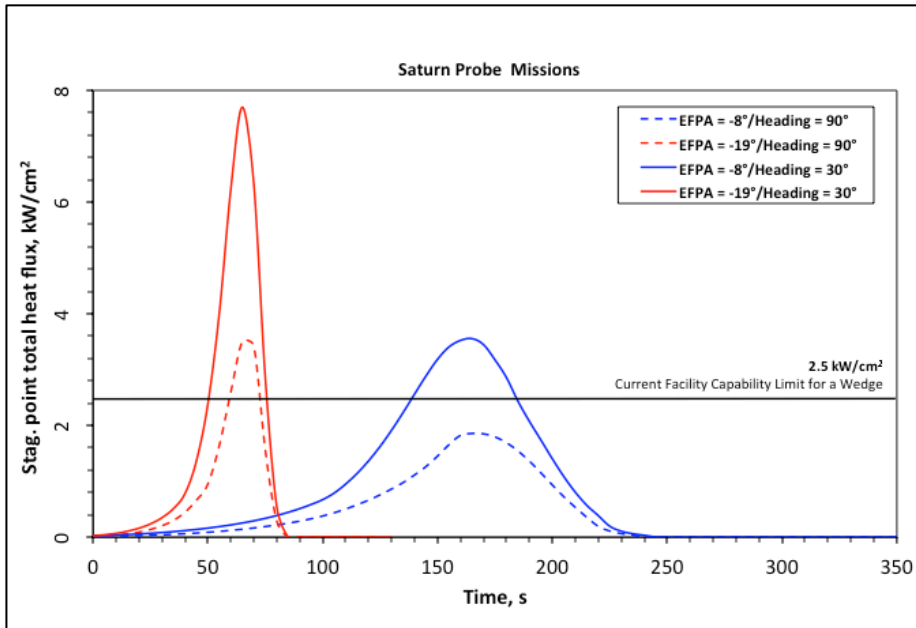
- Capabilities used during Galileo and P-V development no longer exist.
- Test conditions achievable in existing capabilities result in either under or over testing
- NASA ARC funded by SMD
 - 3” nozzle to somewhat mitigate this situation
- Model size is dictated by facility nozzle size and desired conditions:
 - Challenges arise as test article size becomes small relative to unit cell size, e.g. CMCP
- Alternate CP or alternate TPS development testing and eventual certification is not simple given the current ground test facility capabilities and entry mission conditions



Acknowledgement: Mark Smith, AEDC



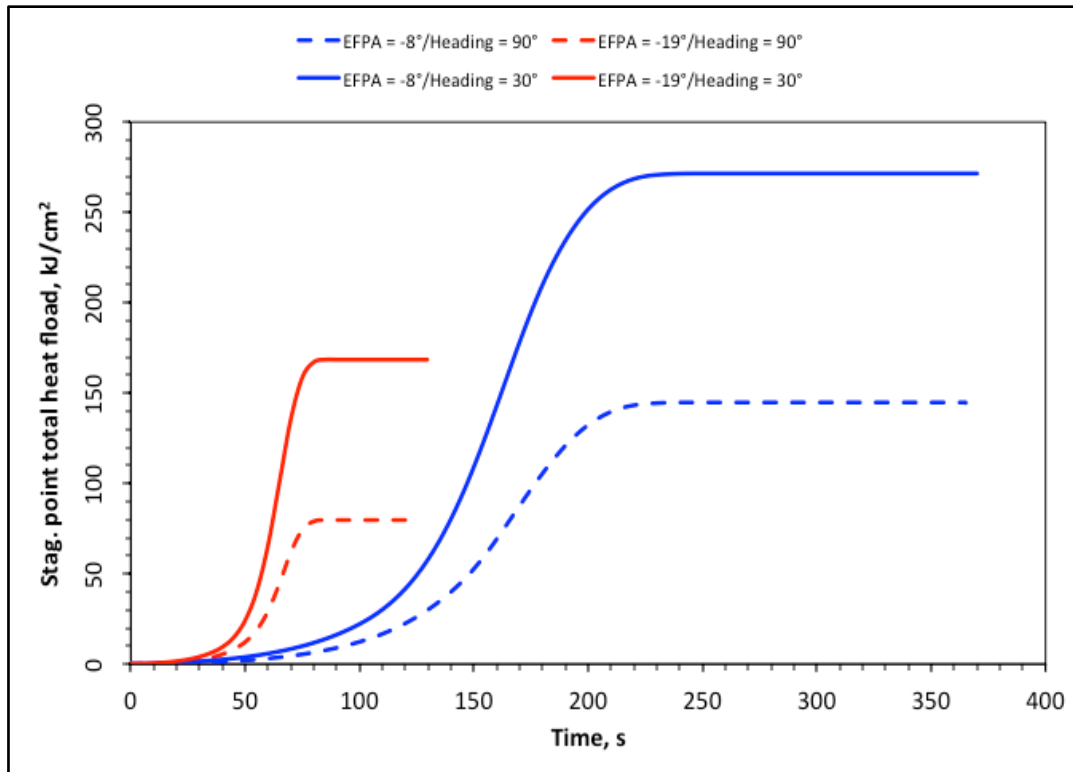
Saturn Probe Missions



- Saturn Probe missions entry environment is similar to Venus
- Saturn and Venus mission proposals can be supported by a near term, focused ablative TPS development
- Woven TPS is such as development
 - A single technology maturation effort to enable the PSDS recommended in-situ science missions with atmospheric entry



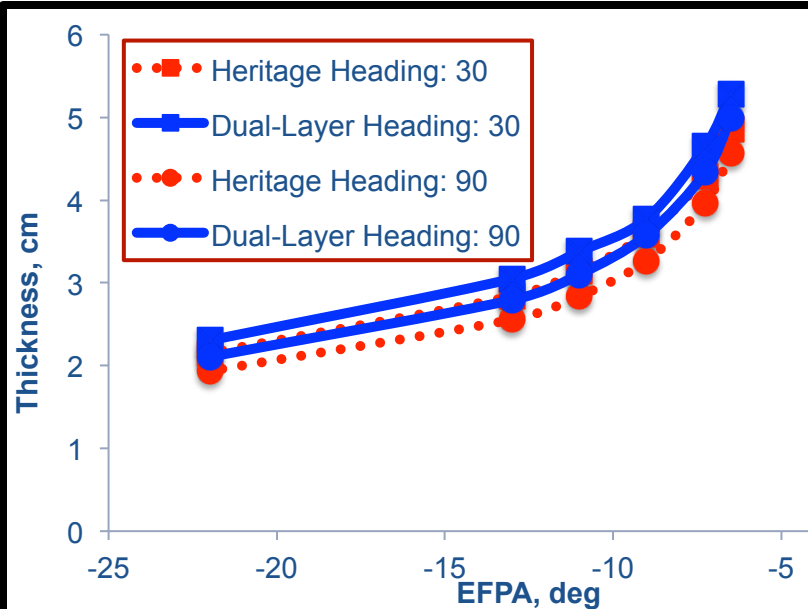
Entry Environment : Saturn Probe



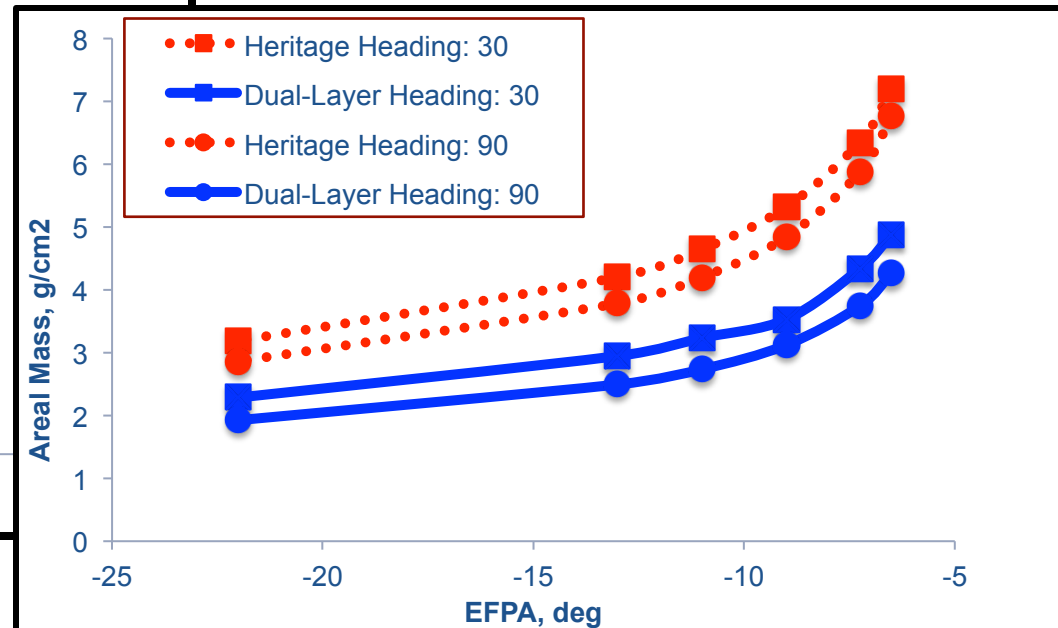
- Steeper entry, at any latitude, results in relatively lower heat-load, due to shorter time of flight but higher heat-flux, pressure and G'load.
 - Shallower entry is preferable from TPS certification (lower mission risk) but TPS mass fraction will be higher
-
- New TPS development needs to target capabilities that are both robust across a wide range of environments (heat-flux, pressure, shear) and mass efficient for large heat-load
 - Needs to be tailorable



Impact of WTPS on Saturn Probe Mission Design



Dual-Layer = WTPS
Heritage = CP



- Heatshield mass using CP is ~40% of Entry Mass for a EFPA of -20 deg at 60 deg heading angle

- **Minimal OML impact:** Zero-margin thickness estimate for carbon phenolic and WTPS is nearly identical for a wide range of entry conditions
- **Significant Mission Flexibility:** TPS mass savings of { 30% - 40%} over a wide range of entry conditions provide a significant mission architecture flexibility; Mission design, with WTPS, can trade risk of certification, mass or lower entry load



What is Woven TPS?

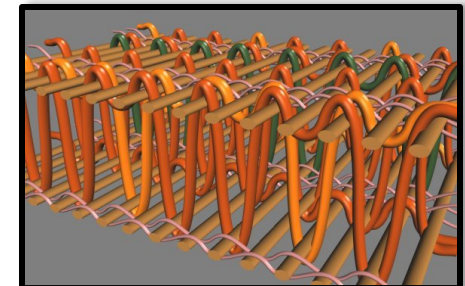
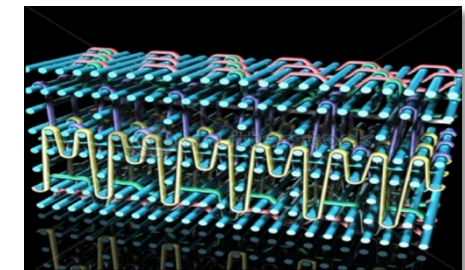
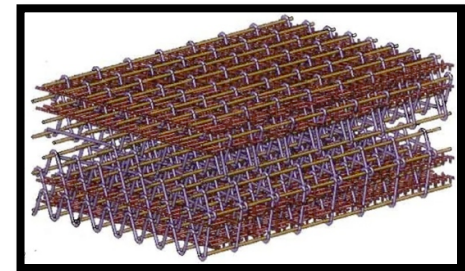


An approach to the design and manufacturing of ablative TPS by the combination of weaving precise placement of fibers in an optimized 3D woven manner and then resin transfer molding when needed

- Ability to design TPS for a specific mission
- Tailor material composition by weaving together different types of fibers and by exact placement using computer controlled, automated, 3-D weaving technology
- One-step process for making a mid density dry woven TPS
- Ability to infiltrate woven preforms with polymeric resins for highest density TPS to meet more demanding thermal requirements

Woven TPS Project Goals:

- Develop and prove feasibility of woven TPS manufacturing technique
- Demonstrate via testing low, mid and high-density WTPS in order to fill the mid-density gap as well as finding a superior replacement for the heritage carbon phenolic





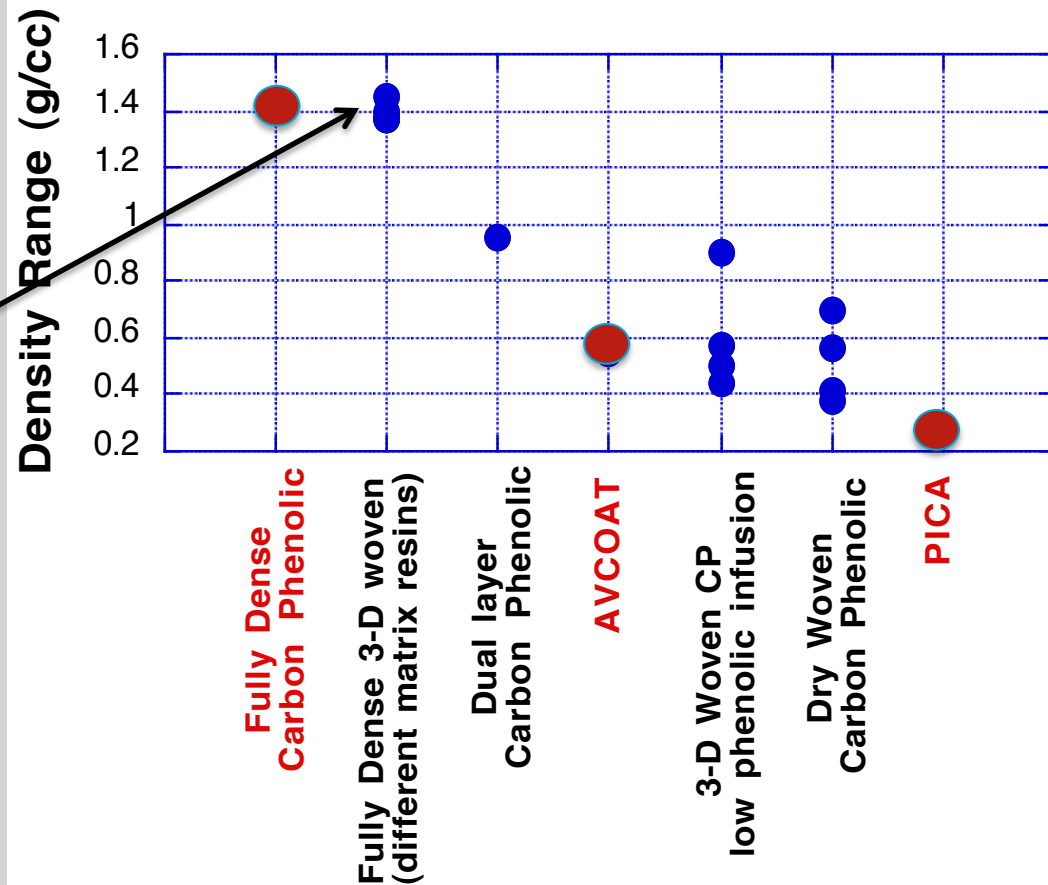
WTPS Accomplishments



- Demonstrated the feasibility of manufacturing low, mid and high-density WTPS in order to fill the mid-density gap as well as a potential replacement for the highest density carbon phenolic

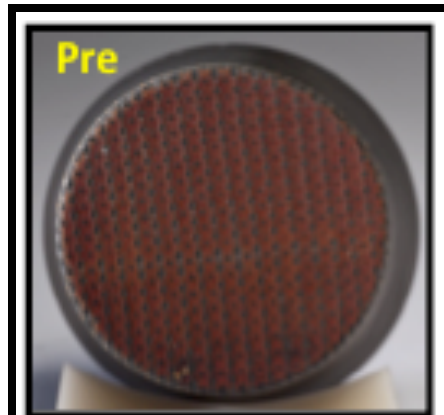


Fully Dense 3-D Woven
(different resins)

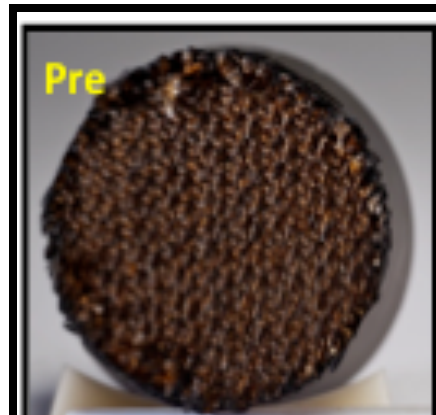




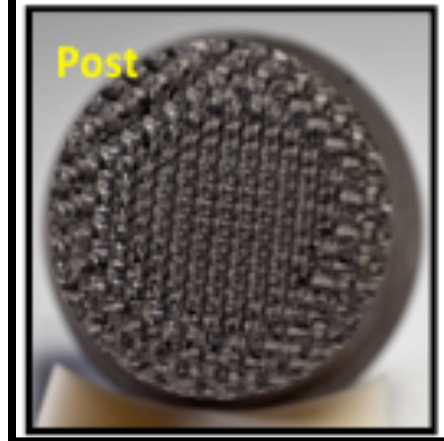
Successfully Arc Jet Tested Woven TPS in IHF and AEDC Arc Jet Facilities



Fully Dense
3-D WTPS



Mid Density
Dry Woven CP Blend



IHF stagnation testing evaluated:

- 17 different Woven TPS, low-to-High density variants
- chop molded and tape wrapped carbon phenolic tested

Testing to date indicates high density 3-D WTPS materials have comparable performance in terms of recession as CP

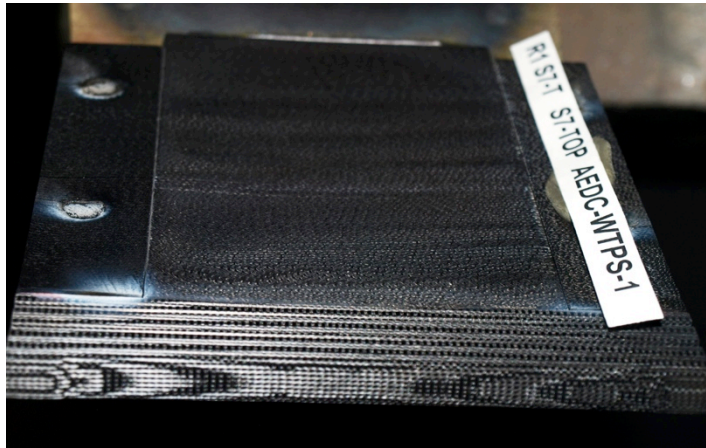


Highlights from AEDC Testing: High Heat Flux, Shear and Pressure Conditions



Traditional Carbon Phenolic

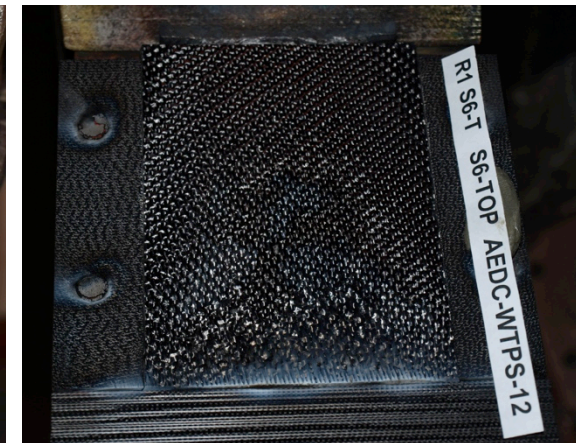
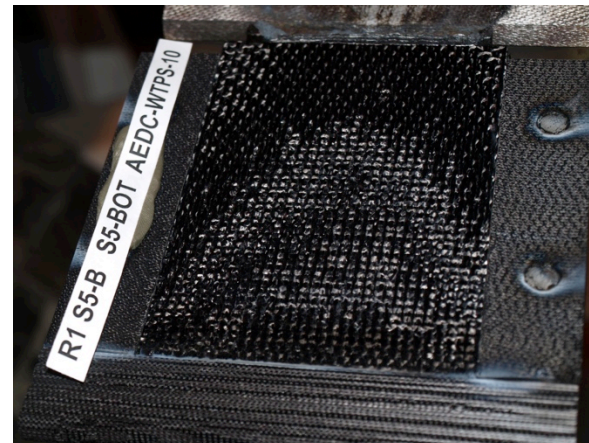
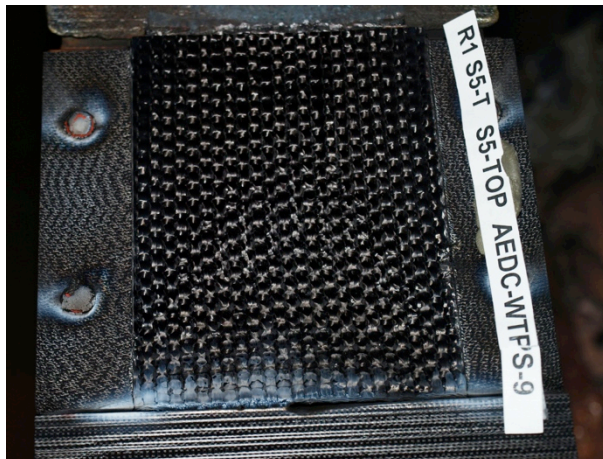
Shingled or
(Tape Wrapped)



Chop Molded



3-D Woven TPS



12 different Woven TPS, Mid-to-High density variants, along with chop molded and tape wrapped carbon phenolic were tested



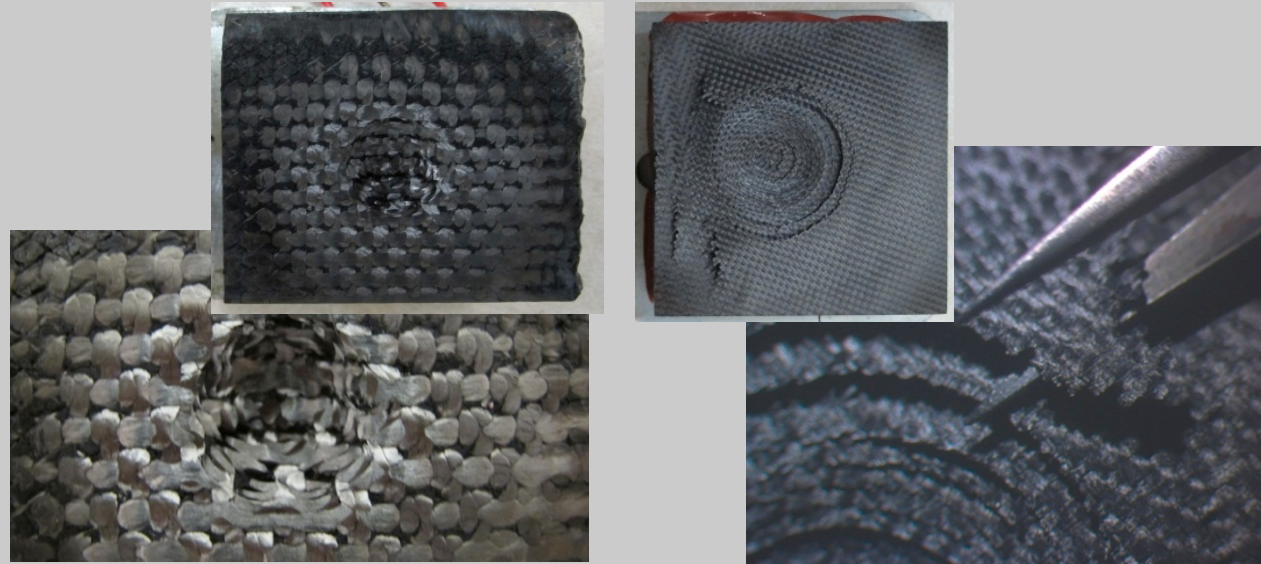
Explored Failure Modes: Woven TPS vs 2-D Carbon Phenolic



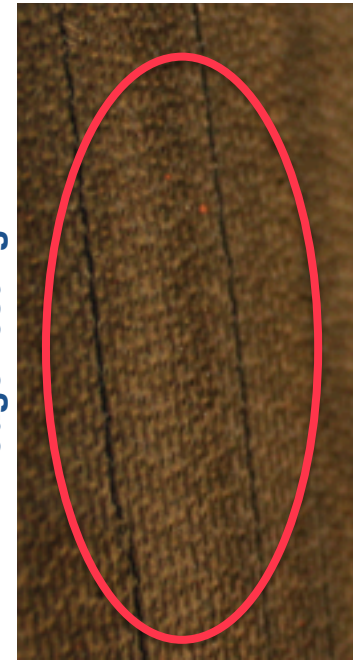
3D Woven TPS

2D Shingled Carbon Phenolic

ARC Testing in mARC



AEDC Wedge Testing



- 2-D Shingled CP exhibits typical failure mode (ply separation) in a simple demonstration test performed at Ames. Similar behavior observed in the AEDC wedge testing - Woven TPS were well behaved
- The effected area is larger in 2-D CP as compared to 3- Woven TPS
- Woven TPS, is not prone such failure mode, as it is robust by design due to 3-D nature of woven preforms.



Summary



- **Successfully met our goal of manufacturing and demonstrating feasibility of Woven TPS for extreme entry environment missions**
 - Able to manufacture low, mid and high density materials using weaving and resin infusion technology
- **Compared to the two types of CP (CMCP and TWCP), a single Woven TPS material/architecture is robust and can meet the mission needs of Venus, Saturn, etc.**
- **Woven TPS family of materials demonstrate**
 - Robustness
 - Amenable to tailoring the properties to meet mission needs
 - Rapid development with a sustainable, US based industrial base achievable.
- **STMD has recently awarded a 3 year WTPS development effort called Heat Shield for Extreme Entry Environment (HEEET)**
 - Objective is to mature HEEET to TRL5/6 by 2016 in order to support proposers to the next NF AO
 - Successful mission infusion requires HEEET project to engage with mission proposing organizations and integrators on a regular basis
 - WTPS Industry Day to be held at ARC in late July



Acknowledgements



- **Our sincere appreciation to:**
 - Grant Rossman (Georgia Institute of Technology), Hank Moody (Consultant), Mark Smith (AEDC), Mike Fowler (NASA JSC), Anthony Calomino (NASA LaRC) and Steven Del Papa (NASA JSC)
 - ARC, JSC and AEDC arc jet crews
 - Our Vendors, especially Bally Ribbon Mills
- **GCDP/STMD and SMD program executives, for their commitment and support, that led to the rapid maturity of the Woven TPS.**