Woven TPS – Enabling Missions Beyond Heritage Carbon Phenolic

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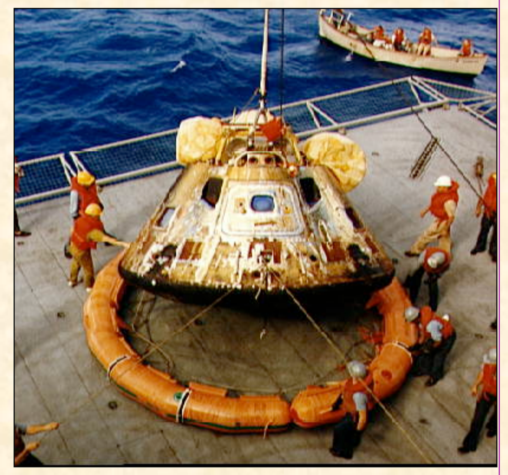
Background – Thermal Protection Systems

- The thermal protection system (TPS) is a barrier that protects the space vehicle from heating during high speed atmospheric entry
- Heritage TPS that protected astronauts from entry heating when returning from the moon (Apollo) & from space station (Shuttle) may not be adequate for missions returning from asteroids or Mars due to higher reentry speeds
- NASA has limited options for TPS to Venus and the Outer Planets
  - *2013 NRC Decadal Survey recommended:*
    - *probes to Venus, Saturn and Uranus*
    - *high speed sample return missions*
- Current TPS materials do not lend themselves to optimization for a particular mission thereby resulting in higher masses or increased risk
- Lack of NASA applications drives costs of maintaining capabilities or incurring high risks of material restart



Potential Capabilities of Current Foreboby Ablative TPS Materials

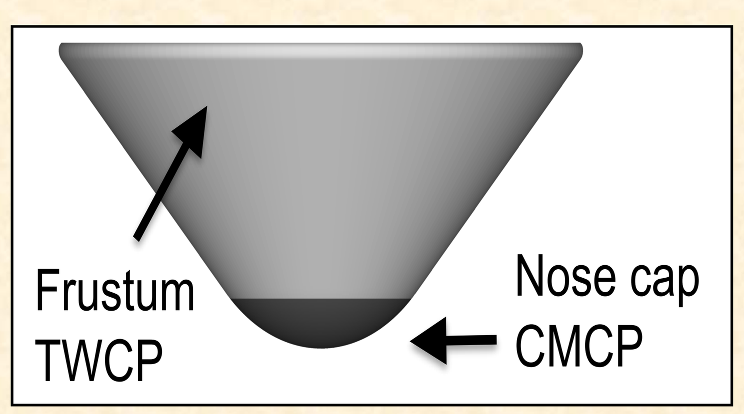
Density	TPS Material	Supplier	Flight Qual or TRL	Potential Limit: Heat flux, W/cm²	Potential Limit: Pressure, atm	Entry velocity, km/s: < 13	Entry velocity, km/s: > 13	Other Potential Missions
FOREBODY HEAT SHIELD								
Low-Mid	PICA	FMI	Stardust	~ 1200	< 1	Fully capable	Potentially capable, qual needed	SR, CEV, Mars
Low-Mid	Avcoat	Textron	Apollo	~ 1000	~ 1	Fully capable	Not capable	Venus (aerocapture)
Low-Mid	ACC	LMA/C-Cat	Genesis	> 2000*	> 1	Potentially capable, qual needed	Potentially capable, qual needed	SR, CEV, Mars
Low-Mid	BPA	Boeing	TRL 3-4	~ 1000*	~ 1	Potentially capable, qual needed	Not capable	Venus (aerocapture)
Low-Mid	PhenCarb family	ARA	TRL 5-6	~ 2,000-4000*	> 1	Potentially capable, qual needed	Potentially capable, qual needed	MSR, CEV, Venus, Earth
High	3DQP	Textron	DOD (TRL 4)	~ 5000	> 1	Capable but heavy	Capable but heavy	SR, Venus
High	Heritage Carbon Phenolic	Several capable, none active	Venus, Jupiter	10,000-30,000	>> 1	Capable but heavy	Capable but heavy	MSR, Venus, Jupiter, Saturn, Neptune

● Fully capable ● Potentially capable, qual needed ● Capable but heavy ● Not capable

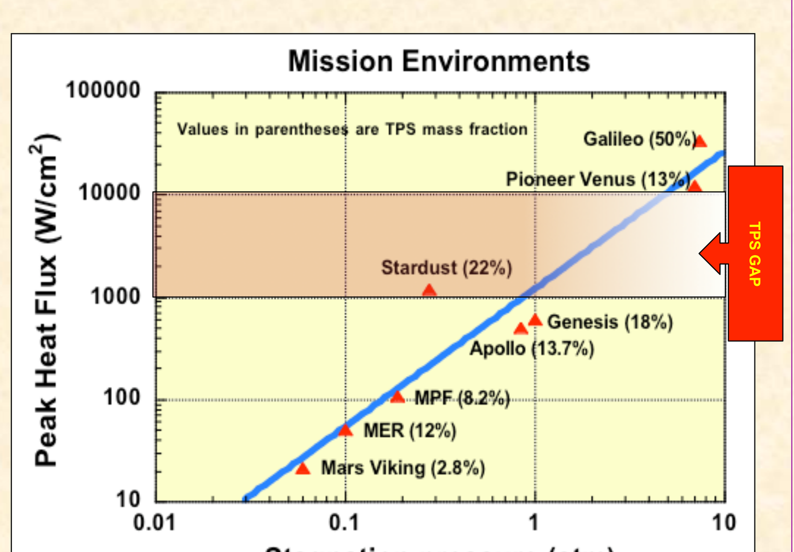
* Never Demonstrated

Heritage Like 2-D Carbon Phenolic (CP)

- Pioneer Venus & Galileo Jupiter probes used 2-D CP
  - Very robust TPS
  - Made with tape-wrapped & chop-molded CP
- Challenges with 2-D heritage like CP
  - Availability of constituents (Avtex)
  - New CP material needs recertification
  - Chop-molded CP has not be used for TPS since 1980s
  - CP is a poor insulator - drives steep-angle entry resulting in high heat flux and G-loads
    - High G-loads problematic for science instruments (sensitivity & certification)
    - High heat fluxes are beyond existing ground test facility capability
- Many missions would benefit from a tailorable mid-density TPS
  - Greater efficiency means lower TPS mass fraction (more science!)
  - Enable lower entry angles & lower G-loads



Typical probe geometry highlighting locations of chop molded and tape wrapped heritage like carbon phenolic



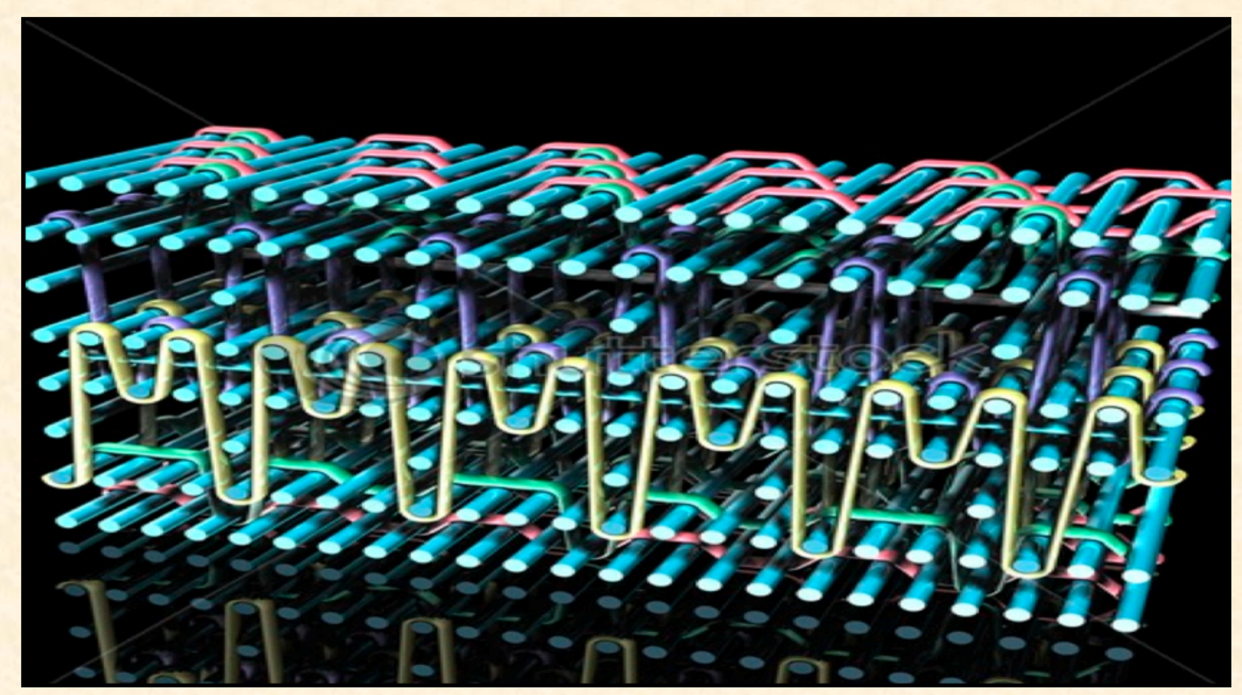
Capability gap identified in currently available TPS materials – potential to develop and insert Woven TPS into these opportunities

Planet Mission Studies	Peak Heat Flux Range (W/cm²)	Pressure Range (atm)	Heat Load Range (kJ/cm²)
Venus[1]	1000 - 2400	4 - 9	11 - 12
Saturn[2]	1900 - 7700	2 - 9	80 - 272

1. Prabhu, D.K., et. al.; IEEE Aerospace Conference, Big Sky, MT, March 2-9, 2013
2. Gary A. Allen, G. A. and Prabhu, D. K.; private communication

Woven TPS – The Concept

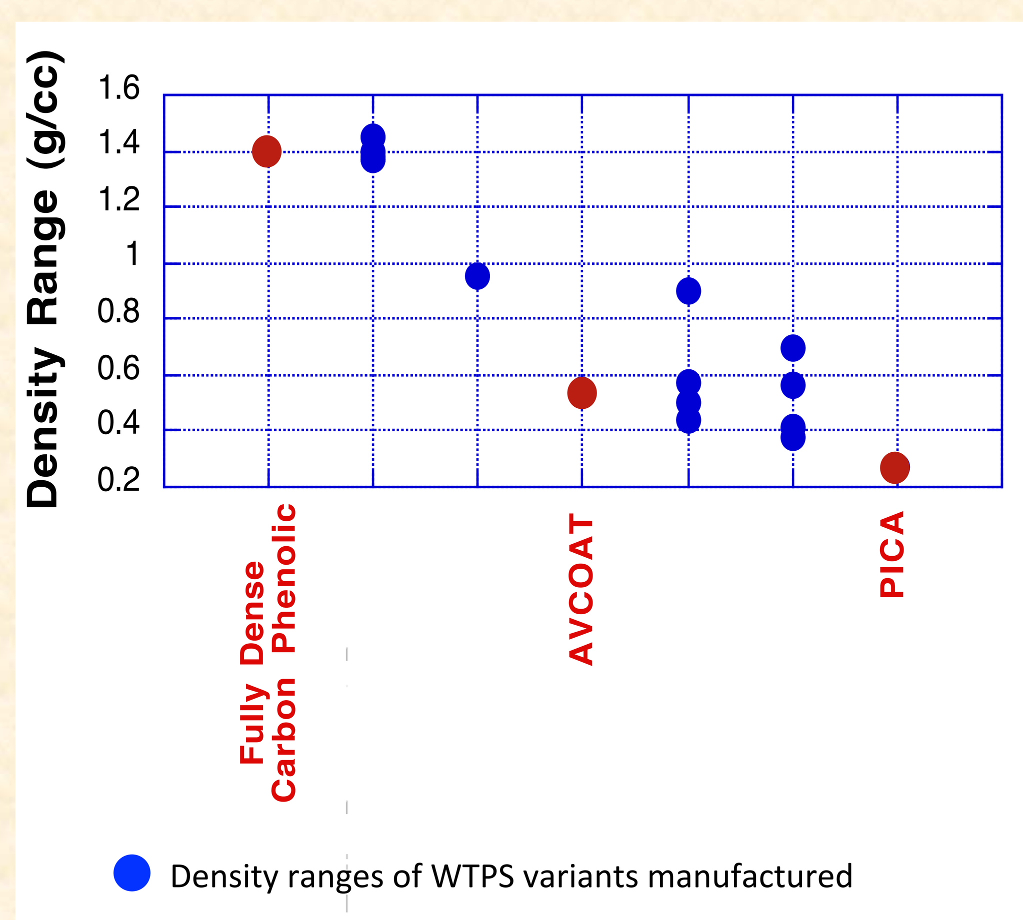
- Woven TPS leverages the mature weaving technology that has evolved from the textile industry to design TPS with tailorable performance by varying the material composition and properties while controlling placement of fibers within a woven structure
- The resulting woven TPS can be ***designed and tailored*** to perform optimally for a wide range of entry environments without substantially changing the manufacturing and certification process
- The woven TPS approach utilizes commercially available weavers, using equipment, modeling and design tools to optimize the weave. This allows for the control of material composition and density resulting in tailored performance - by leveraging this technology NASA will not be burdened with maintaining the capability or having to accept the risk for material restart
- Woven TPS approach allows design and manufacture of ***ablative*** TPS materials by specific placement of fibers in a 3D woven structure
- Weaving flexibility allows :
  - Ability to design TPS to meet specific mission needs
  - Tailoring composition by weaving together different fiber types (carbon, glass, other)
  - Tailoring density

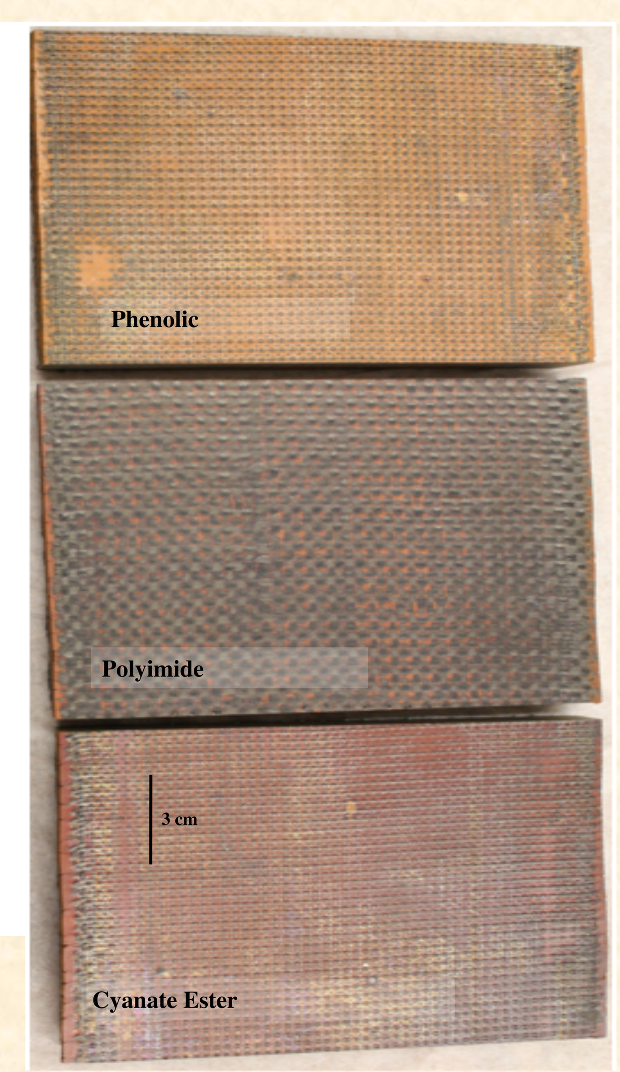


Schematic of complex 3D weave illustrating TPS design possibilities

Woven TPS – Tailorable Manufacturing

- Many varieties of woven TPS materials produced spanning a density range of 0.38 – 1.5 g/cm^3





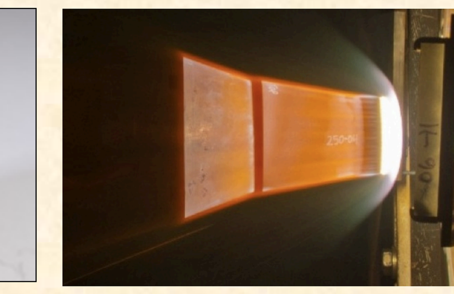
Examples of fully dense preforms with various resins

Arc Jet Testing (IHF at NASA Ames)

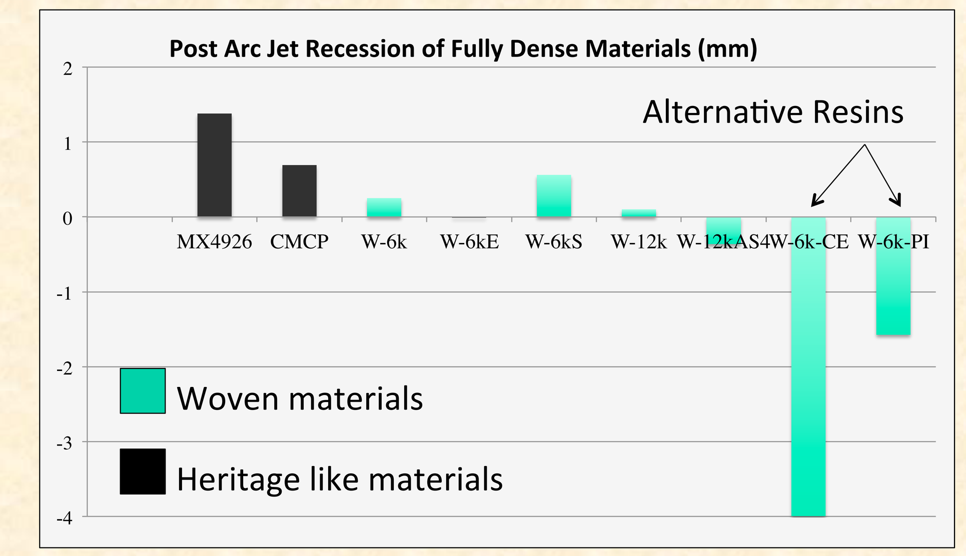
Testing Conditions:

- Cold Wall Heat Rate: ~1700 W/cm^2
- Stagnation pressure ~ 1.3 atm
- 2" dia. flat face model geometry

Pre test assembled model



Model during test



Recession Comparison - 3D Woven Variants

- Lower recession compared to 2-D heritage like carbon phenolic materials

Alternative Resin Systems Evaluated

- Cyanate Ester & Polyimide materials had net expansion likely due to insufficient post-cure
- Subsequent testing (at a lower heat flux) of post-cured samples showed comparable ablation to phenolic

Arc Jet Testing (AEDC)

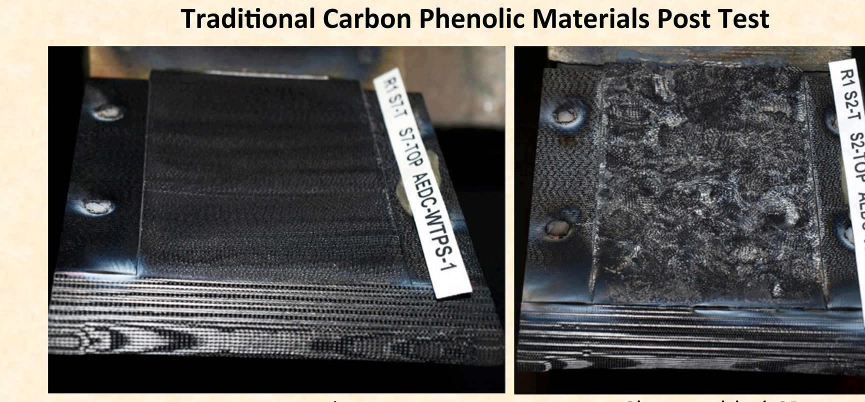
Testing Conditions:

- Cold Wall Heat Rate: ~1500 W/cm^2
- Stagnation pressure ~ 2.6 atm
- 15° wedge configuration in H3 facility
- 12 materials evaluated

Failure Modes: Woven TPS vs 2-D Carbon Phenolic

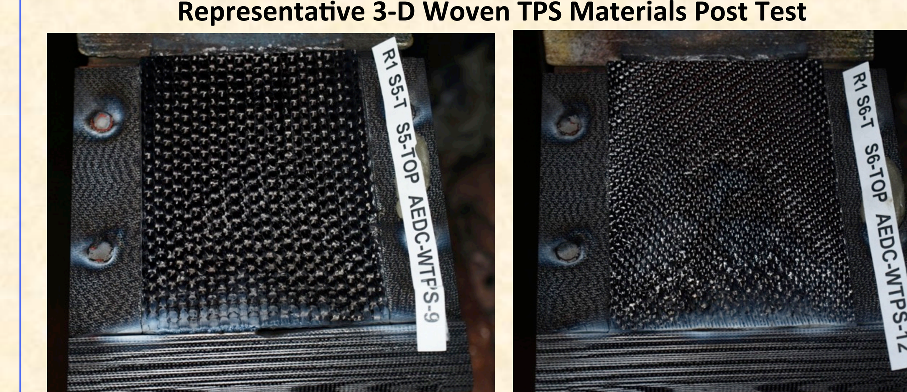
- 2-D exhibits ply separation in the AEDC wedge testing
- As a 3-D material, Woven TPS is not prone to this failure mode

Traditional Carbon Phenolic Materials Post Test



Tape wrapped CP — Chop molded CP

Representative 3-D Woven TPS Materials Post Test



Summary

- Woven TPS is a game-changing approach to designing, manufacturing, and integrating flight-certified TPS by tailoring the material for a specific mission while leveraging the mature US weaving industry
- Initial arc jet testing of wovens and comparisons to heritage like carbon phenolic materials are very encouraging
- Woven TPS did not reveal any unexpected failure modes akin to delamination observed in 2-D materials

Acknowledgement

- This work is funded by NASA's Office of the Chief Technologist Game Changing Development Program.
- Authors also acknowledge arc jet testing assistance from AEDC and NASA Ames arc jet testing crews, Mike Olson and Jerry Ridge.