3D Woven Thermal Protection Systems

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Weaving Partner:

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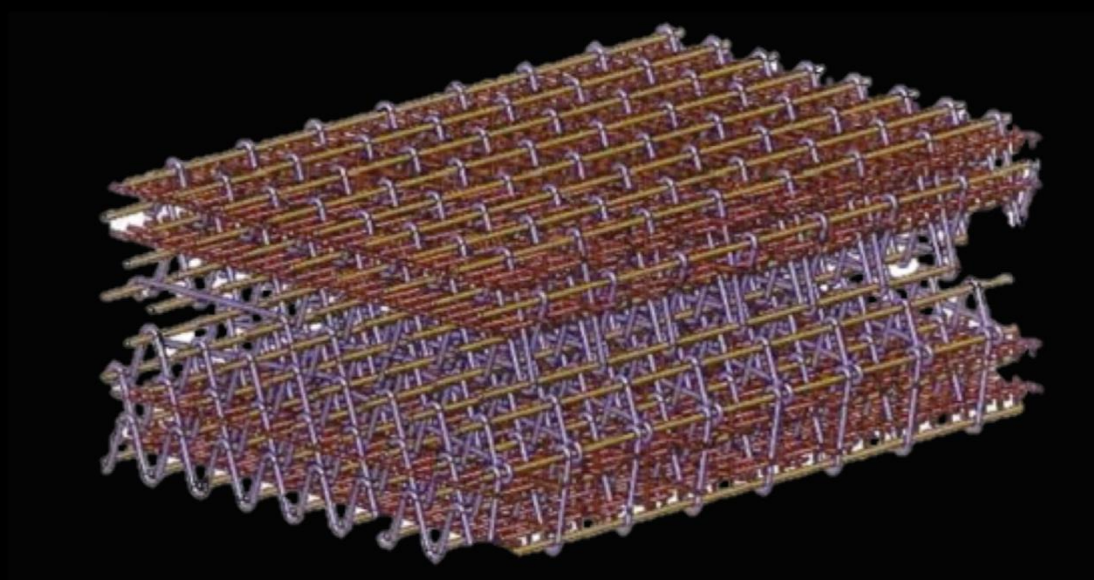
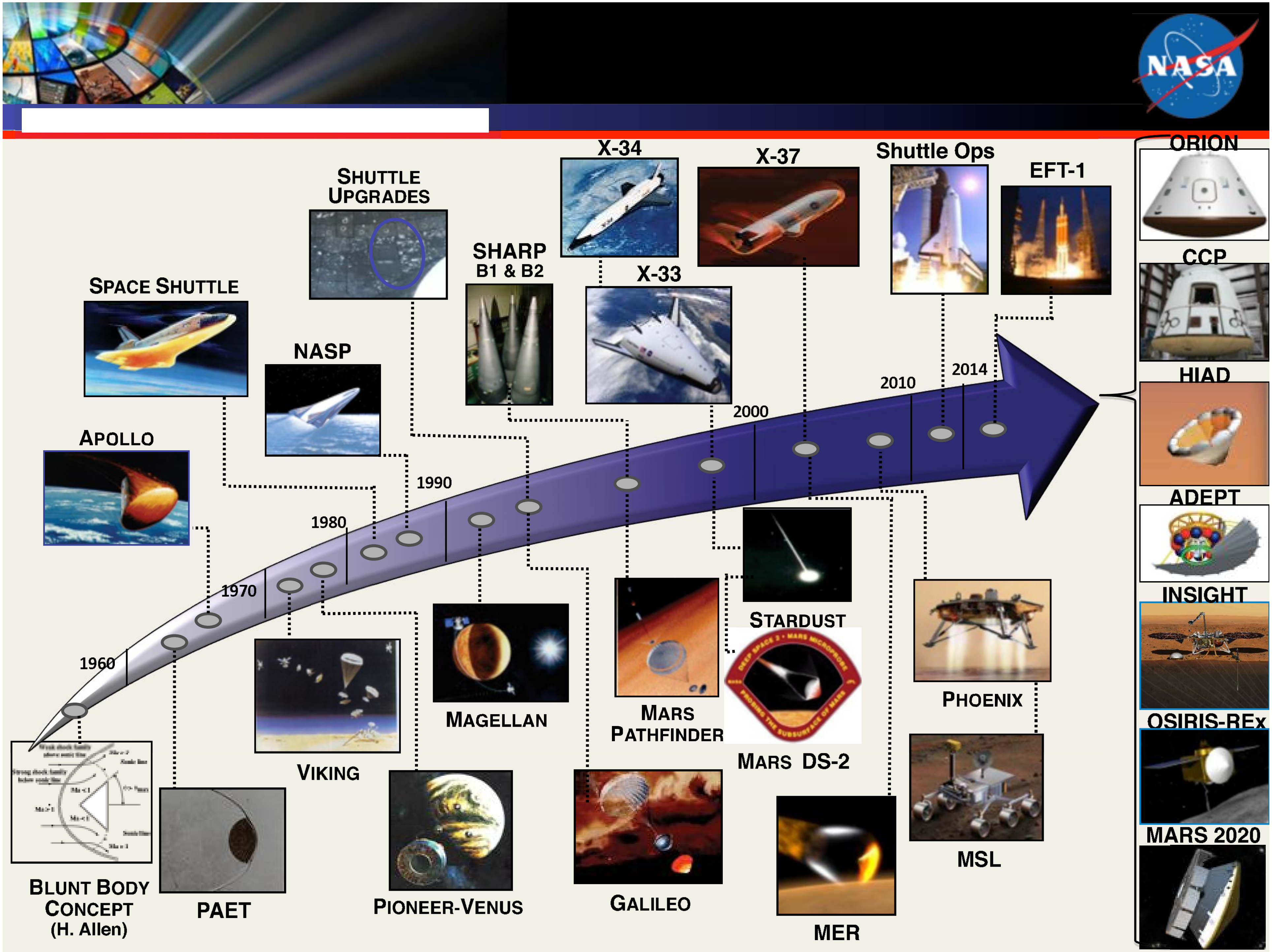
- **Thermal Protection System Background & Motivation for 3D Woven TPS**

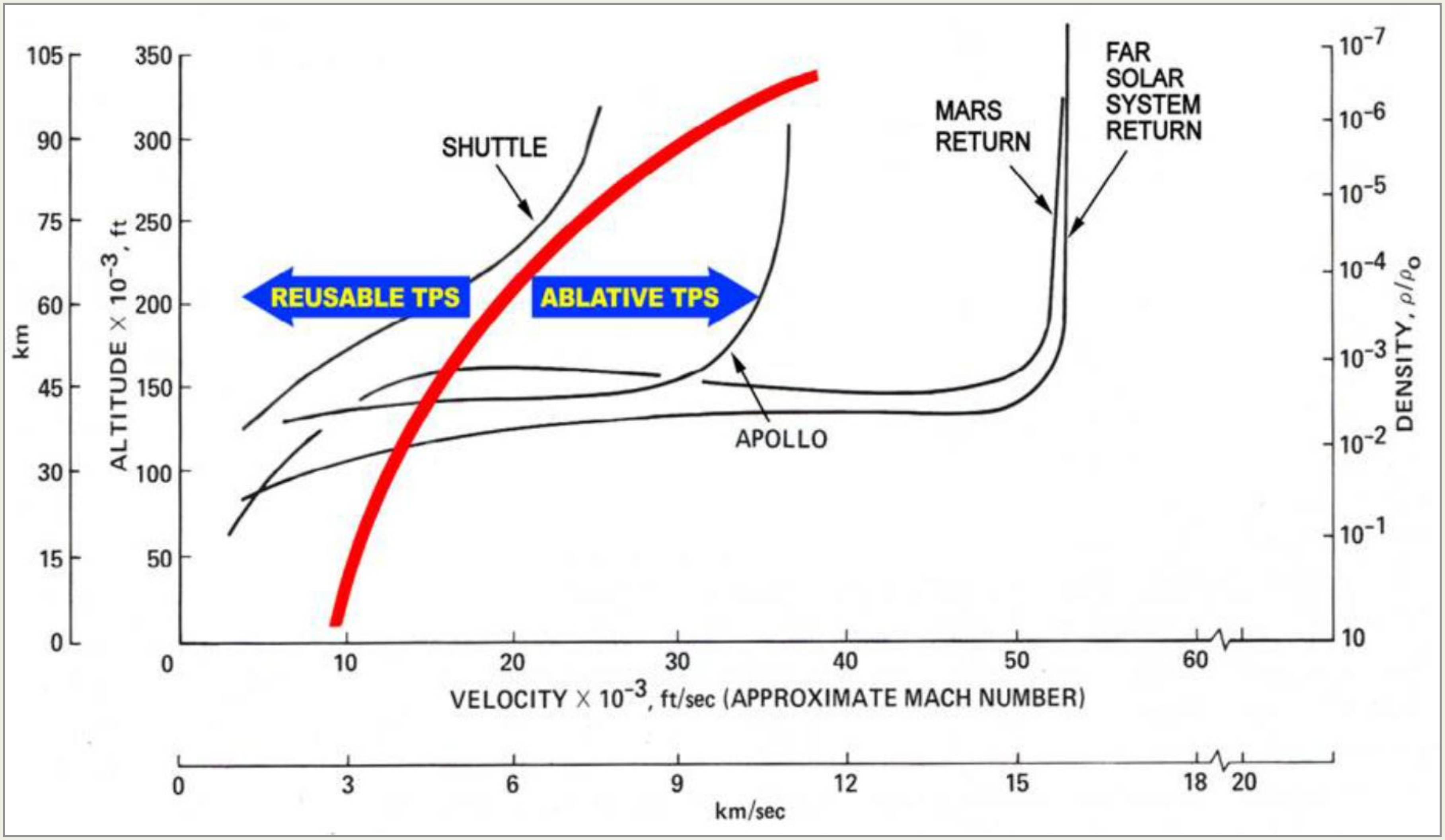
- **Initial Woven TPS Development (2011-2012)**

- **Heatshield for Extreme Entry Environment Technology (HEEET)**
  - **Efficient carbon/phenolic TPS to enable planetary probe missions**

- **3D Multi-functional Ablative TPS (3D-MAT)**
  - **Structural ablative material for the Orion compression pad**



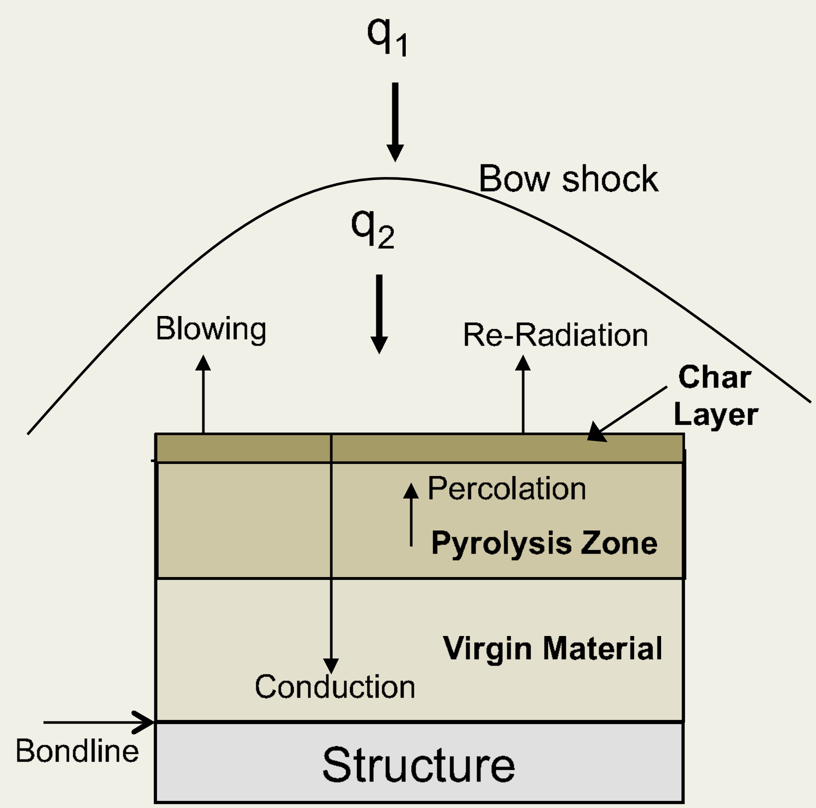

NASA
ORION
CCP
HIAD
ADEPT
INSIGHT
OSIRIS-REx
MARS 2020
X-34
X-37
Shuttle Ops
EFT-1
SHUTTLE UPGRADES
SHARP B1 & B2
X-33
SPACE SHUTTLE
NASP
APOLLO
1960
1970
1980
1990
2000
2010
2014
STARDUST
MARS DS-2
MARS PATHFINDER
PHOENIX
MSL
MAGELLAN
VIKING
BLUNT BODY CONCEPT (H. Allen)
PAET
PIONEER-VENUS
GALILEO
MER

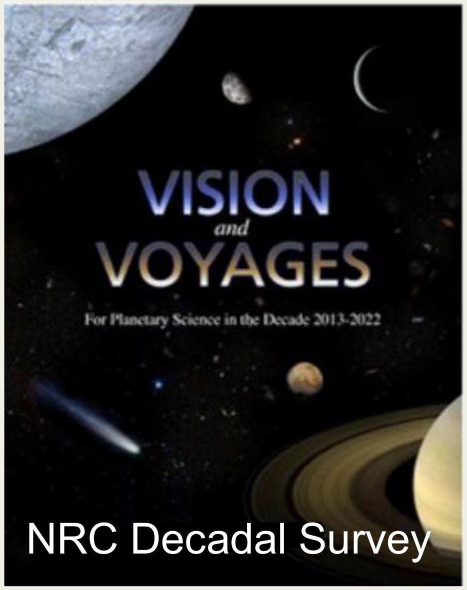


Adapted from John Howe, "Hypervelocity Atmospheric Flight: Real Gas Flow Fields," NASA TM 101055, 1989

When exposed to atmospheric entry heating conditions, material will pyrolyze, char, & reject heat in the following ways:

- Pyrolysis of polymer (endothermic)
- Blowing into boundary layer (reducing incoming heat flux)
- Formation of char layer and re-radiation

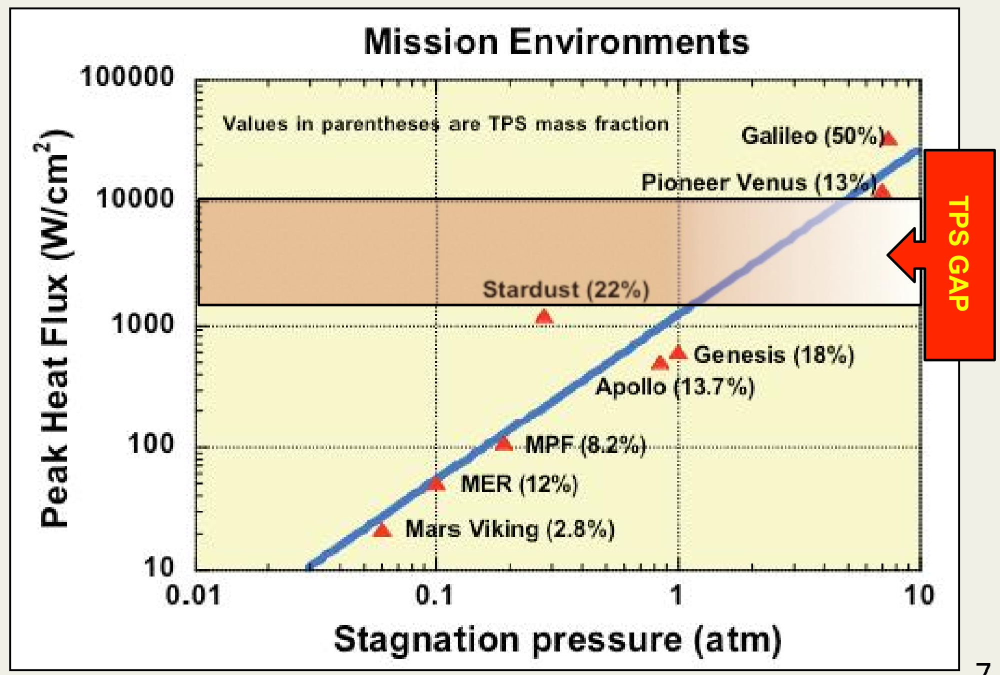


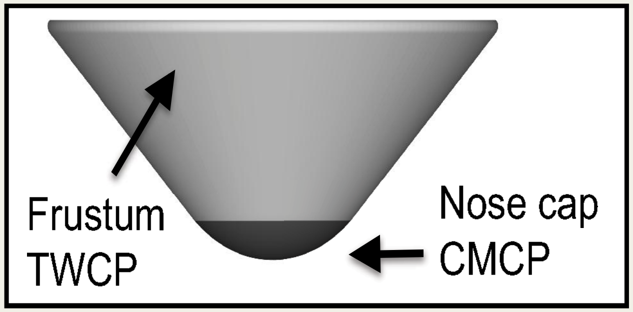


- **High priority NASA missions include flying probes to Venus, Saturn, Uranus and high speed sample return missions to Earth (2013 NRC Decadal Survey)**
- **No TPS materials are currently qualified for probe missions & few potential options exist**

Planetary Probe Entry Conditions

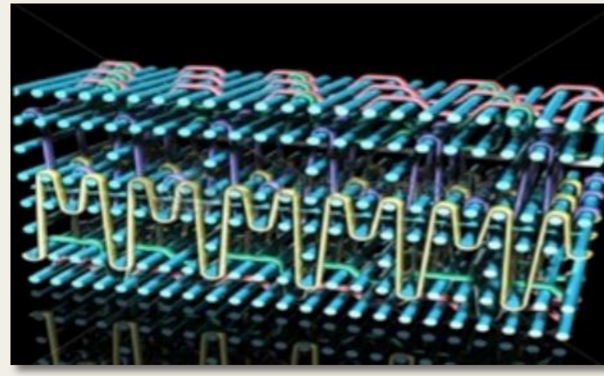
Venus	**2400 - 4900**	**4 - 9**	**11 - 12**
Saturn	**1900 - 7700**	**2 - 9**	**80 - 272**

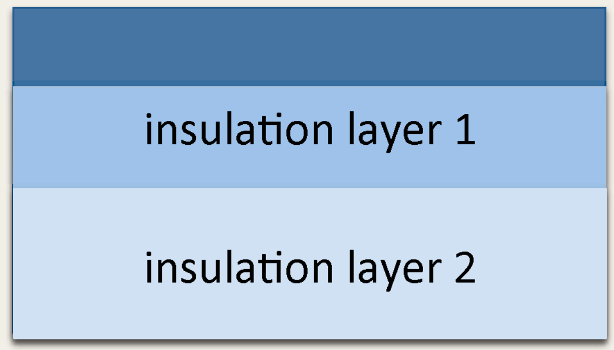


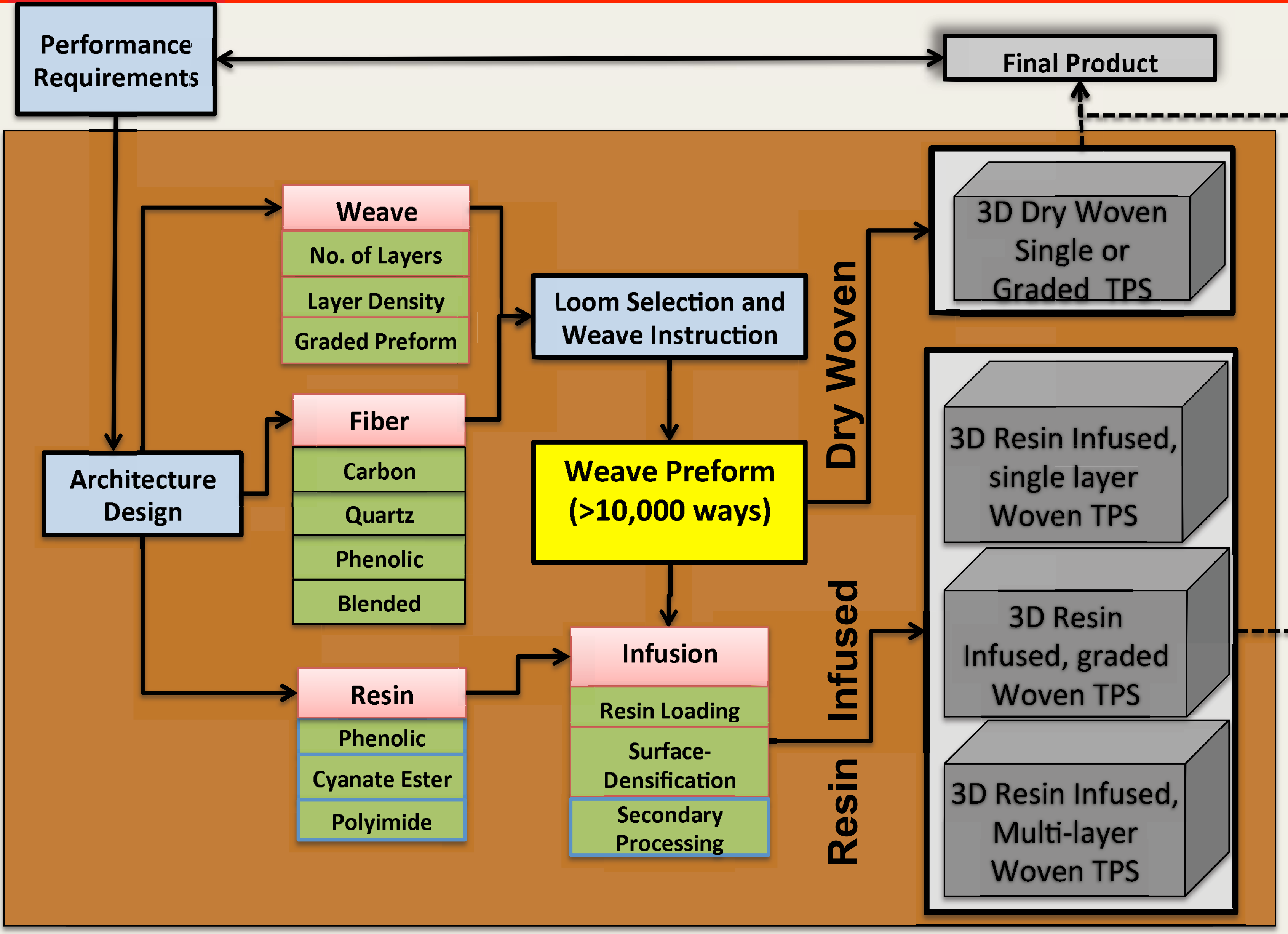


- **Pioneer Venus & Galileo Jupiter probes used 2D CP**
  - Very robust TPS
  - Made with tape-wrapped (TW) & chop-molded (CM) CP
- **Challenges for using traditional CP**
  - Heritage CP used for entry no longer available (Avtex rayon)
  - New CP material would need to be certified
  - Chop-molded CP has not be used for TPS since 1980s
  - High thermal conductivity drives need to use short-duration, steep-angle entry resulting in high heat flux, pressure, and G-loads
    - High G-loads problematic for science instruments (sensitivity & certification)
- **An improved TPS material option should:**
  - Offer greater efficiency resulting in lower TPS mass fraction (more science!)
    - mid-density
    - multi-layered to handle high surface heat heating while minimizing conduction
  - Use modern materials & processes for sustainability
    - NASA planetary probe missions are infrequent

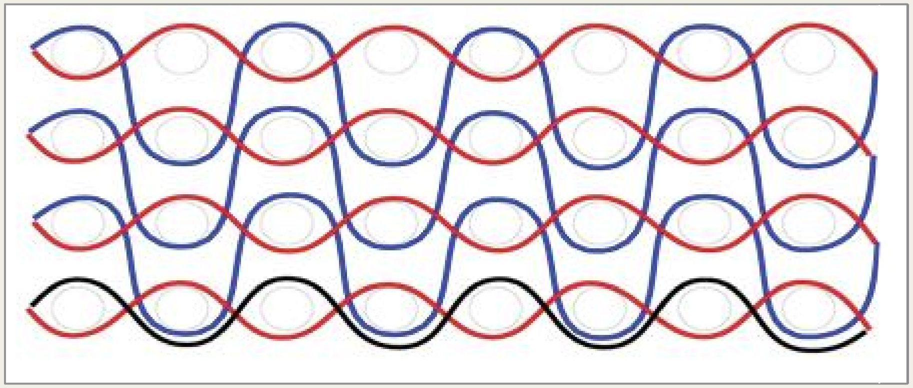
- **Contemporary automated 3D weaving technology is very flexible & customizable**
- **Many variables can be tailored within a preform**
  - Fiber composition (e.g. carbon, polymer, ceramic)
  - Fiber denier (fineness)
  - Weave density (fiber volume fraction)
  - Weave architecture (e.g. layer-to-layer, 3D orthogonal)
- **Resin infusion likewise can be tailored**
  - No resin (dry weave)
  - Surface densification
  - Low-loading infusion / partial densification
  - Full densification
- **Manufacturing flexibility enables designing a material for specific mission requirements**
- **WTPS leverages a mature weaving industry & high-volume fiber products that are not NASA-unique – for improved sustainability & life cycle cost**



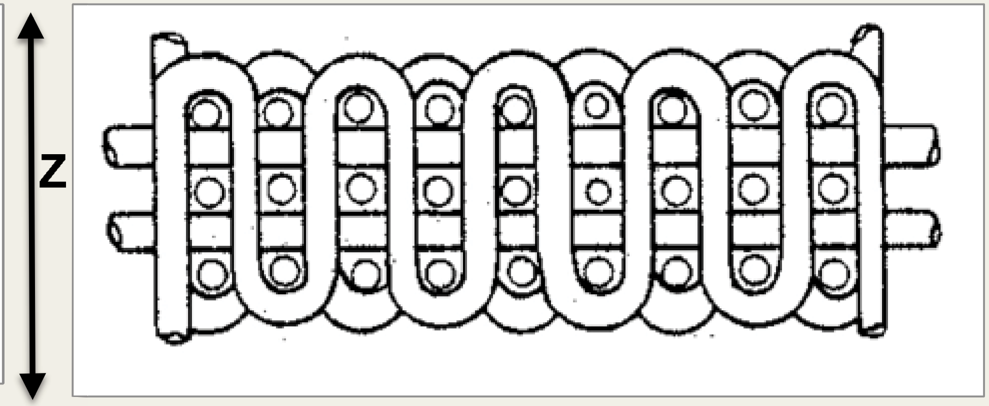



Performance Requirements
Final Product
Weave
No. of Layers
Layer Density
Graded Preform
Loom Selection and Weave Instruction
Fiber
Carbon
Quartz
Phenolic
Blended
Architecture Design
Weave Preform (>10,000 ways)
Dry Woven
3D Dry Woven Single or Graded TPS
Resin
Phenolic
Cyanate Ester
Polyimide
Infusion
Resin Loading
Surface-Densification
Secondary Processing
Resin Infused
3D Resin Infused, single layer Woven TPS
3D Resin Infused, graded Woven TPS
3D Resin Infused, Multi-layer Woven TPS

3D Layer-to-Layer



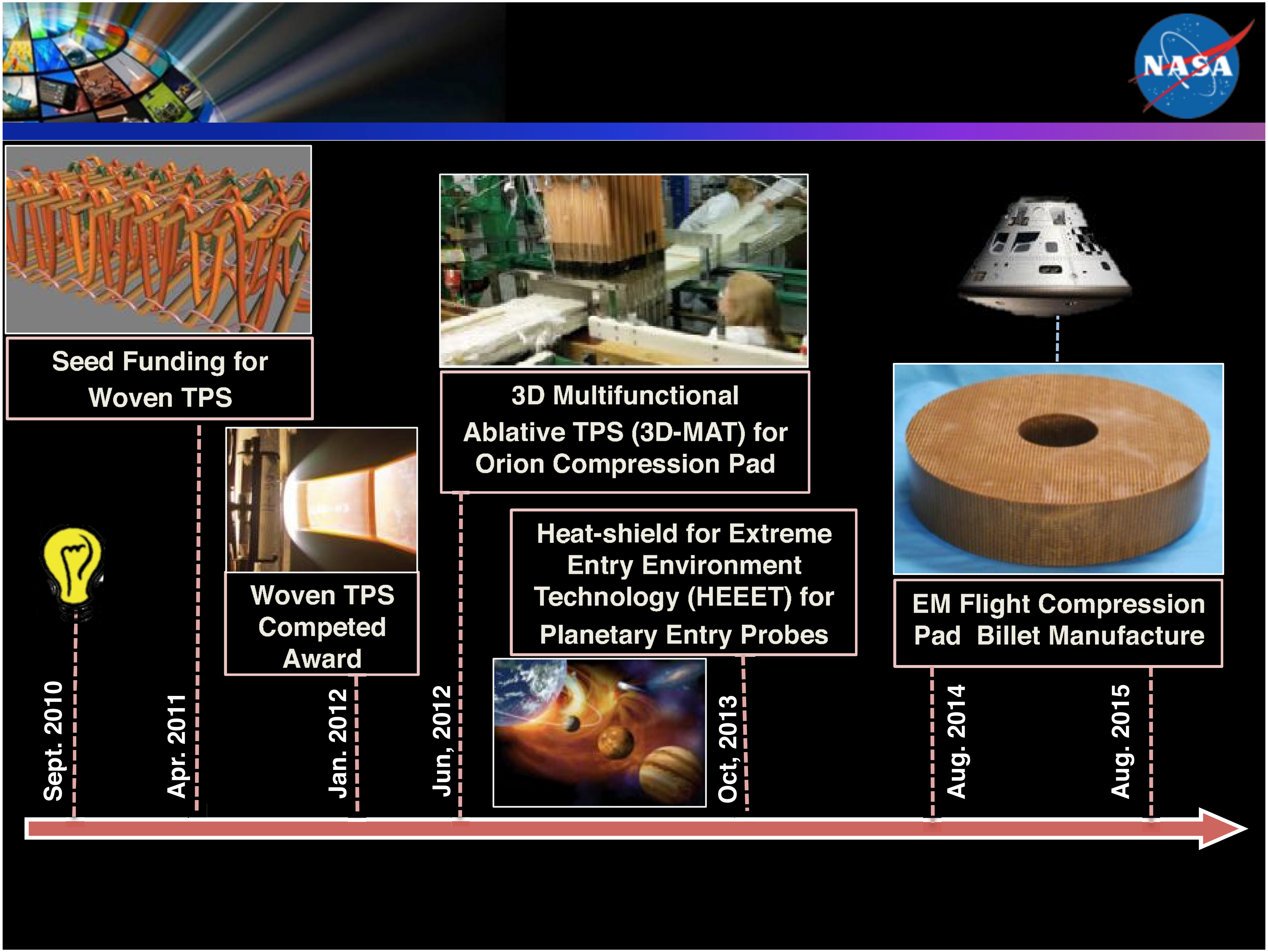
3D Orthogonal



- Ties a layer to one layer below (or two below, etc.)
- Limits thermal conduction in Z-direction
- Lower Z-strength than 3D orthogonal

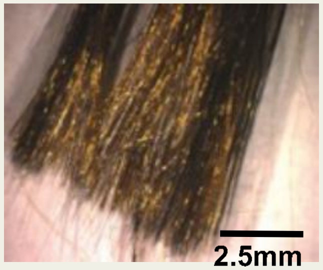
- Each Z-fiber goes through all layers
- Very high Z strength & stiffness
- Higher Z-direction thermal conduction

Woven TPS projects have leveraged both weave types (in separate TPS materials and within a single material)

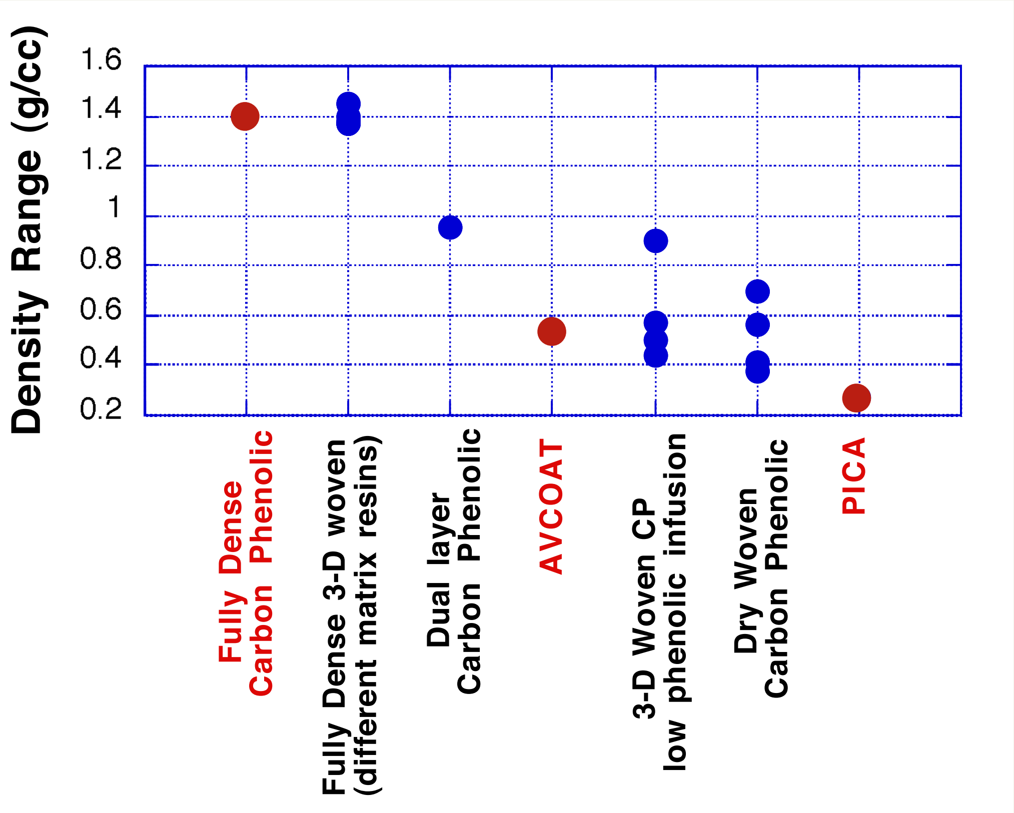

NASA
Seed Funding for Woven TPS
Woven TPS Competed Award
3D Multifunctional Ablative TPS (3D-MAT) for Orion Compression Pad
Heat-shield for Extreme Entry Environment Technology (HEEET) for Planetary Entry Probes
EM Flight Compression Pad Billet Manufacture
Sept. 2010
Apr. 2011
Jan. 2012
Jun, 2012
Oct, 2013
Aug. 2014
Aug. 2015

- Many varieties of woven TPS materials produced spanning a density range of 0.38 – 1.5 g/cm^3
- Developed a hybrid yarn made from carbon & phenolic fibers

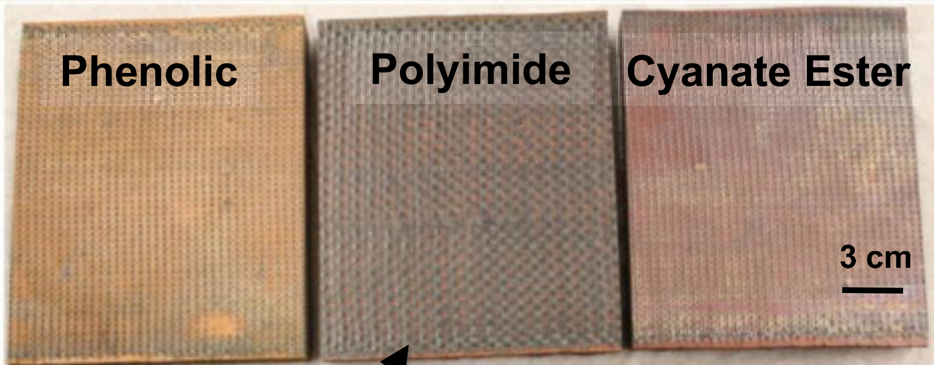
Phenolic Fibers

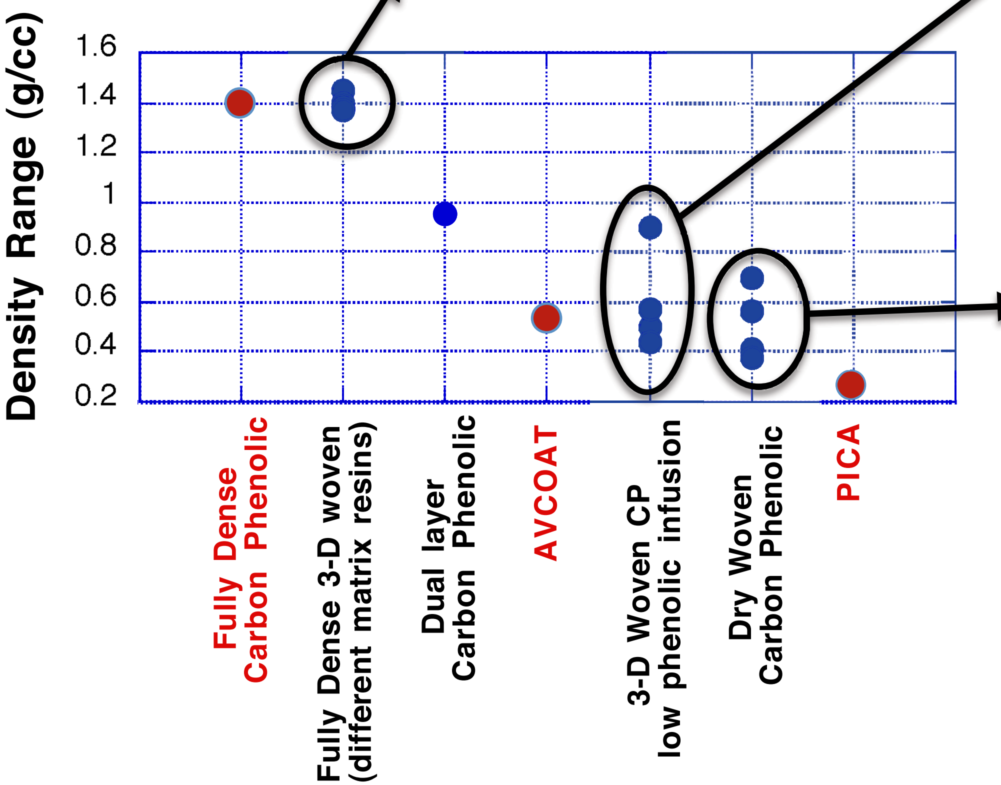


Hybrid Yarn (Carbon+Phenolic)

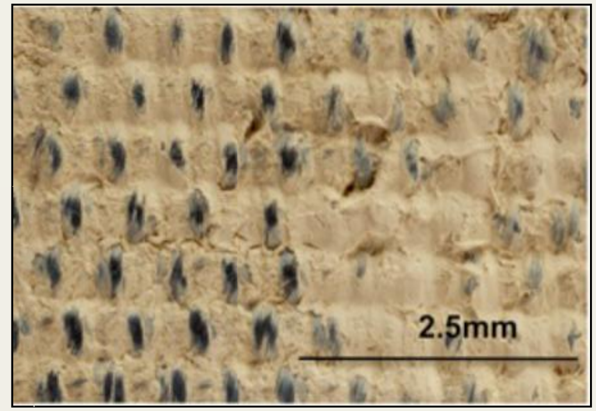


Fully Dense: Carbon Preforms with Various Resins



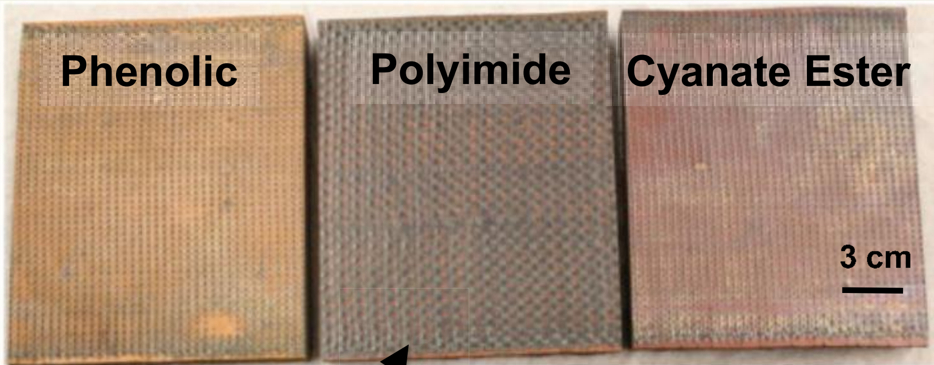


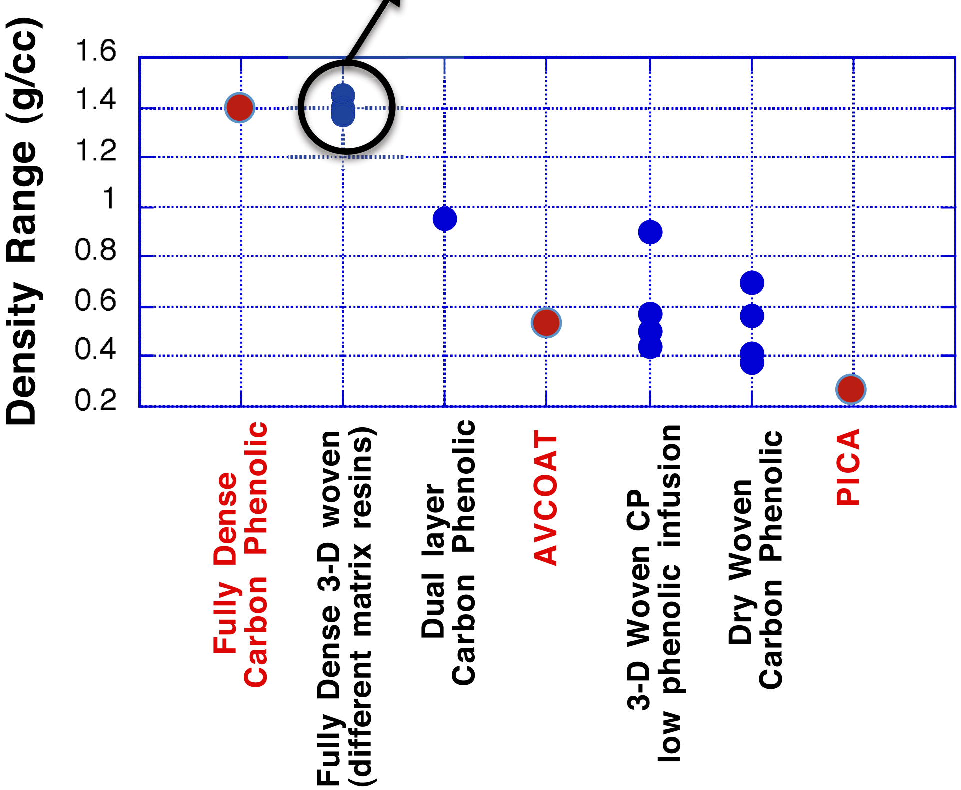
Low Loading of Phenolic Resin



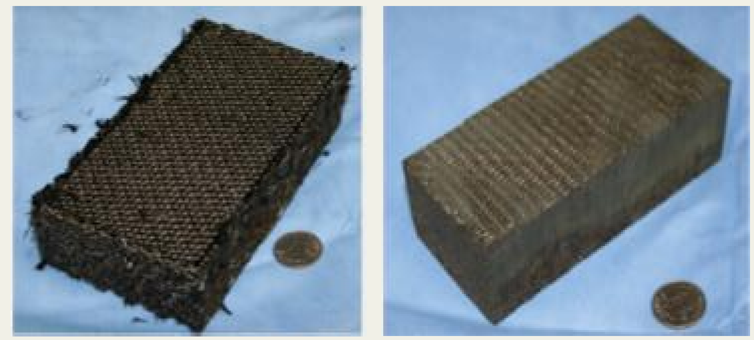
Flexible, Dry-Woven, 2-Layer 3D CP Family

Fully Dense: Carbon Preforms with Various Resins

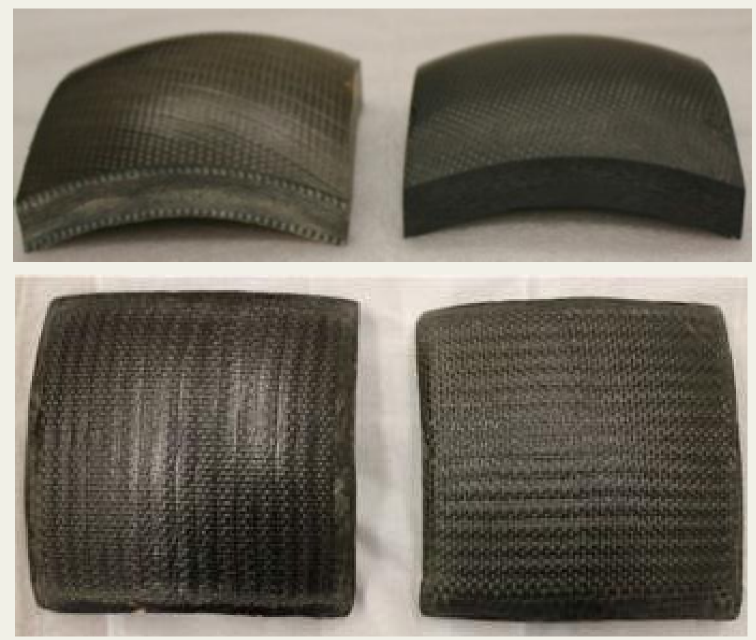


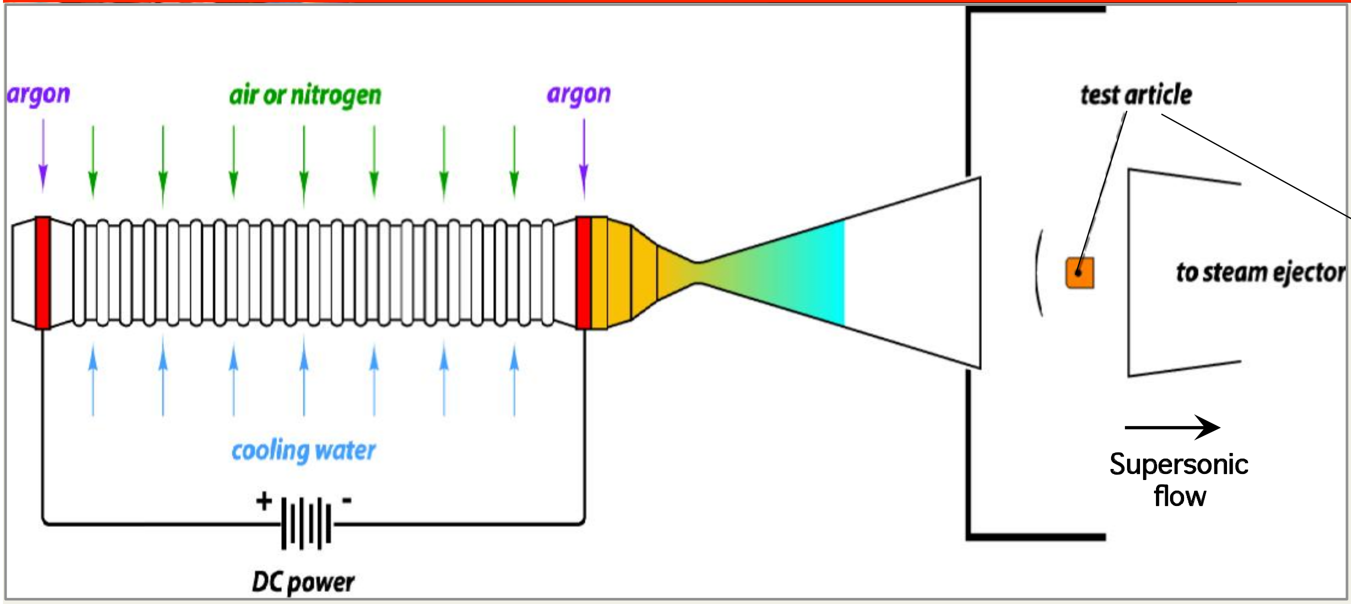


3D Carbon Phenolic



Molded Preform + Phenolic Infused





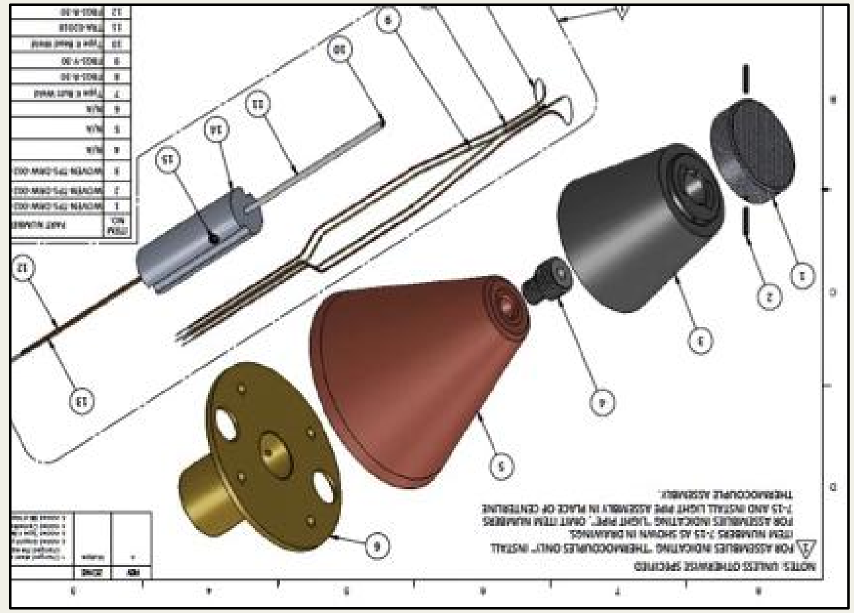
Objective

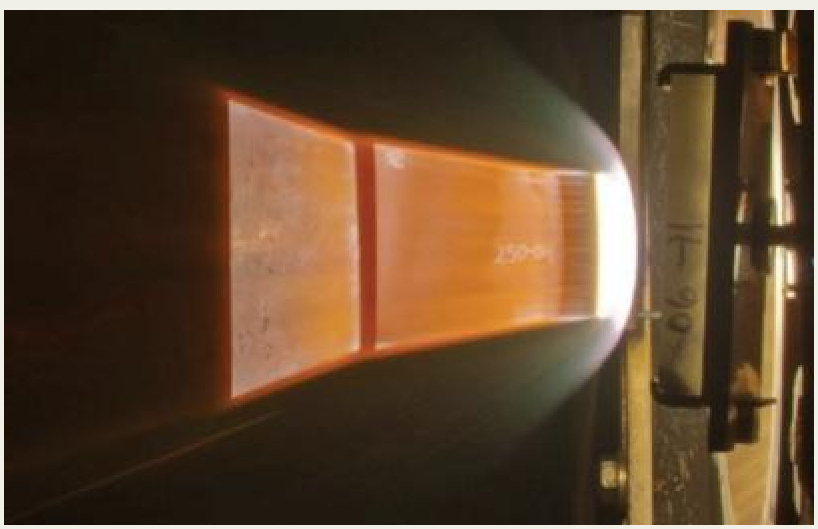
- Create heating & pressure environments relevant to planetary entry

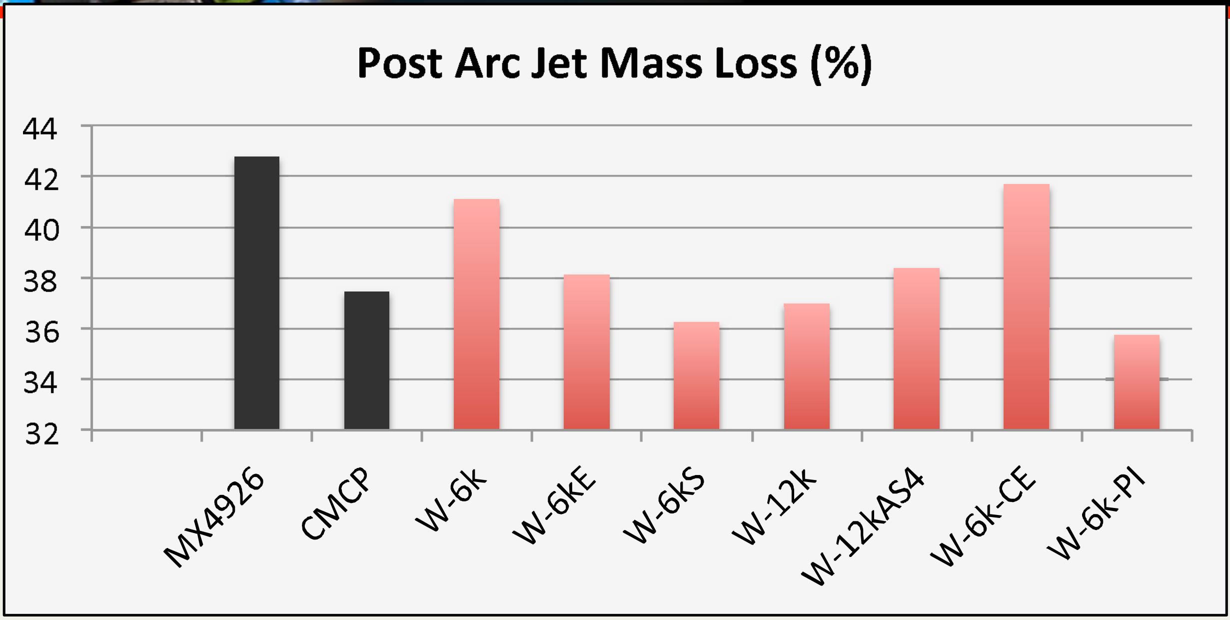
Test Facility

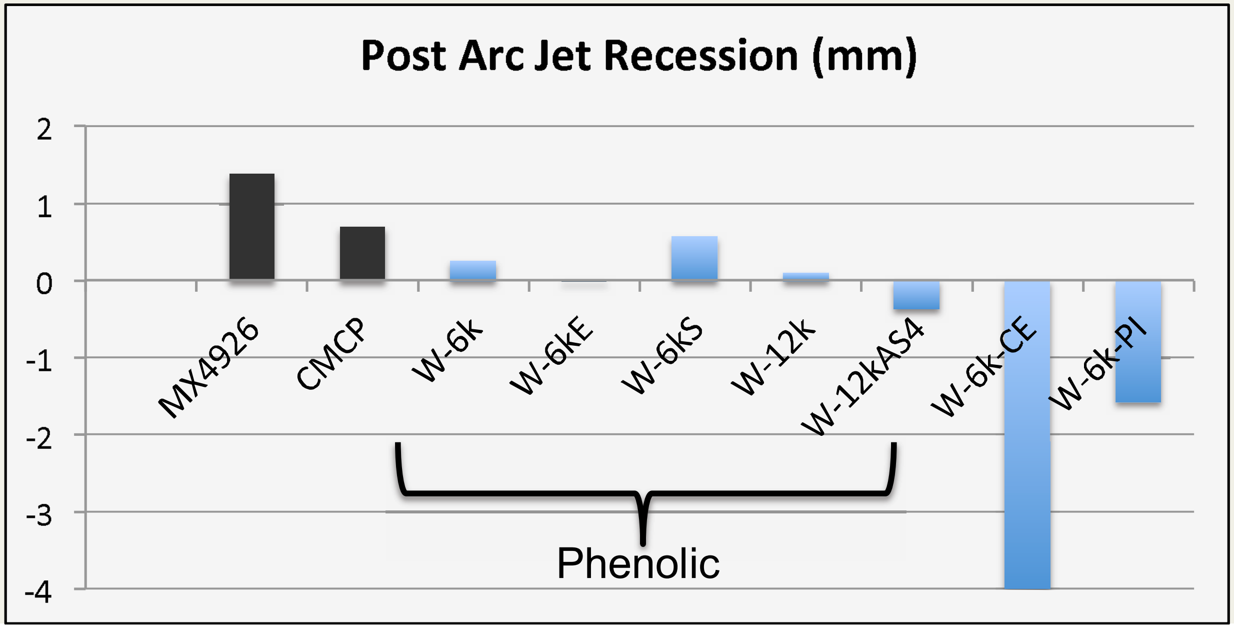
- Gas flow is heated by electric discharge in a water-cooled, constricted arc column
- The hot gas is expanded through a converging-diverging nozzle into a chamber where the test article is mounted on a water-cooled mechanical swing arm
- The electrical power, gas flow rate, nozzle configuration, and distance of the test article from the nozzle exit plane are adjusted to achieve the desired stagnation pressure and temperature (or heat flux)

- **1700 W/cm^2, 1.3 atm**
  - Space Shuttle Entry: 6 – 60 W/cm^2
- **2” dia. flat face puck**
- **Durations:**
  - Fully dense: 20 seconds (11 models)
  - Low–Mid dense: 7 seconds (6 models)
- **Backface thermocouple**









3DCP Variants

Lower recession & mass loss compared to 2DCP

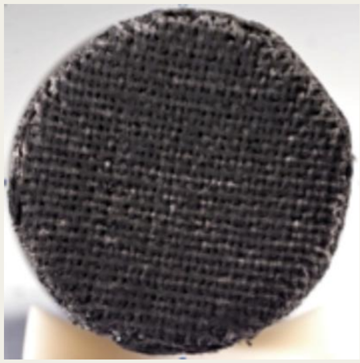
- TWCP MX4926N (20° shingle) reference mtl
- CMCP from industry, funded by NASA

Alternative Resin WTPS

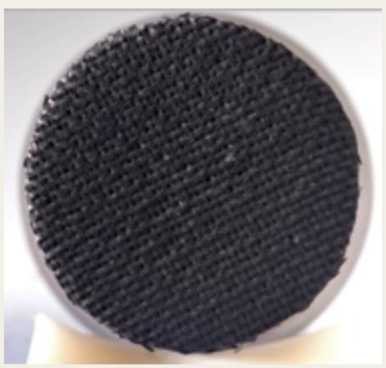
Cyanate Ester & Polyimide materials had net expansion due to insufficient post-cure

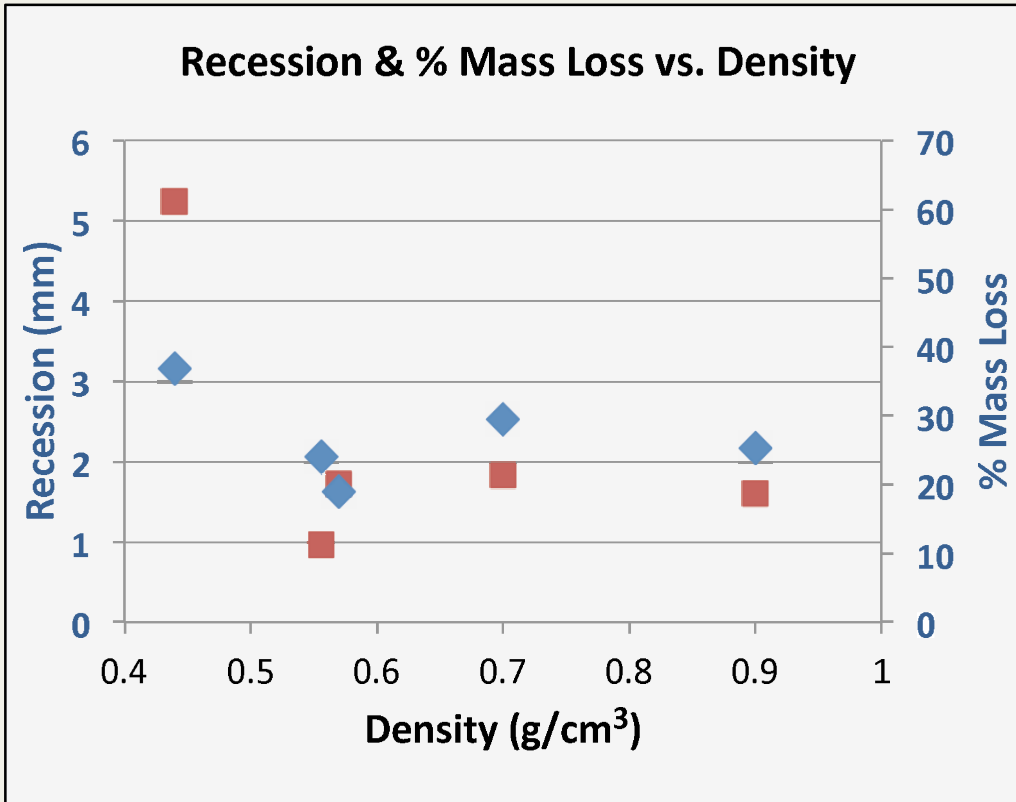
Subsequent testing of post-cured samples showed comparable ablation to phenolic

Dry Woven Carbon Phenolic

Pre-Test	Post-Test
	

Woven CP + Low Loading Phenolic

Pre-Test	Post-Test
	



- Lowest recession was for surface-densified woven CP at 0.56 g/cm^3
- Samples below 0.5 g/cm^3 exhibited spallation at this high condition

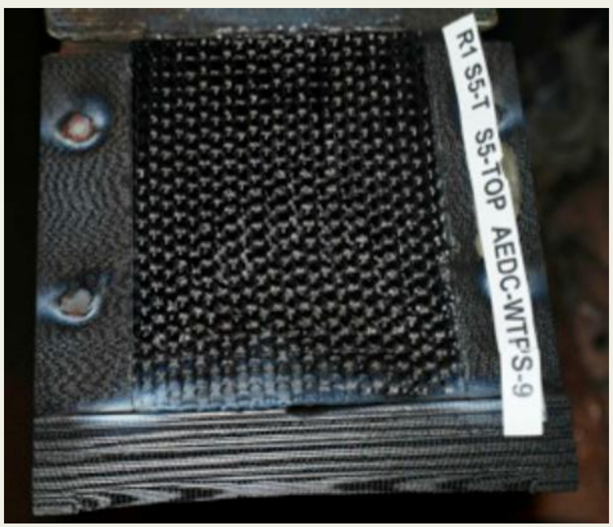
- H3 facility
- 15° wedge
- 1500 W/cm^2
- 2.6 atm
- high shear
- Historical test for screening CP performance

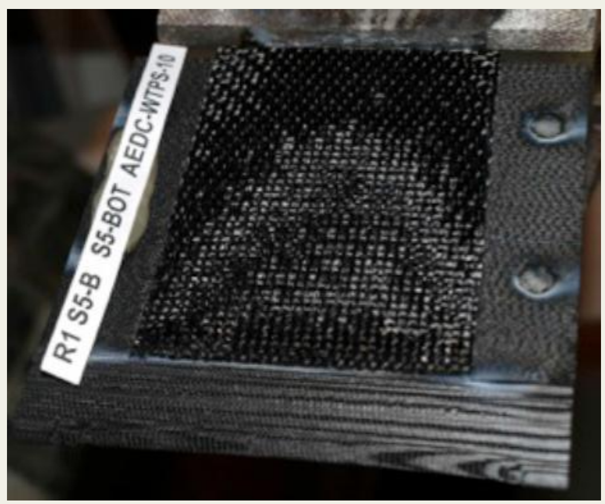
Traditional Carbon Phenolic

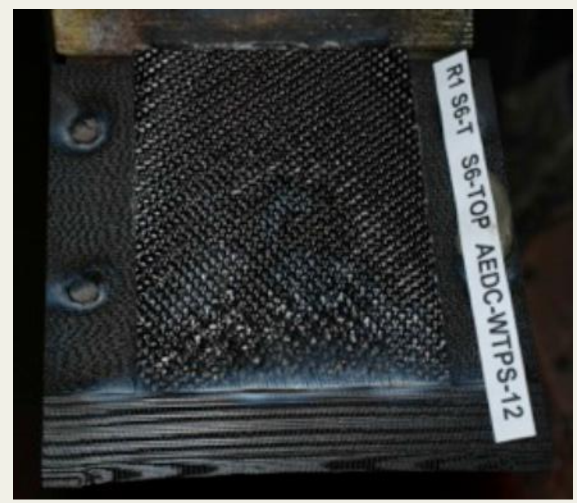
Shingled (Tape Wrapped)

Chop Molded

3-D Woven TPS (12 total tested)



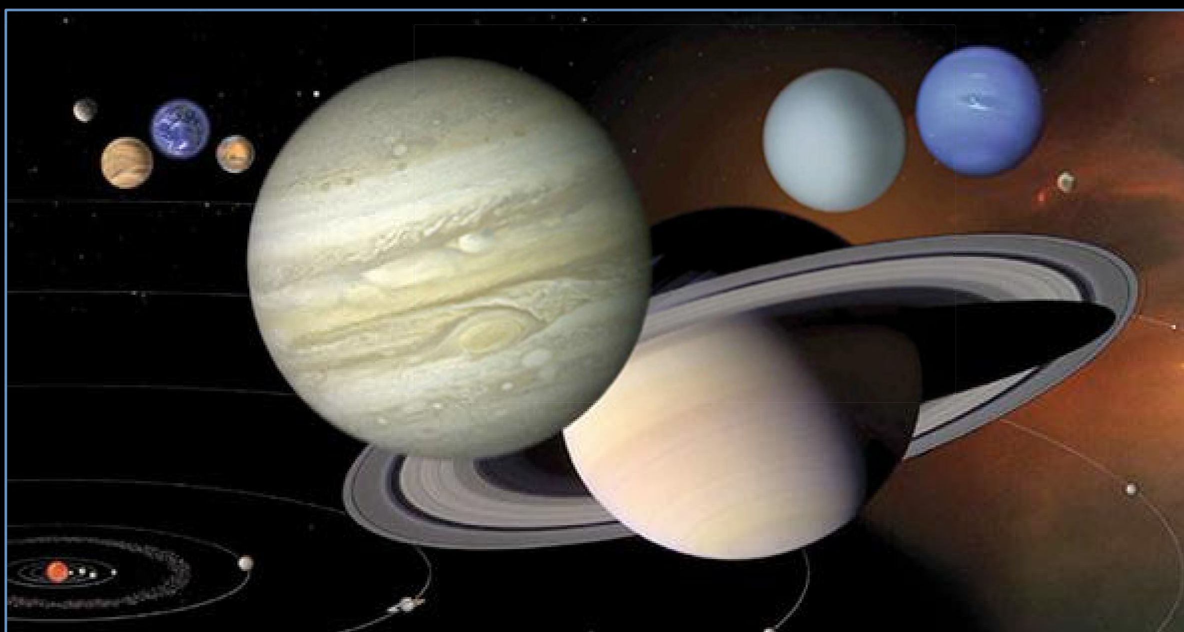


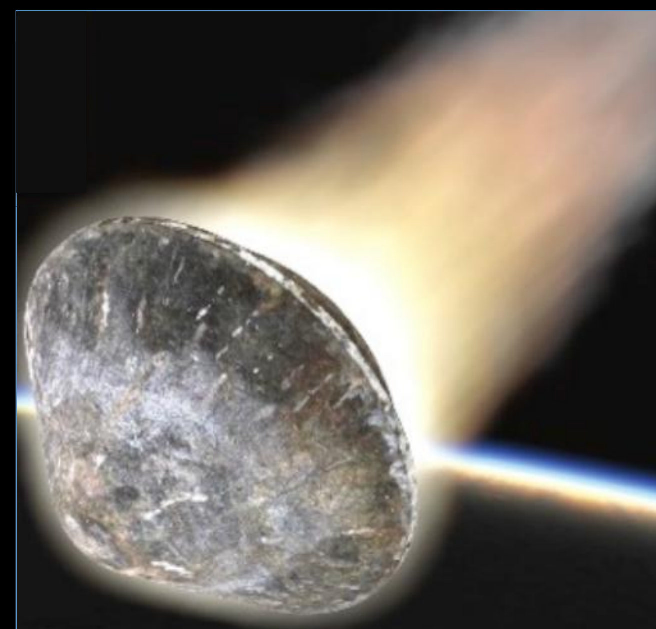


- Demonstrated Woven TPS approach using 3D weaving industry, commercially available fibers, and NASA and industry resin infusion processes

- Manufactured & tested a wide variety of materials
  - Showed aerothermal robustness via arc jet testing alongside 2DCP
  - Material property characterization enabled thermal & structural modeling

- Demonstrated viability for tailoring TPS with:
  - weave type (3D ortho, layer-to-layer)
  - fiber & resin compositions
  - multi-layered architecture
  - density & fiber volume
  - dry-woven/partial-densification/full-densification
  - hybrid carbon/phenolic yarn
  - complex curvature molding

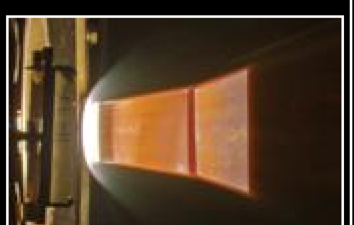




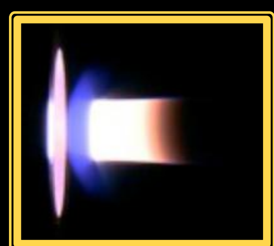
- HEEET is developing a Thermal Protection System to enable planetary probe missions in the near future
- Several Discovery & New Frontiers class mission proposal teams will need a viable TPS solution to be at Technology Readiness Level (TRL) 6 by ~2017
- HEEET team has developed a set of requirements from a mission performance perspective
  - Sought input form community via HEEET workshop
  - Project goal is to verify that HEEET meets these requirements by 2017
- NASA's Science Mission Directorate has incentivized the adoption of HEEET by mission proposers with respect to proposal risk & mission finances (Discovery)

FY’13 | FY’14 | FY’15 | FY’16 | FY’17

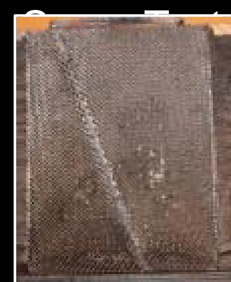
Yarn/Resin



IHF Screening

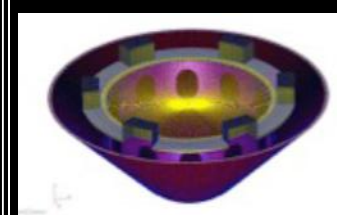


IHF-5000 W/cm2



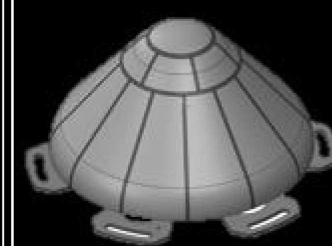
AEDC Seam Test

Loom Upgrade



Carrier Structure

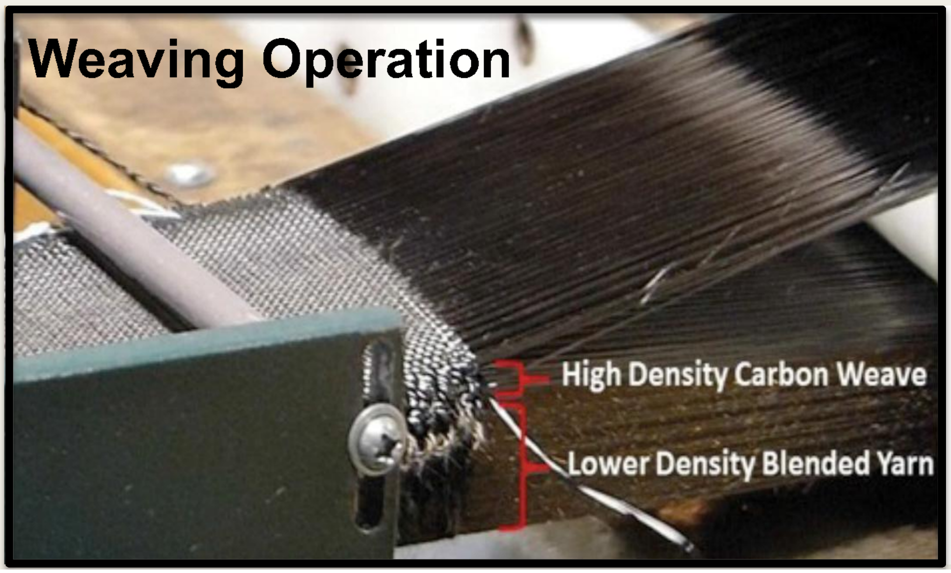
Manufacturing Demo. Unit

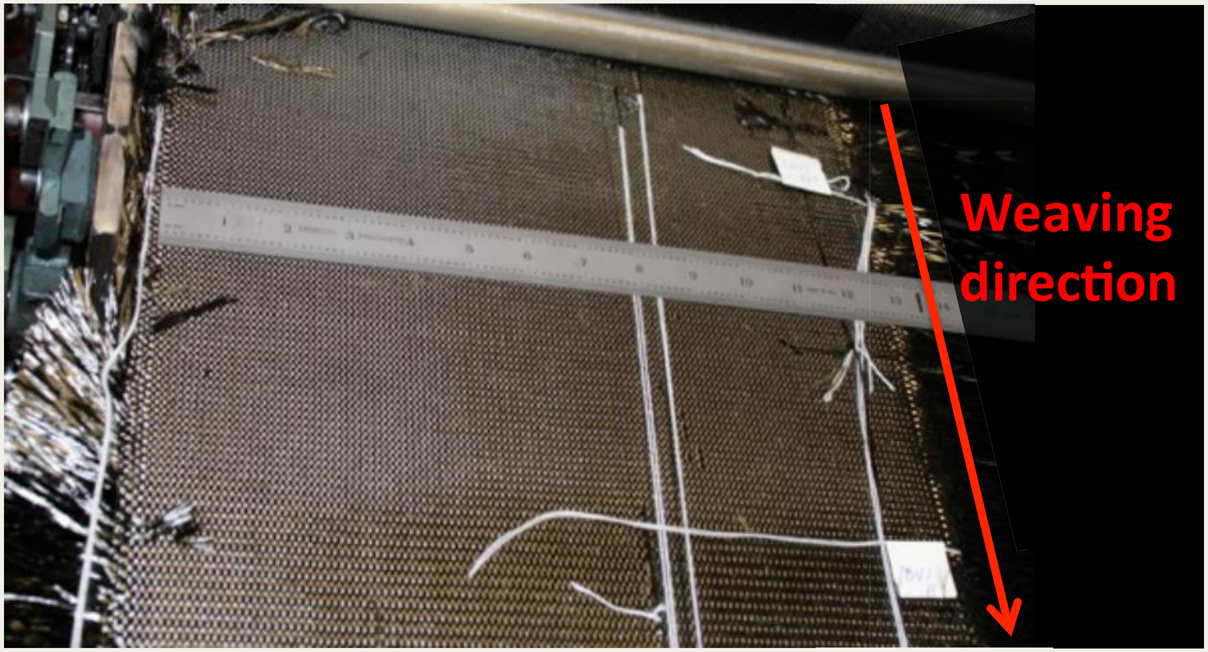


Engineering Test Unit

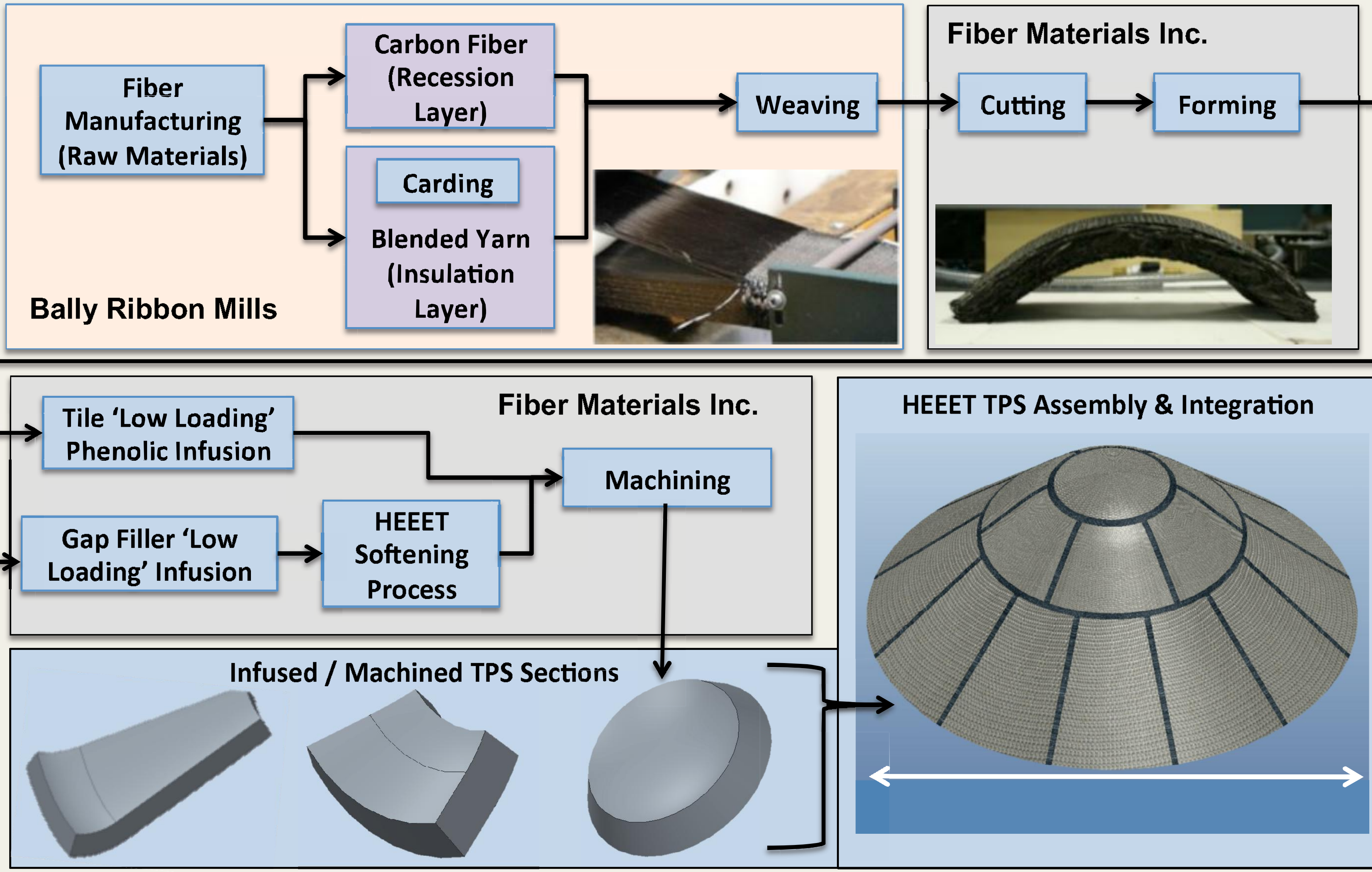
Dual-Layer 3D woven material infused with low loading phenolic resin matrix

- **Recession layer**
  - Layer-to-layer weave using fine carbon fiber - high density for recession performance
- **Insulating layer**
  - Layer-to-layer weave with carbon phenolic blended yarn - lower density for insulation
- **Material Thickness:**
  - Currently 2.1” thick (0.6” recession, 1.5” insulating), able to weave 3” thick
- **Material Width:**
  - Currently 12” wide material, scaling up to 24” width in 2016

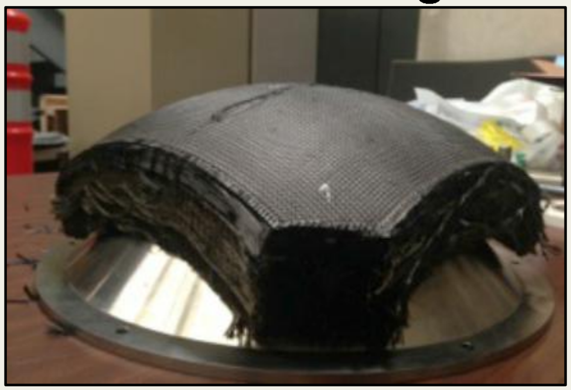




- **Successful scale-up from 6” to 12” width**
  - Weaving rate: 12” length per day
  - Thickness: 2.1”
- **2016 plan: scale up to 24” width**

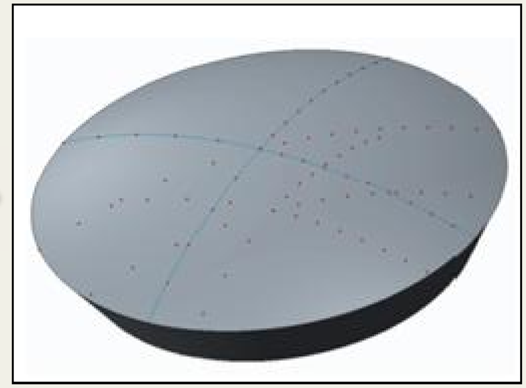

Fiber Manufacturing (Raw Materials)
Carbon Fiber (Recession Layer)
Carding
Blended Yarn (Insulation Layer)
Bally Ribbon Mills
Weaving
Fiber Materials Inc.
Cutting
Forming
Fiber Materials Inc.
Tile 'Low Loading' Phenolic Infusion
Gap Filler 'Low Loading' Infusion
HEEET Softening Process
Machining
Infused / Machined TPS Sections
HEEET TPS Assembly & Integration

Nose Forming



Infused Nose Tile

Drawing for Machining



Infused Flat Panel 12” x 18” x 2”

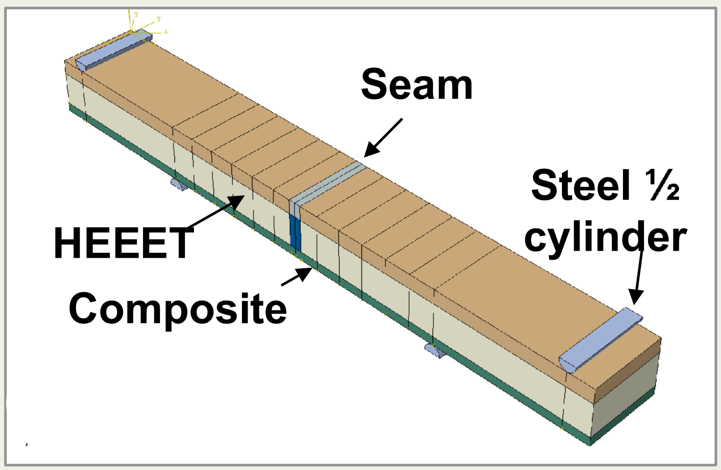
Extracted Core

2.1” thickness

Resin infiltration uniformity confirmed by coring, density measurements, & CT scan inspection

- Since HEEET cannot be made & molded into a single piece heatshield for 1-3 meter diameter sphere-cones, a tiled architecture with seams is necessary
- Structural and aerothermal performance of the seams is critical & makes up a significant portion of the development program
  - Many seam approaches have been traded
  - Test campaign is designed to verify performance

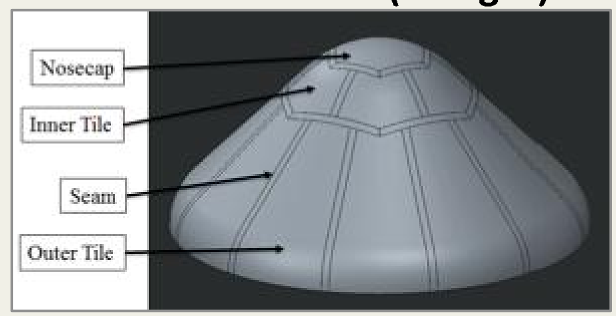
4-point Flexure Testing



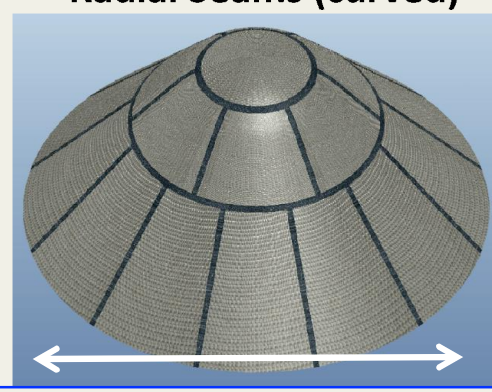
Seam testing to be performed at room temperature & with surface heating (LHMEL laser)

Seam Concepts

Radial Seams (straight):



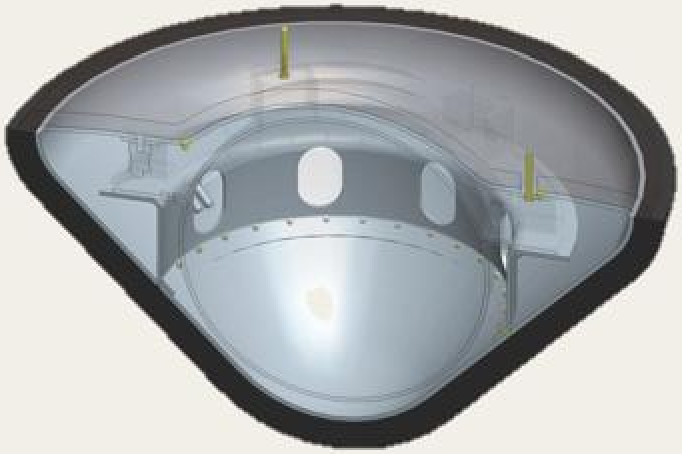
Radial Seams (curved)



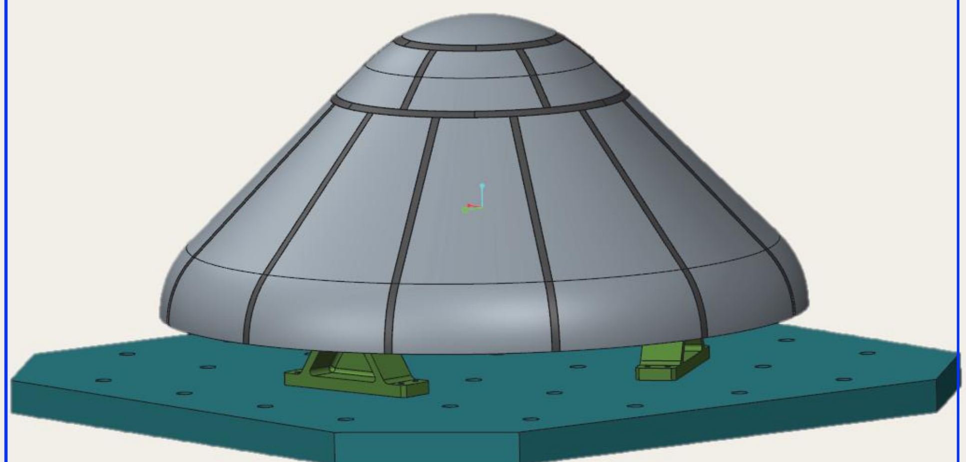
Non-radial Seams

- Successful ETU build & testing required to attain TRL 6
- ETU manufacturing & testing requirements derived from entry missions likely to use HEEET
- ETU testing planned:
  - Static Mechanical
  - Vibration
  - Shock
  - Thermal-Vacuum
  - Non-Destructive Evaluation

Entry Probe & ETU Cross-Section



ETU setup for Vibration Test



LHMEL

- Laser heat fluxes to 8000 W/cm^2
- Bounds Saturn stag. heat flux
- No flow
- Small samples

IHF 3" Nozzle

- Combined heat flux & pressure
- Small samples (1" diameter)

AEDC H3 (Stagnation 2")

- Very high pressure (~14 atm)
- Bounds Venus mission peak pressure

AEDC H3 (Wedge)

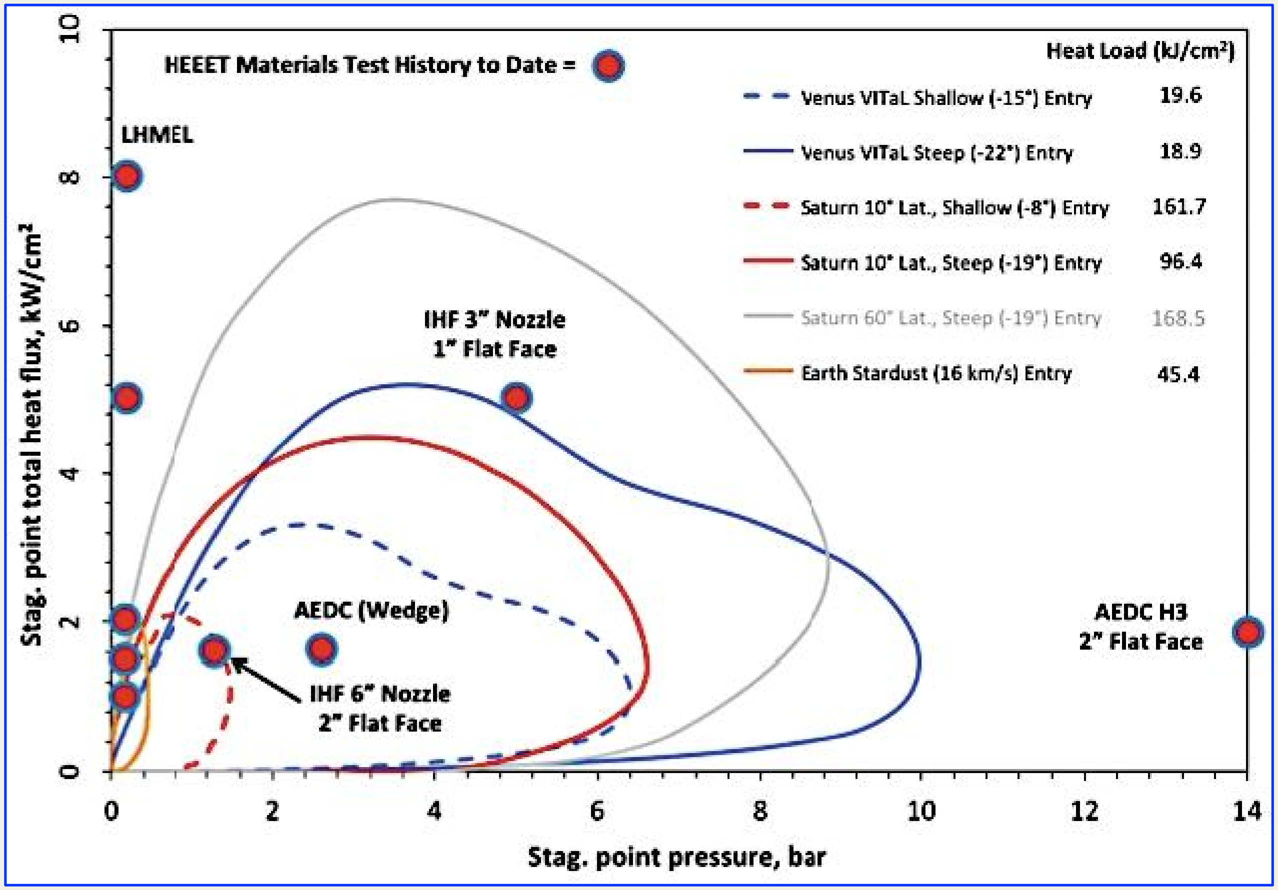
- Allows testing in combined heating, pressure & shear envir.
- Large samples (4" x 5")

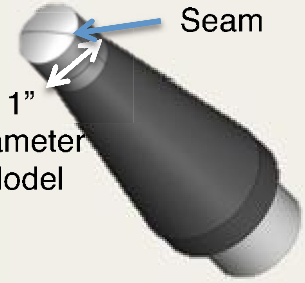
IHF 6" Nozzle

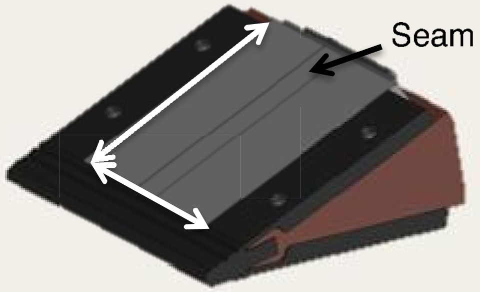
- Lower heating than IHF 3" but bigger sample

AHF 12" & IHF 13" Nozzles

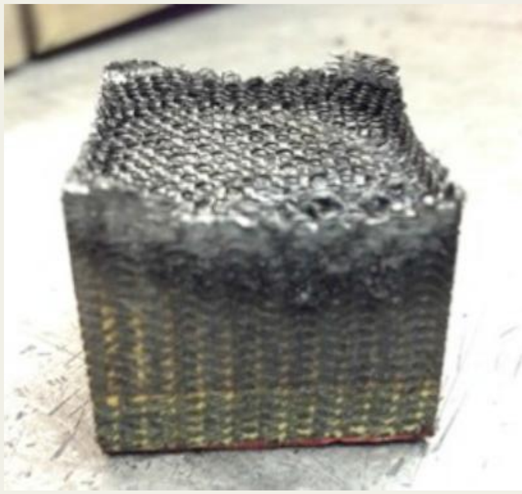
- Thermal response model devel.

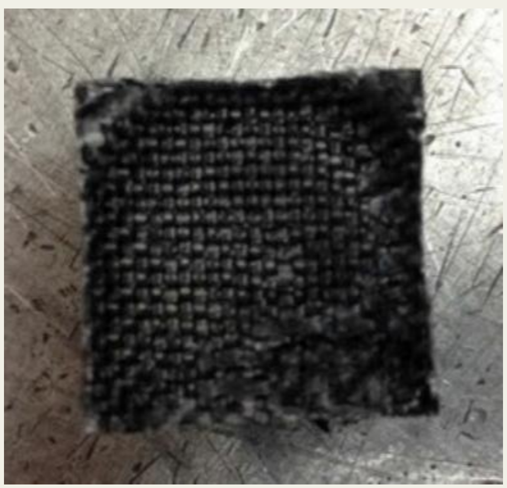






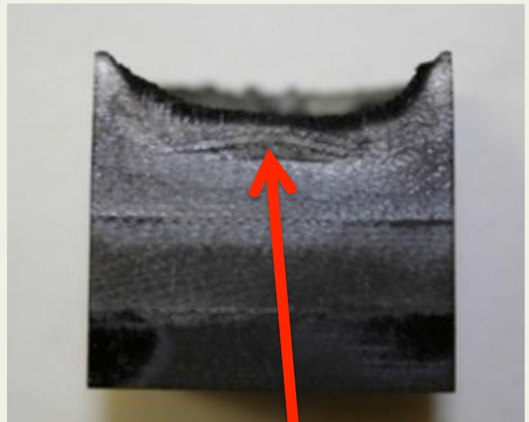
HEEET Acreage

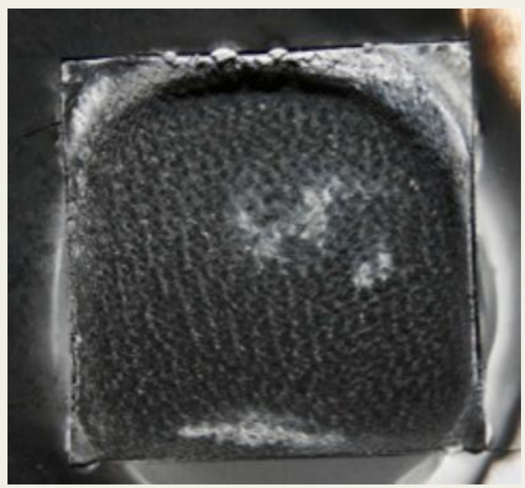




No surface spallation, delamination or cracks

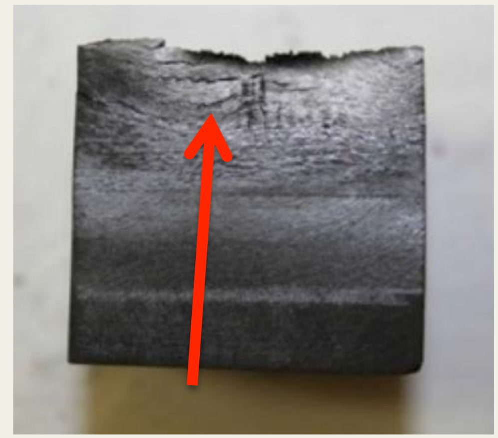
Tape Wrapped CP





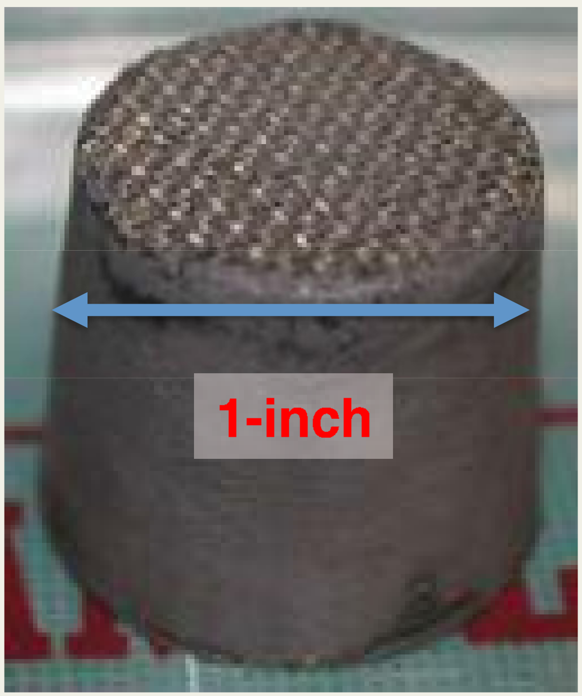
Ply separation & sub-surface cracking

Chop Molded CP

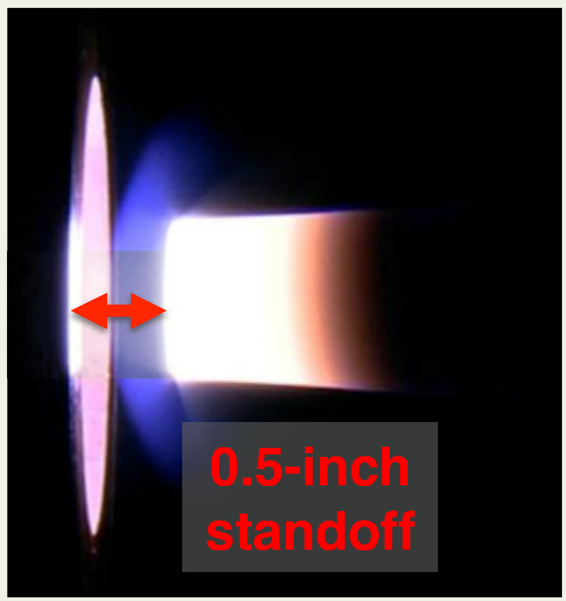


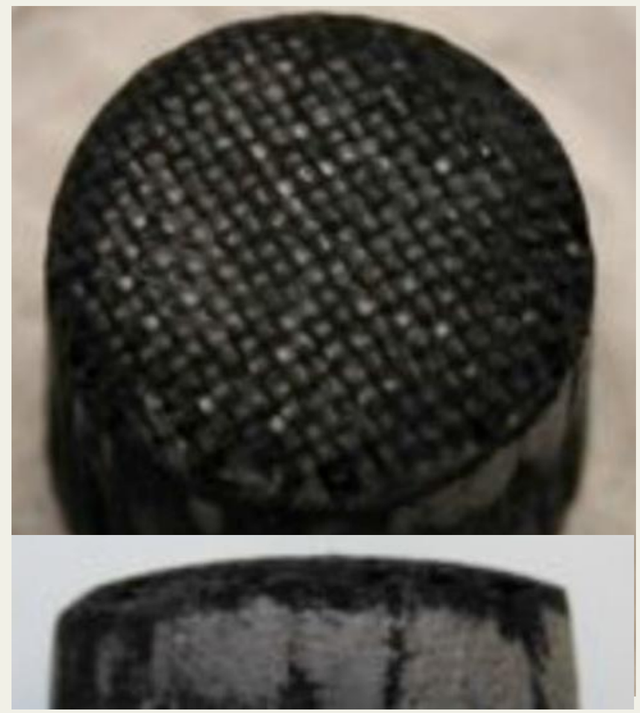
Ply separation & sub-surface cracking

- Acreage HEEET (no seams)
- Model edge ~6000 W/cm^2 and ~7000 Pa shear
- Small (1" d) sample size to attain the high heating
- Significant sidewall heating
- <u>No unusual ablation!</u>



Pre-Test

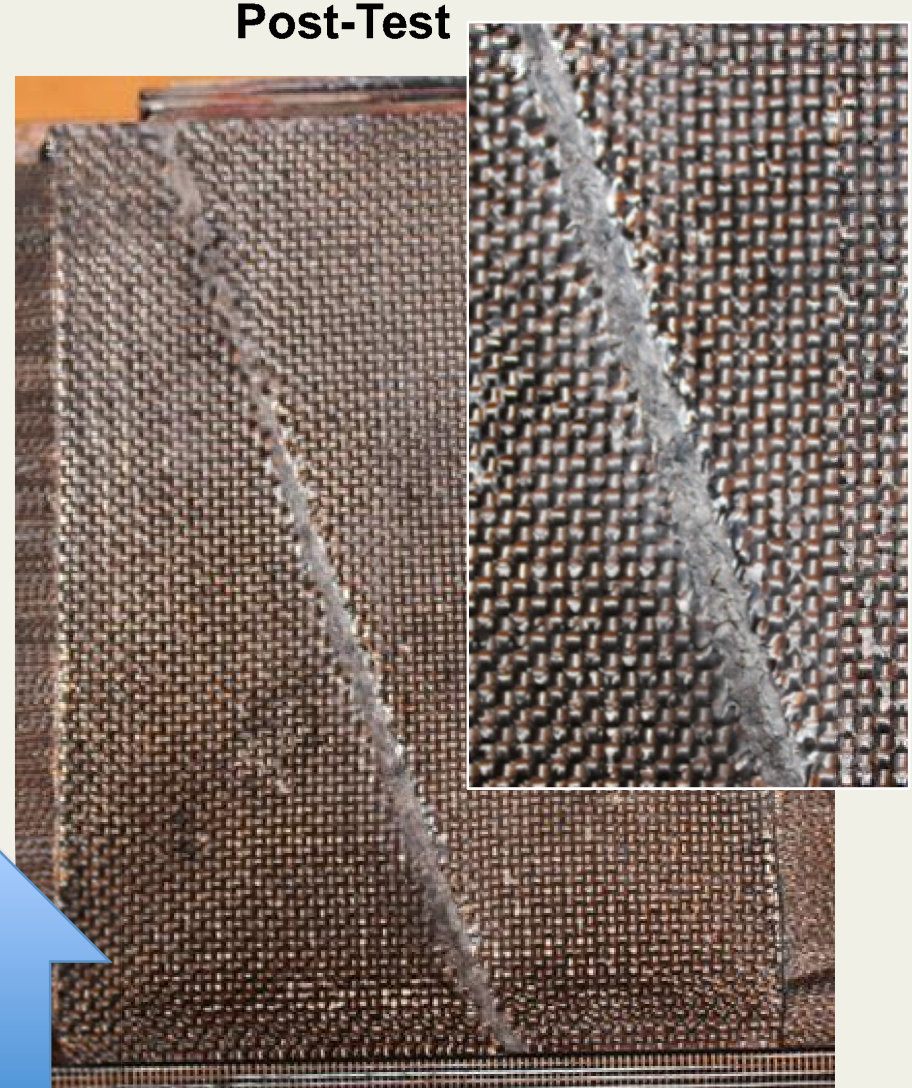




Post-Test

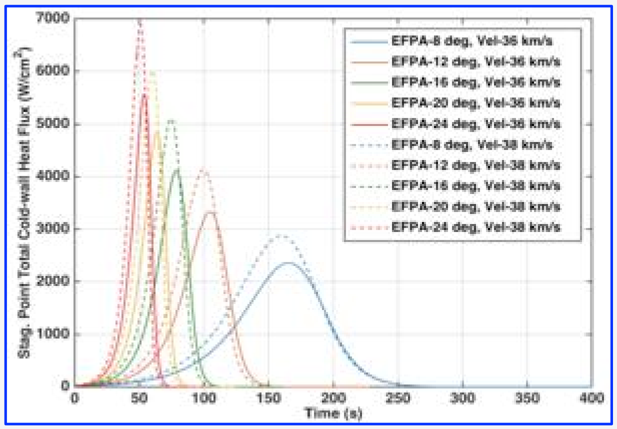
Pre-Test

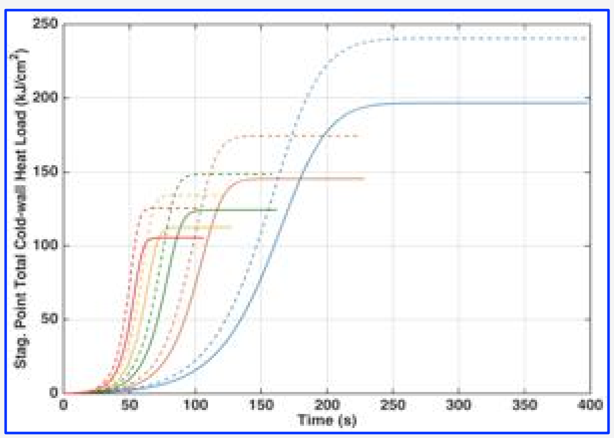
Post-Test

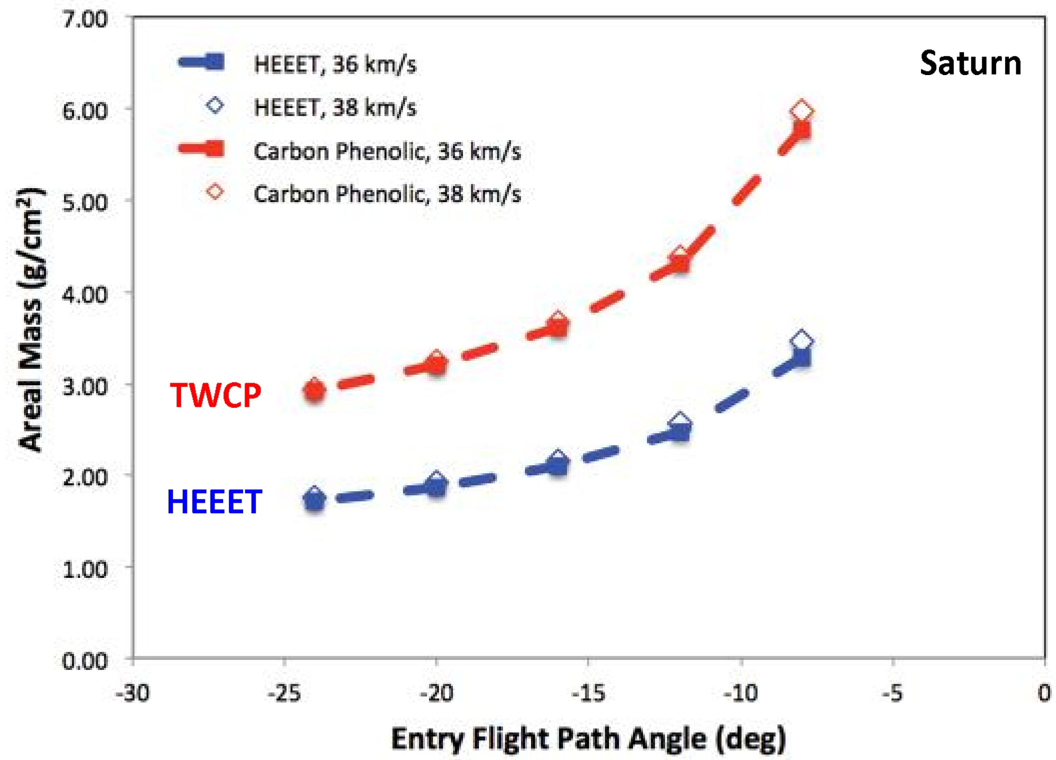


Saturn Case Study

- 200 kg, 1 meter, 45° sphere cone
- 36 & 38 km/s entry velocities
- -8° to -24° entry flight path angles
- Stag point heating analysis





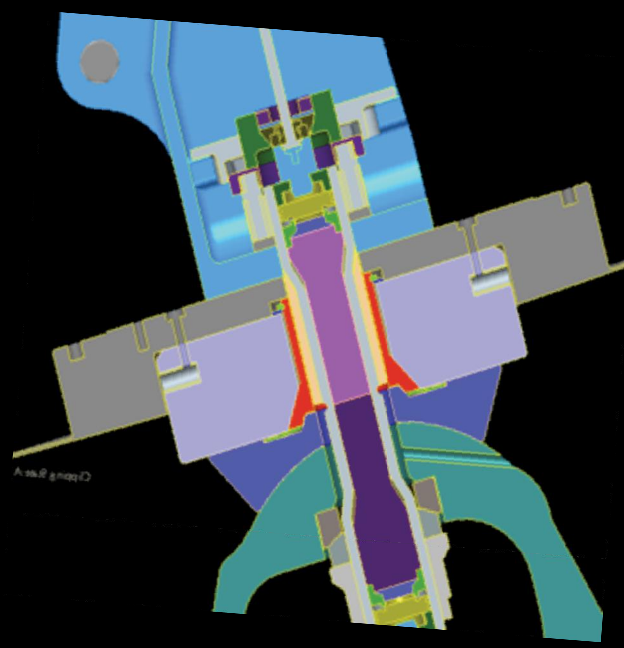


HEEET versus Traditional Carbon Phenolic

- **Areal mass for HEEET dual layer TPS is <u>~40% less</u> than that of tape-wrapped carbon phenolic**
  - Similar mass benefit for Saturn & Venus missions
- Thickness sizing results using preliminary HEEET model and heritage CP model; zero margin

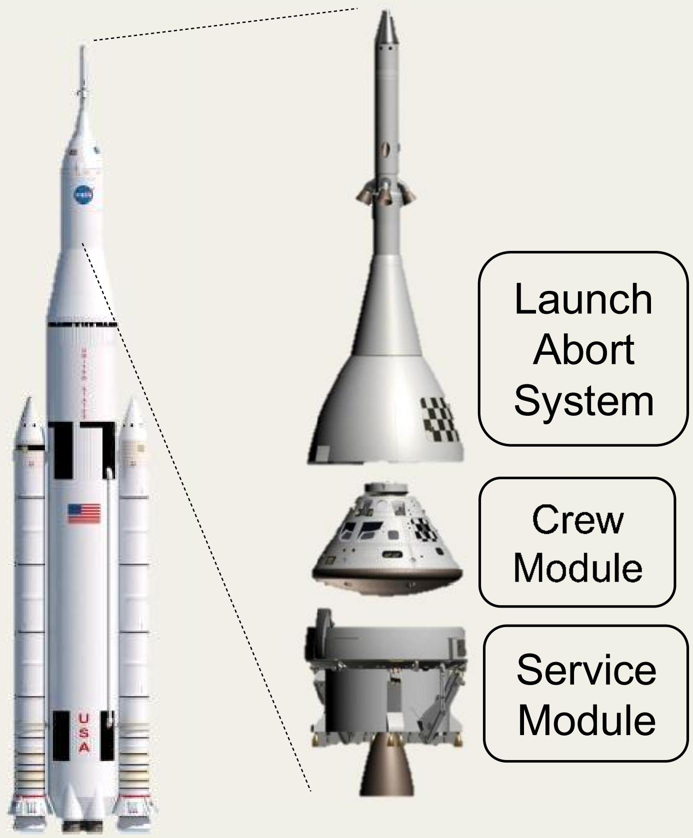
Analyses by Prahbu & Mahzari

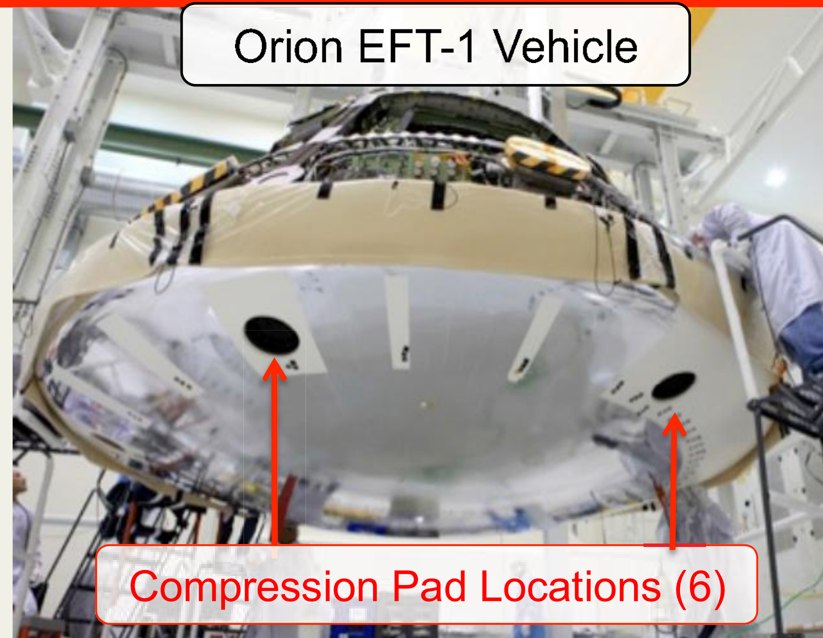
- **HEEET is leveraging the tailorability of the Woven TPS approach to design, manufacture and integrate a TPS for the extreme entry environments of future planetary probe missions**
- **A comprehensive set of requirements has been developed which is guiding design, testing & analysis**
- **Arc jet testing so far indicates that HEEET acreage material is very robust and performs as well as "heritage-like" carbon phenolic**
- **Seam design has undergone substantial progress and is expected to meet structural and aerothermal requirements**
- **Project is currently on target to mature HEEET to TRL 6 by FY17 in time for adoption by Discovery and/or New Frontiers mission proposers**



Peak Altitude: 3,600 miles
(Space Station: 220 miles)

- **Orion Multipurpose Crew Vehicle astronaut missions to Mars targeted for 2030s**
- ***Significant* technical hurdles to overcome on the path to human Mars missions!**
- **This talk will discuss one challenge we've addressed on the ablative heat shield**



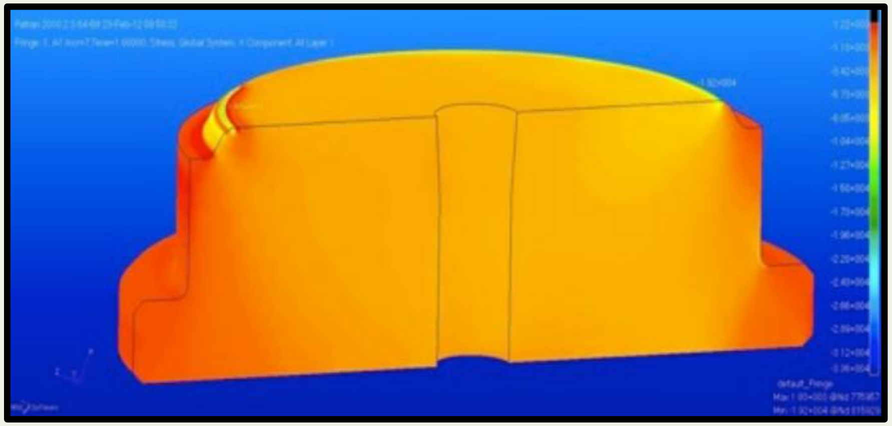


Orion EFT-1 Vehicle

Compression Pad & Explosive Bolt

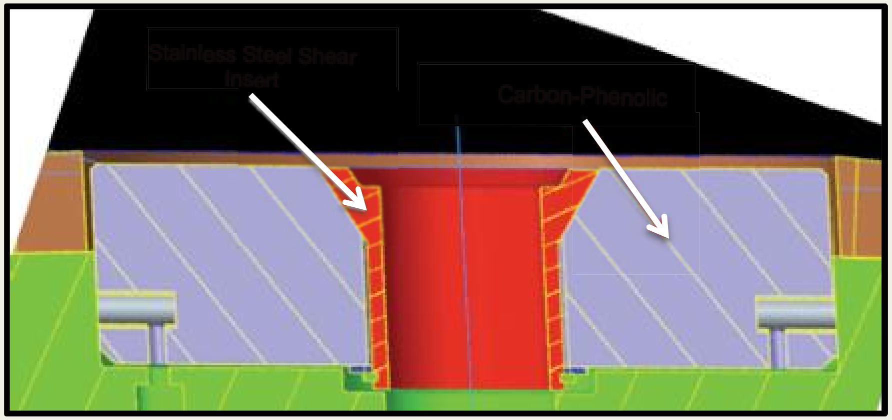
Orion compression pads are the interface between Crew Module (CM) & Service Module (SM)
Required to withstand:
- **Launch & ascent structural loads**
- **Pyro-shock (CM/SM separation event)**
- **Earth re-entry (high heating, ablation)**

Initial Pad Design: All Composite



This design failed for 2D carbon phenolic laminate: poor inter-laminar strength

EFT-1 (Earth Orbit) Only Design



Metallic insert used for first flight where entry heating was relatively low

- 2D laminates have insufficient strength to take all structural loads
- Metallic insert is problematic as it creates a thermal short, results in melt flow onto surrounding materials
- Future Orion missions will go beyond Earth orbit & have significantly higher heating compared to EFT-1 flight
- A robust 3D composite would eliminate the need for the metallic insert

- **A variety of 3D weave architectures & compositions combined with 3 different resin systems were initially produced, tested & assessed against**

Fiber(s)	Quartz	Carbon	Carbon	Carbon	X/Y: Carbon Z: Quartz
Weave	3D Orthogonal	Layer-to-Layer	3D Ortho.	3D Ortho.	3D Ortho.
Z-loading	33%	5-10%	16%	33%	16%
Resin	Phenolic, Cyanate Ester, Polyimide	Phenolic	Phenolic	Phenolic	Phenolic
Structural Performance	Good	Poor	Fair	TBD	TBD
Thermal Performance	Good	Poor	Fails	Fails	TBD

<u>Orion requirements drove material selections:</u>

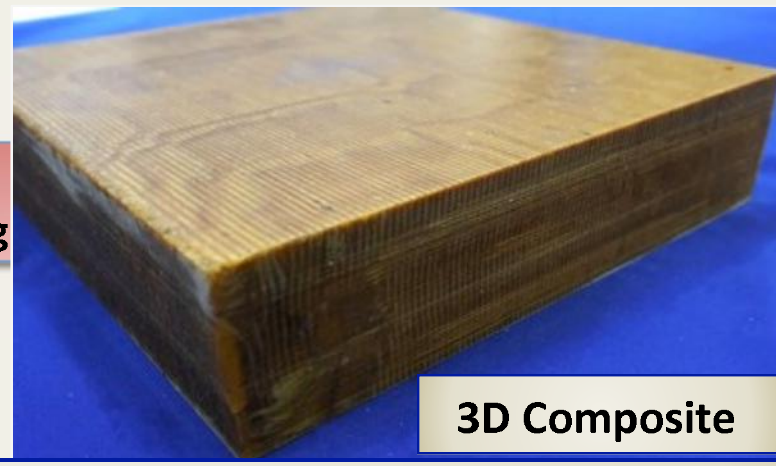
- **3D orthogonal weave, high fiber volume (57%):** ***structural robustness***
- **Fused quartz fiber:** ***high temperature capability with low thermal conductivity***
- **Low viscosity cyanate ester resin system infused via resin transfer molding (RTM):** ***full densification of large 3D preforms***

Quartz Yarn

3D Weaving

3D Preform

Resin Infusion



3D Composite

Final Machining

<u>Significant challenges</u>:

1) Scaling up manufacturing well beyond SoA
2) Making these processes robust enough for flight hardware
3) Doing the development on an aggressive schedule to support flight

- **First ever achievement of continuous, automated weaving at 13"x 12" x 3" scale**
  - 57% fiber volume, 1/3 of fibers in X/Y/Z directions
  - Cross-section scale up by a factor of 4 was challenging!

photo: Ken Kremer

Cyanate Ester Resin Transfer Molding with San Diego Composites

- **Resin infusion & *full densification (<2% porosity)* of 3" thick preforms was not established**
- **Resin Transfer Molding (RTM) is widely used for full densification of thin (typically <0.25") composites**
- **5 separate approaches failed before we developed this RTM process with San Diego Composites**

3D-MAT developed an RTM process for large scale preforms yielding billets with low porosity

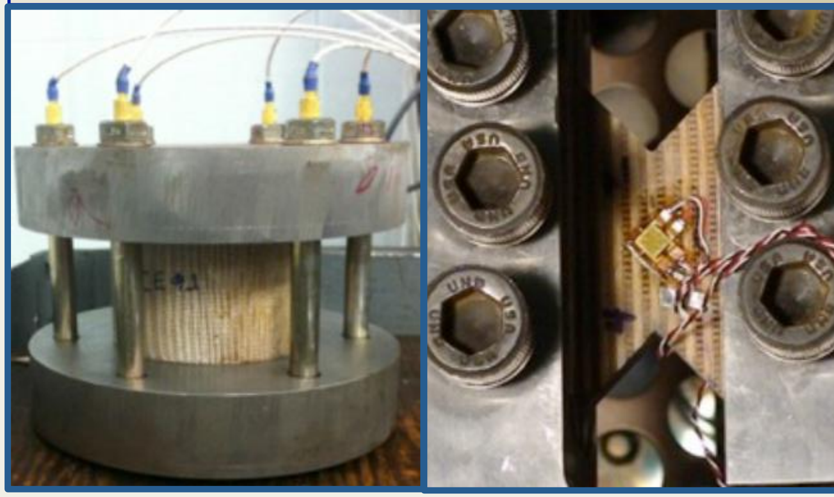
Material Property Testing:

Full suite for thermal & structural model development

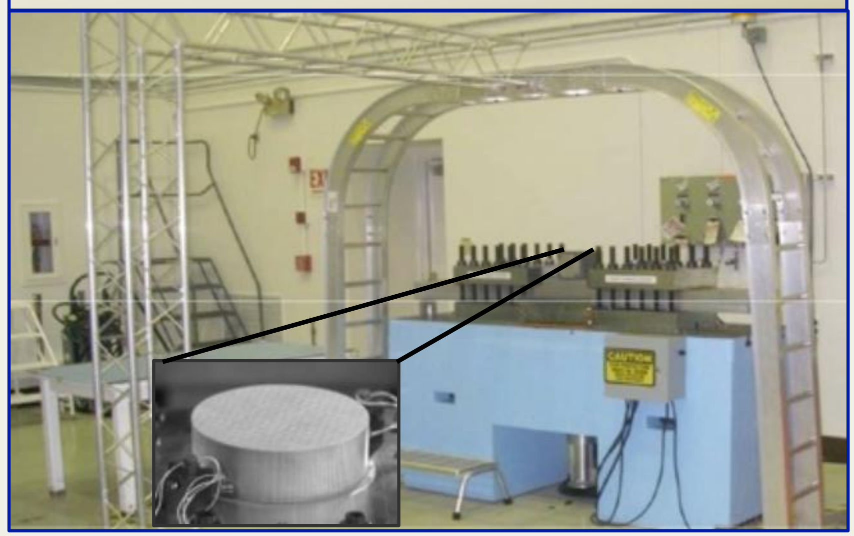
Compressive Strength On-axis (X,Y,Z)	140%
Tensile Strength Interlayer (Z) In-Plane (X/Y)	900% 245%
Thermal Conductivity Interlayer (Z) In-Plane (X/Y)	75% 55%

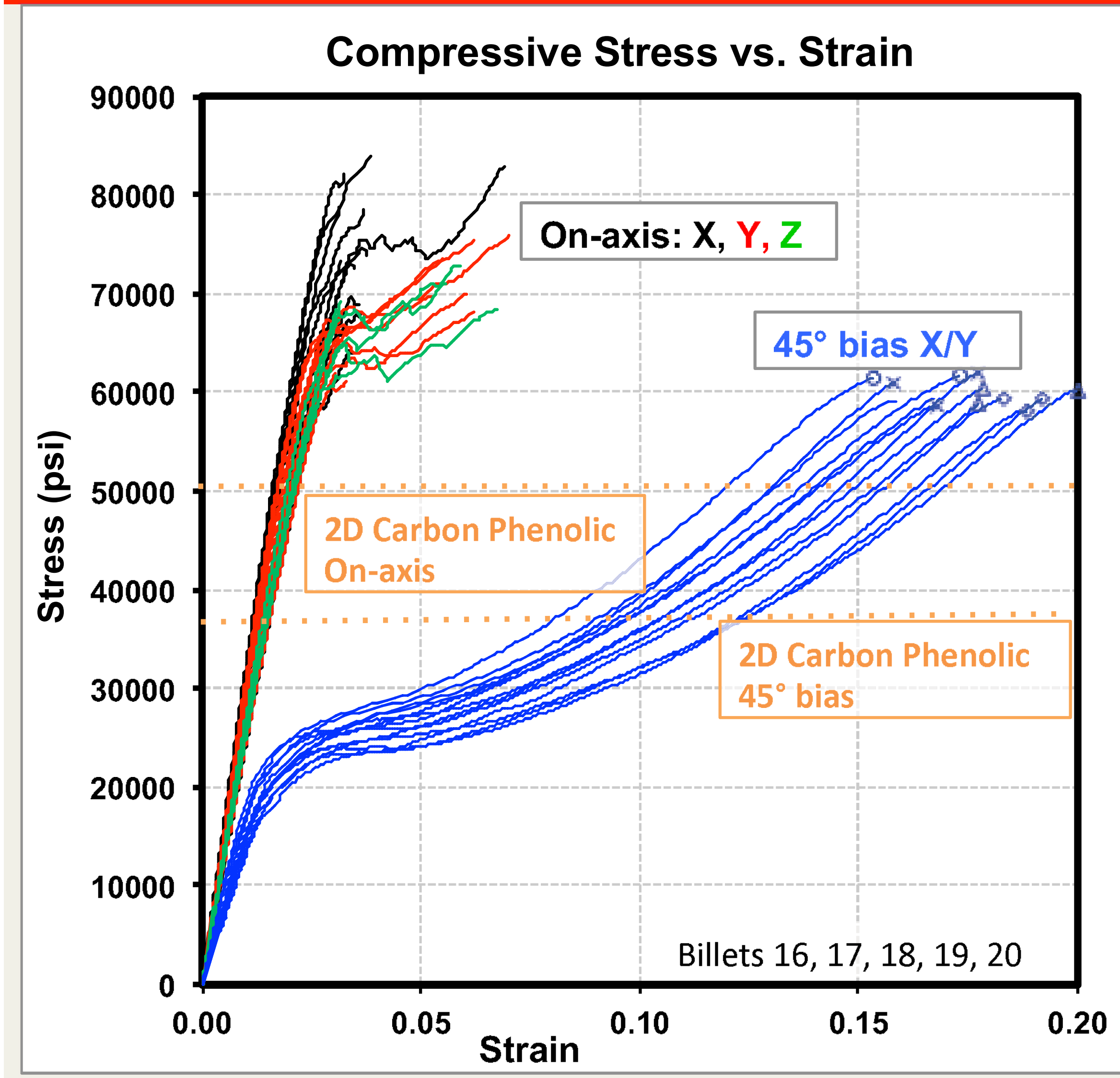
Significantly enhanced properties compared to EFT-1 compression pad material

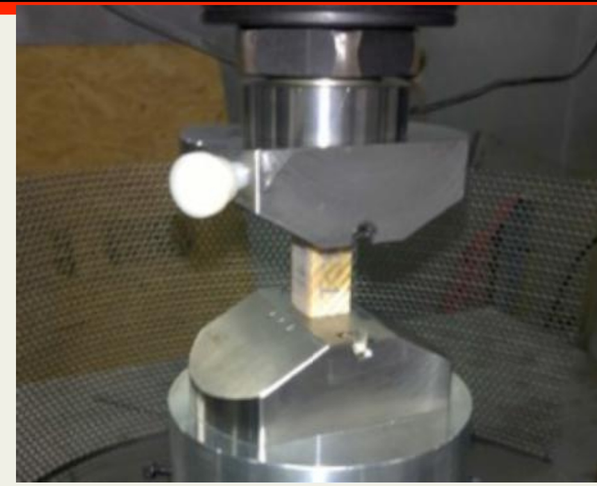
Structural Testing

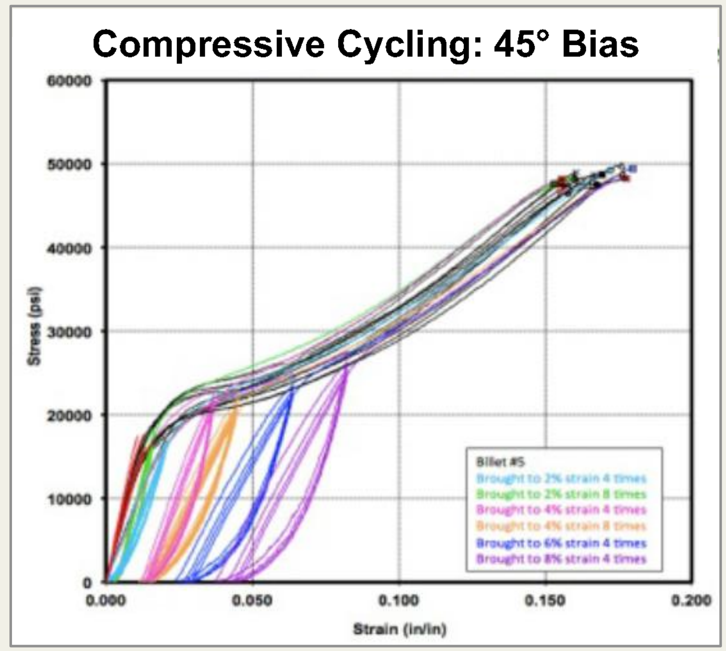


Pyroshock Simulation









Very robust compressive performance!

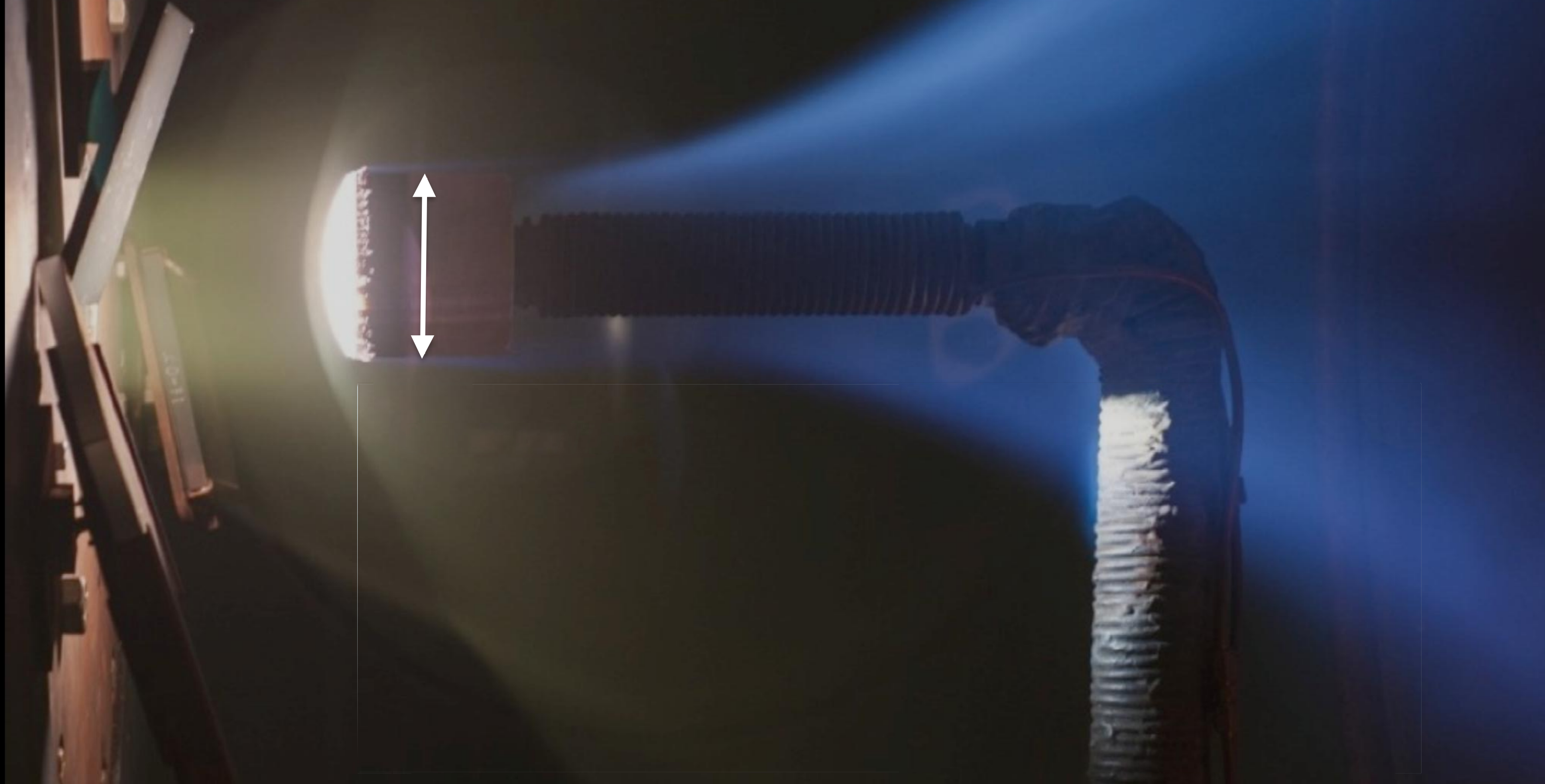
Conditions Tested in 20 MW TP3 Facility

Heat Flux: 140 – 660 W/cm^2 (Shuttle: 6 – 60 W/cm^2)

Pressure: 3 – 55 kPa

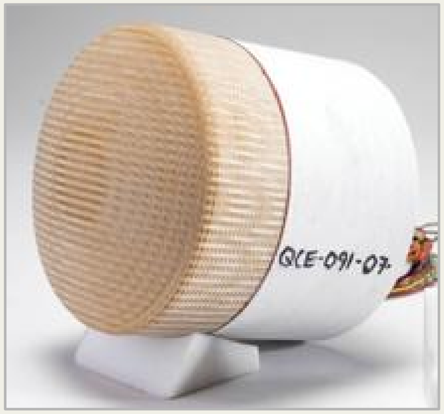
Duration: 60 – 200 s

Max Surface Temp: 1550 – 2400 °C



Sting 5: QCE-091-10-PC

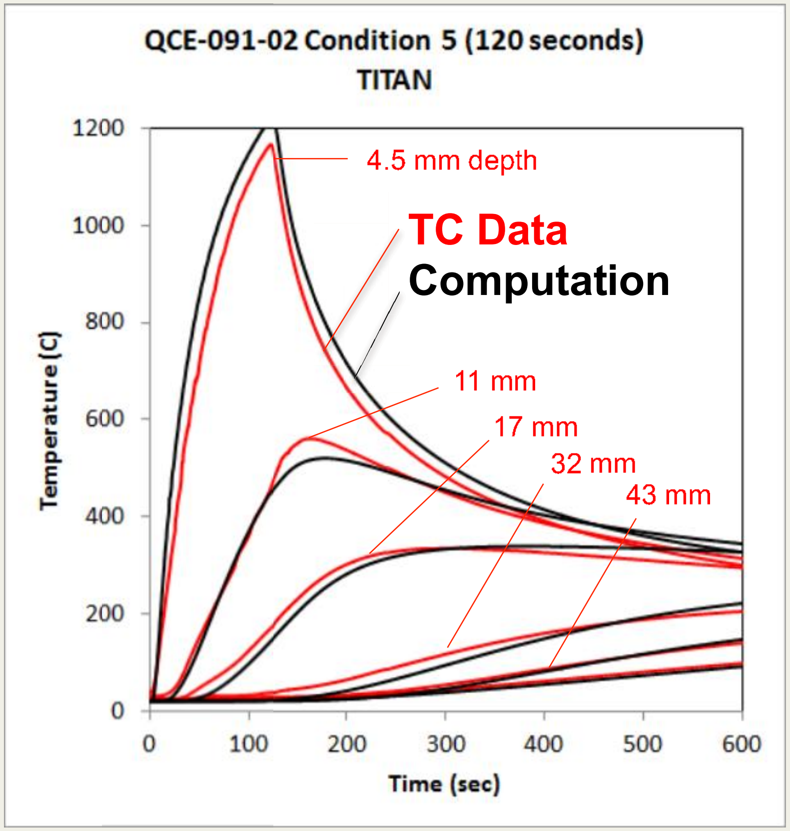
Pre-test



Post-test

Post-Test Cross-Sectioned

Thermal Response Modeling

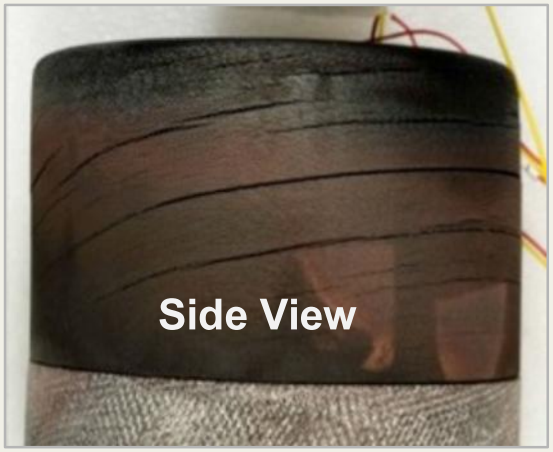


Ablation chemistry & property-based thermal response model predicts the temperature as a function of depth & time (thermocouples at various depths)

Arc jet testing of 3DMAT revealed no failure modes whereas carbon phenolic consistently cracks between lamina

Post-test 3DMAT

Post-test 2D CP



All EFT-1 carbon phenolic pads contained inter-laminar cracks post-flight

- **3DMAT project addressed a material capability need for Orion by developing a 3D woven quartz fiber / cyanate ester composite with robust structural and aerothermal performance**
  - Continuous, automated weaving the high fiber volume quartz preform has been achieved at a scale never before demonstrated (12” wide x 3” thick)
  - Full densification of large preforms has been accomplished with a new resin transfer molding process
- **TRL 4/5 achieved in 3 years via manufacturing development & testing**
- **Orion Program recently produced 31 billets for EM-1 flight and development (2018 lunar flight test)**
  - Based on the superior thermal/structural properties of 3D-MAT, Orion is now planning to use this material in various parts of the vehicle back-shell
- **3DMAT development team is working with other aerospace companies for whom the 3DMAT material may fulfill a critical need**

- NASA's Space Technology Mission Directorate has invested in 3D Woven TPS development as a promising technology to enable a variety of mission-tailored TPS solutions with improved sustainability and life cycle cost compared to many traditional NASA TPS materials

- HEEET is developing a mass-efficient, dual-layer carbon/phenolic system tailored for planetary probe missions and will deliver the system at TRL 6 in FY17 for potential Discovery and New Frontiers class missions

- 3D-MAT has developed a structurally robust quartz / cyanate ester composite to meet the needs of the Orion Exploration Mission compression pad and will begin flying in 2018

Acknowledgments – 3DMAT

Special Thanks

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  - Adam Beerman
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  - Milad Mahzari
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- **Science and Technology Corp:**
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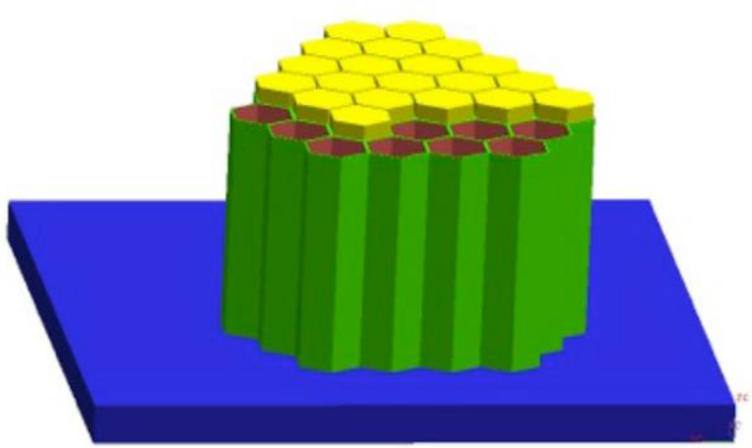
  - Stewart Walker
- **NASA JSC:**
  - Mike Fowler
- **NASA ARC, AEDC, LaRC and LHMEL test facilities and their crews**

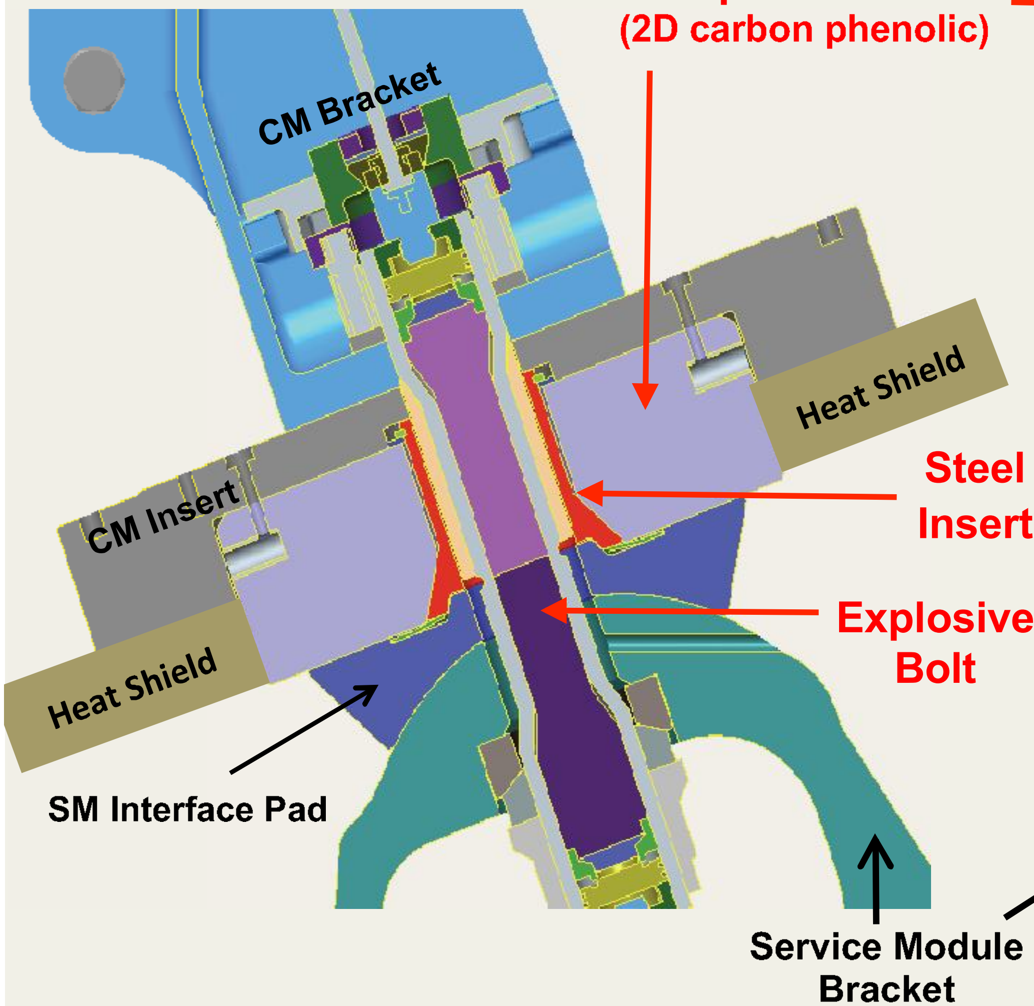
end

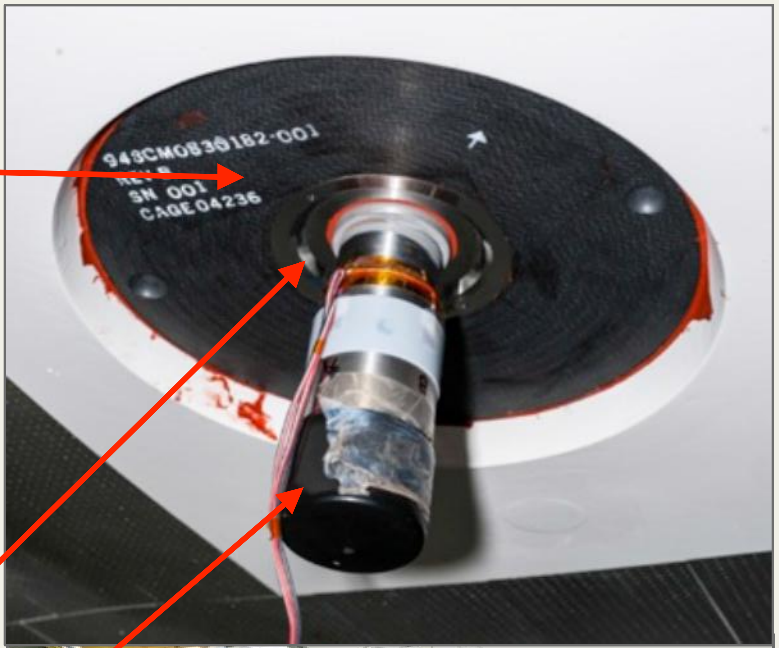
- **TPS materials typically have no other government or commercial applications**
- **TPS materials tend to use unique manufacturing processes and specialized ingredients**
  - Given that entry probe missions are infrequent, NASA is burdened with the cost of maintaining capability or the risks of restarting it
  - Example: Avcoat for Orion/MPCV

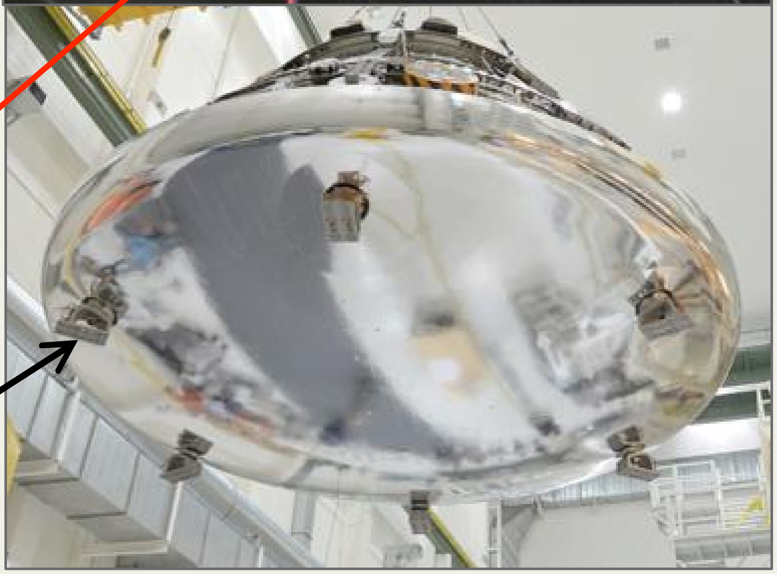
Hand-Filled Honeycomb



Retention & Release Mechanism

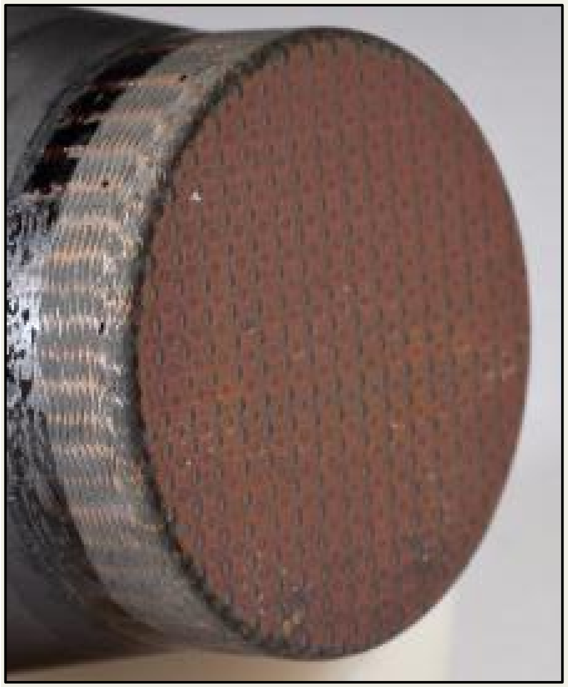




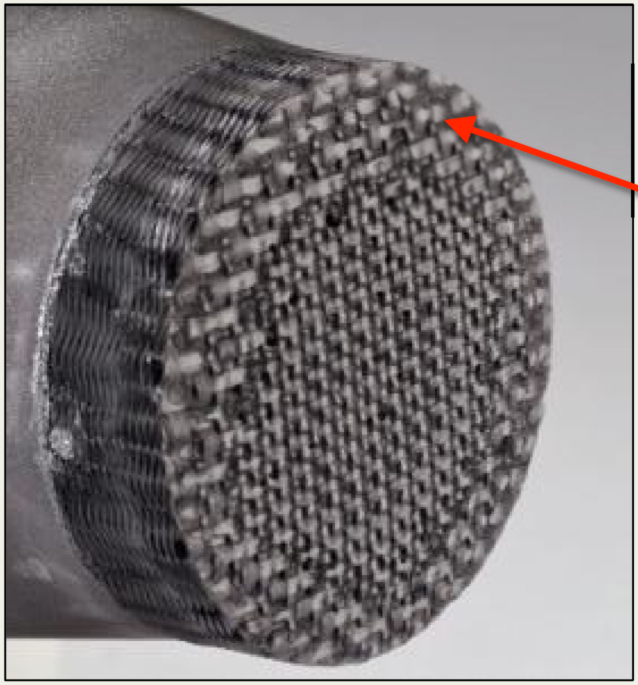


- Fine weave at top for surface-roughness control
- Coarse weave below ablation zone for more efficient weaving

Pre-Test



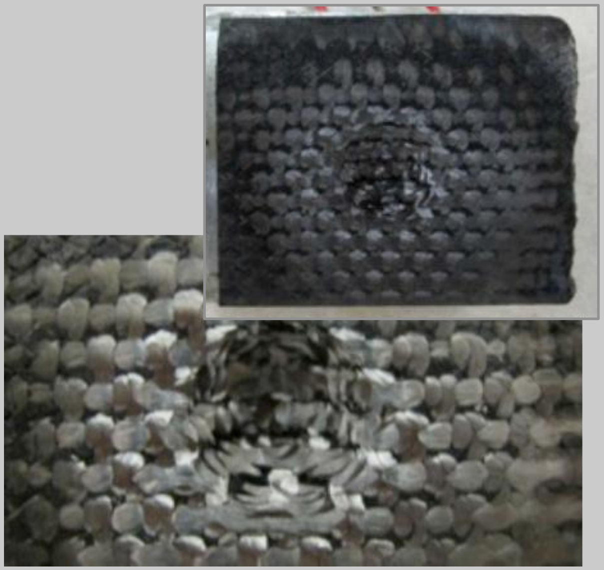
Post-Test



- Model edge condition was more severe
- Higher ablation exposed coarse weave at edges
- No failure associated with ablating through transition layer

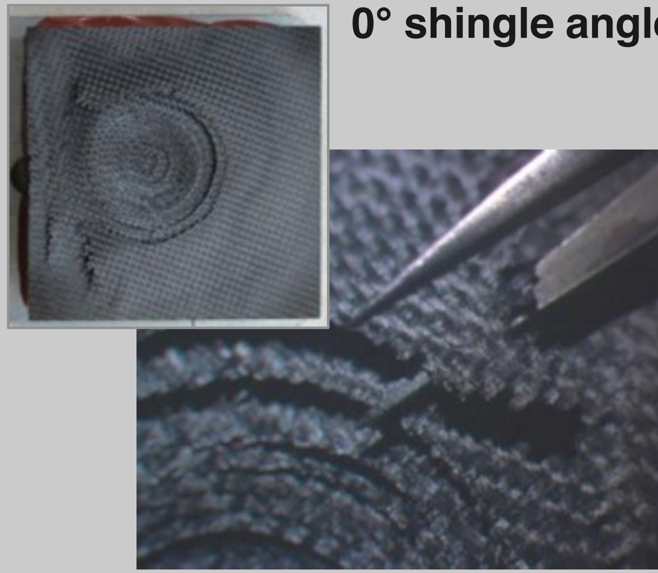
Testing in mini-Arc Jet

3D Woven TPS



2D Laminate Carbon Phenolic

0° shingle angle

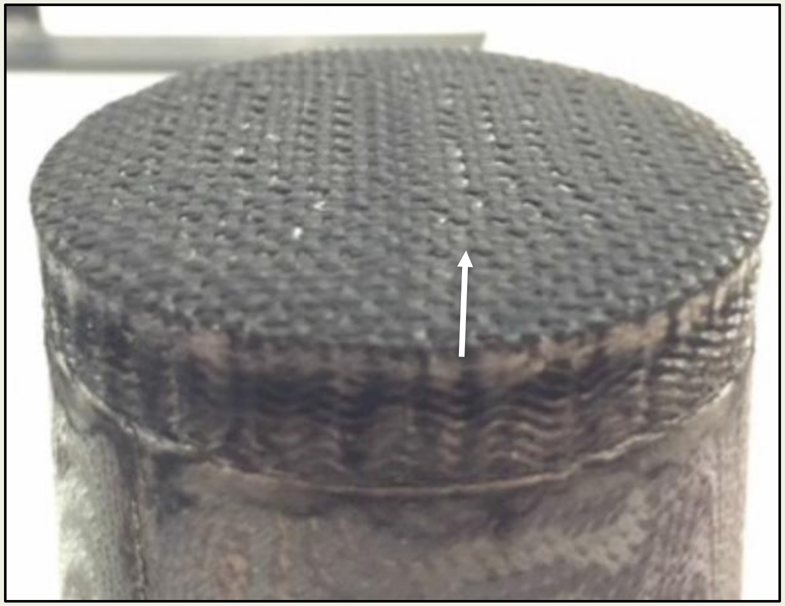


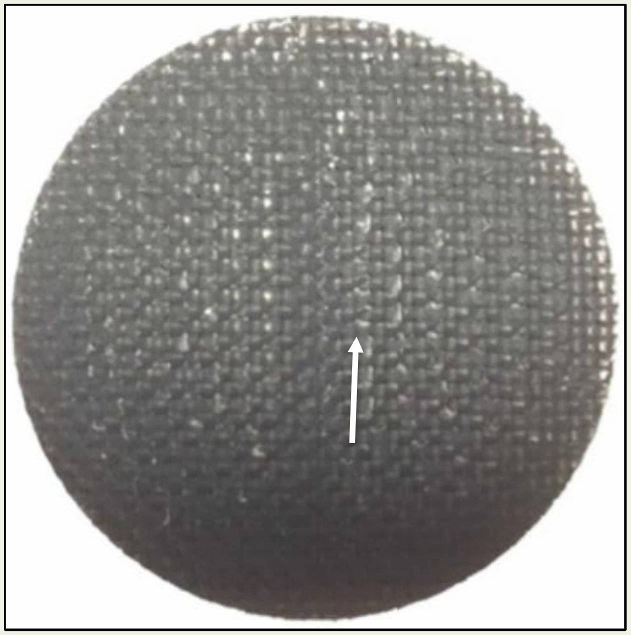
AEDC Wedge: 2D CP Cracking

- **2D CP (laminate or tape wrapped) exhibits ply separation in a simple demonstration test performed at NASA Ames**
  - **Similar behavior observed in the AEDC wedge testing**
- **As a 3D material, Woven TPS is not prone this failure mode**

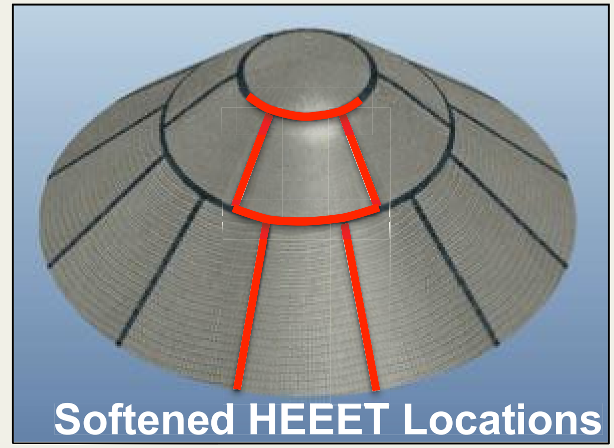

Sting 5: QCE-091-05-PC

- **Testing performed in IHF 6" nozzle at the following conditions:**
  - Heat Flux: 1,850 W/cm^2
  - Pressure: 1.3 atm
  - Shear: 0Pa (~2000 Pa at model edge)
  - Time: 15 seconds
- **Model below is a thin Adhesive.**
  - Representative of targeted seam adhesive thickness
  - Very uniform recession: "Aerothermally Monolithic"

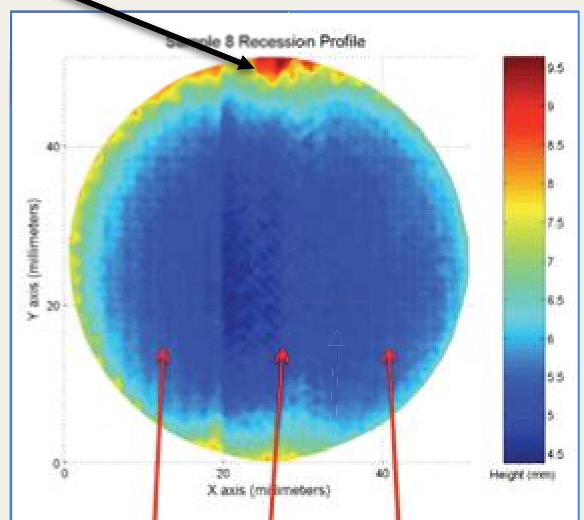




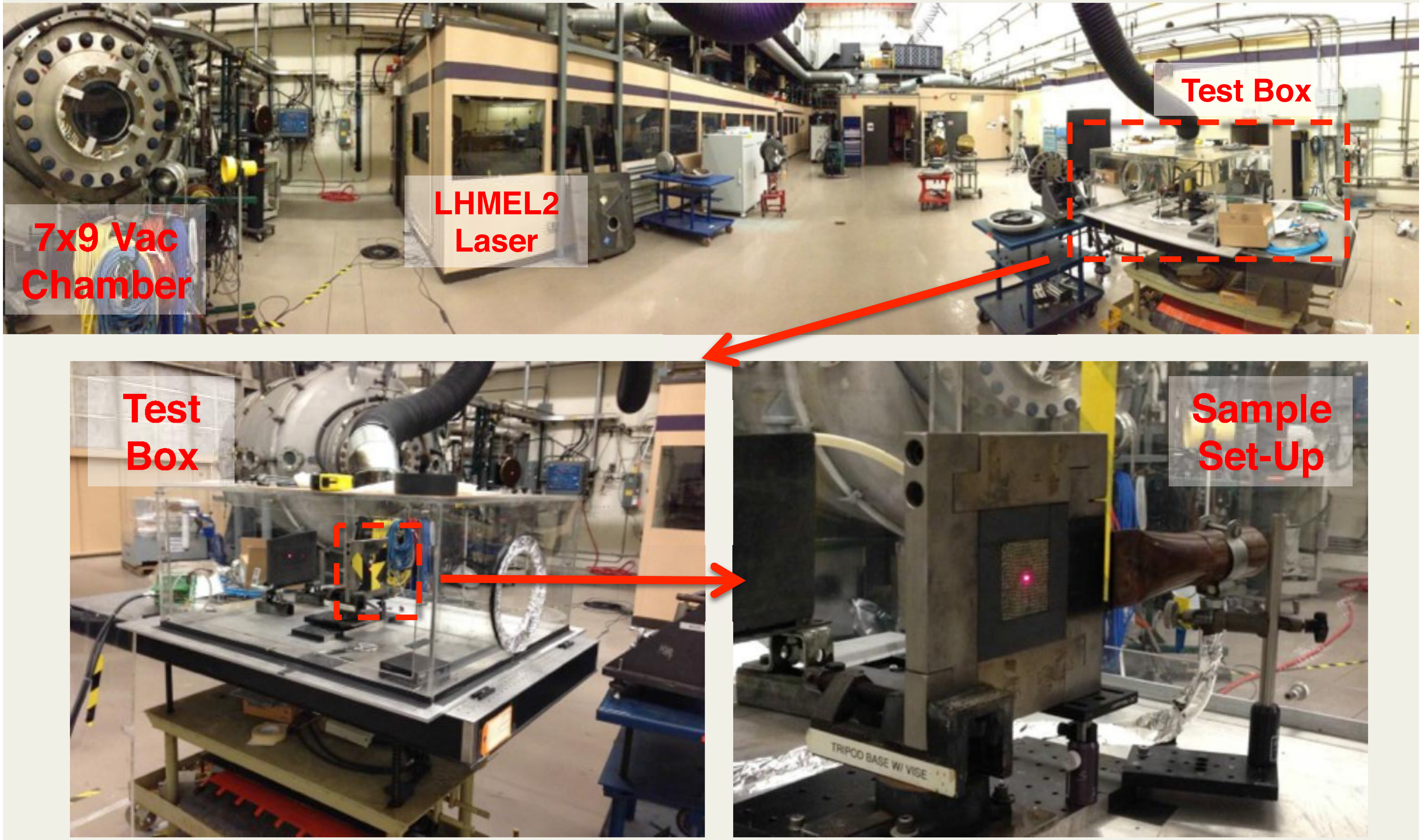
- **IHF 6” nozzle at the following conditions:**
  - Heat Flux: 1,850 W/cm^2
  - Pressure: 1.3 atm
  - Shear: 0Pa (~2000 Pa at model edge)
  - Time: 15 seconds
- **Model below is a Softened HEEET test specimen.**
  - Edge effects are believed to be a test artifact



Softened HEEET Test Specimen



Recession Measurements


7x9 Vac Chamber
LHMEL2 Laser
Test Box
Test Box
Sample Set-Up
TRIPOD BASE W/ VISE

Given:

– the lack of qualified ablative TPS for probe missions

– the challenges of sustainability, affordability, & TPS optimization

We sought to explore 3D weaving as an approach for making efficient & tailorable TPS materials that are sustainable & thereby more affordable than heritage materials

- **Aerothermal test campaign spans four facilities and 12+ conditions**
- **Test range:**

Heat Flux (W/cm^2)	Pressure (atm)	Shear (Pa)
250 - 8000	0 – 14 atm	0 - 4000

- **Test Objectives:**
  - Test acreage & seam material to guide architecture down-select & verify requirements
  - Demonstrate performance under high heat flux, pressure and shear environments for relevant Venus &/or Saturn mission profiles (look for failure modes)
  - Develop a thermal response model for mission proposers use in TPS sizing & analysis
- **Facilities:**
  - IHF @ NASA Ames
  - AHF @ NASA Ames
  - AEDC H3 @ Arnold Engineering Development Complex / Arnold AFB
  - LHMEL 2 @ Laser Hardened Materials Evaluation Lab / Wright Patterson AFB

Acreage (Post-test)

Seam (Post-test)

- **Successfully demonstrated high-pressure capability of HEEET**
- **Acreage shows uniform recession and robust insulating layer**
  - **Post-test, model continued to burn before N2 quench resulting in some frayed and charred fibers**
  - **Video of the model in the flow does not show any frayed tows**

Thermal	Compression pad to Avcoat/carrier-structure interface shall maintain positive margin against the 500 °F maximum bondline temperature
Structural	Compression pad shall carry compression moment & shear loads
Structural	Tension tie shall maintain preload with losses due to creep & joint relaxation
Structural	Compression pad shall thermally function after exposure to the separation bolt pyro-shock event
Size	Pad material shall be manufacturable to at least 3” thickness by 11” diameter

Project Challenges

- **Aggressive schedule to develop in time for Orion PDR (2015) & EM-1 flight (2018)**
  - 2012 3DMAT project start date
- **Weaving & resin infusion process development to meet size requirement**
  - Scale up = challenging!
  - Multiple process refinements needed during development