The State of the Art: Ablative Thermal Protection Systems

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NASA Ames Research Center

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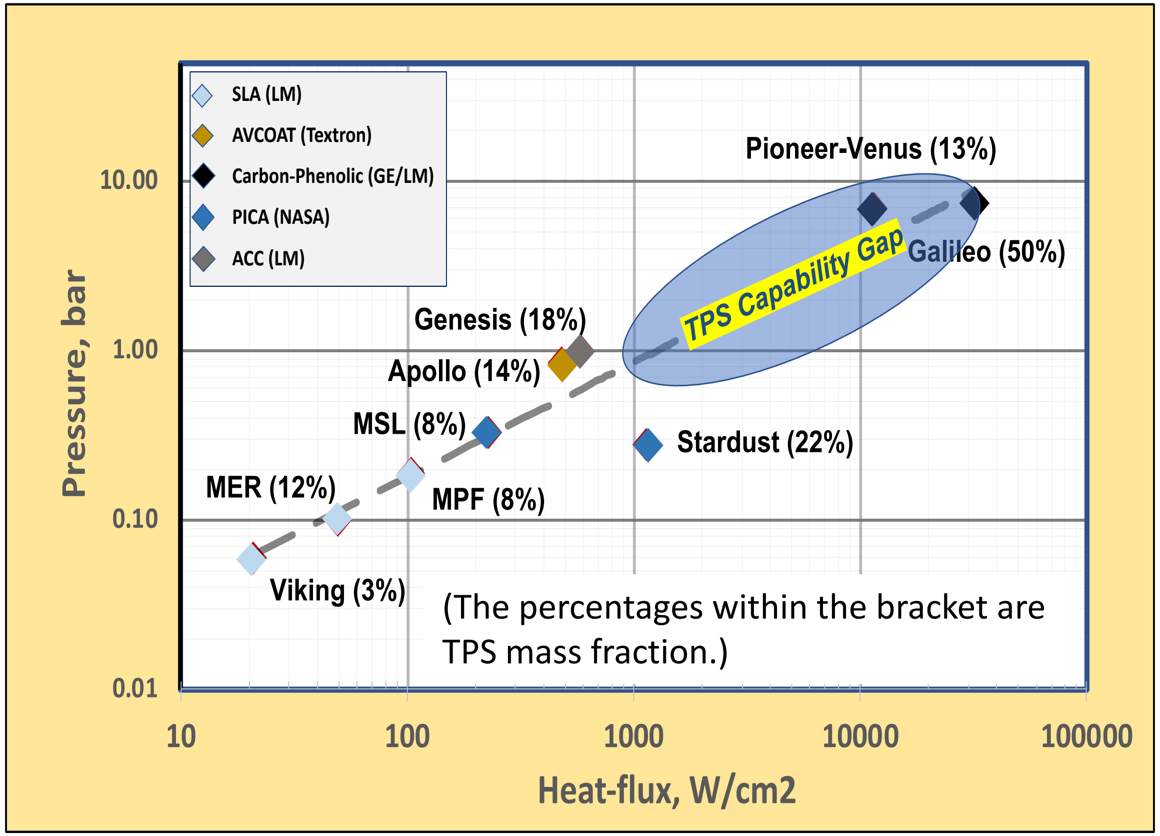
Ablator Microstructures/Architectures

- Honeycomb Reinforced Materials
  - Avcoat, SLA-561V, SRAMs, Phencarbs, BLA, BPA, etc…
- Resin Infiltrated Preforms
  - SIRCA, PICA, conformal PICA
- Dual Layer Materials (not integrally woven)
  - Carbon/Carbon-FiberForm (Genesis)
  - 3-Dimensional Quartz Phenolic HD/LD
- Continuous Fiber Composite Materials (laminated)
  - Uncoated Carbon/Carbon, Carbon/Phenolic (Tape Wrapped), Silica/Phenolic (Tape Wrapped)
- Monolithic Plastics
  - Teflon, etc…
- 3-D Wovens
  - Ablative and structural (3D-MAT)
  - Single to Multi layer integrally woven layers (HEEET and 3MDCP)
  - 3-D C-C
- Others:
  - Chop Molded Carbon/Phenolic
  - Sprayable SLA
  - Syntactic foams (Acusil)
  - Block Avcoat

- What is the inherent microstructure/architecture of SOA TPS ablators that make them suitable for certain entry environments?
- Is the process partially automated/controlled?



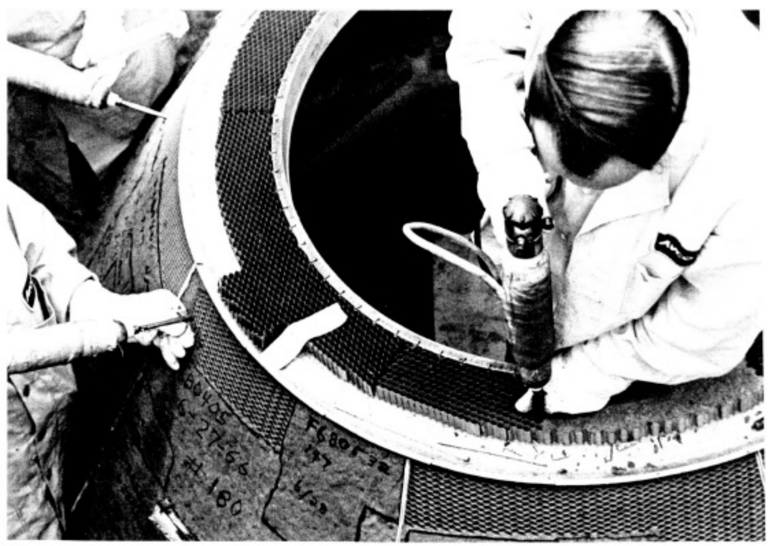
Honeycomb Reinforced Materials

Honeycomb Benefits
- Stabilizes the char, preventing/reducing char spallation
- Monolithic approach
- Provides a method to verify bond to carrier structure

Honeycomb
- Composition: Silica/Ph, Glass/Ph, Carbon/Ph
- Cell Shape: Hexagonal, Flexcore,
- Cell Size
- Cell Wall Thickness

Resins
- Phenolic Resins: Higher Heat Fluxes
  - PhenCarbs (ARA), Boeing Phenolic Ablator (BPA
- Epoxy / phenolic Resins: Higher Heat Fluxes
  - Avcoat (Textron: Apollo)
- Silicone Resins: Lower Heat Fluxes
  - Super Lightweight Ablator (LM), SRAMs (ARA), Boeing Lightweight Ablator (Boeing)

Fillers
- Microballoons: Silica/Glass and Phenolic
- Fibers: Silica/Glass, Ceramic and Carbon
- Others: Cork, etc…



AVCO technicians injecting ablator into honeycomb (Apollo command module had 300,000 cells)

Manufacturing Techniques:
- Hand Packing
- Hand Injecting (Avcoat)
  - Caulking gun
- Press Ablator Preform into Honeycomb (or vice versa)
  - Vacuum bagging or closed die molding

Features leading to flaws (potentially)
- Touch labor leading to density variability
- Separation at ablator to H/C interface

Honeycomb Reinforced Materials

Comparing Compositions of SLA-561V and BLA

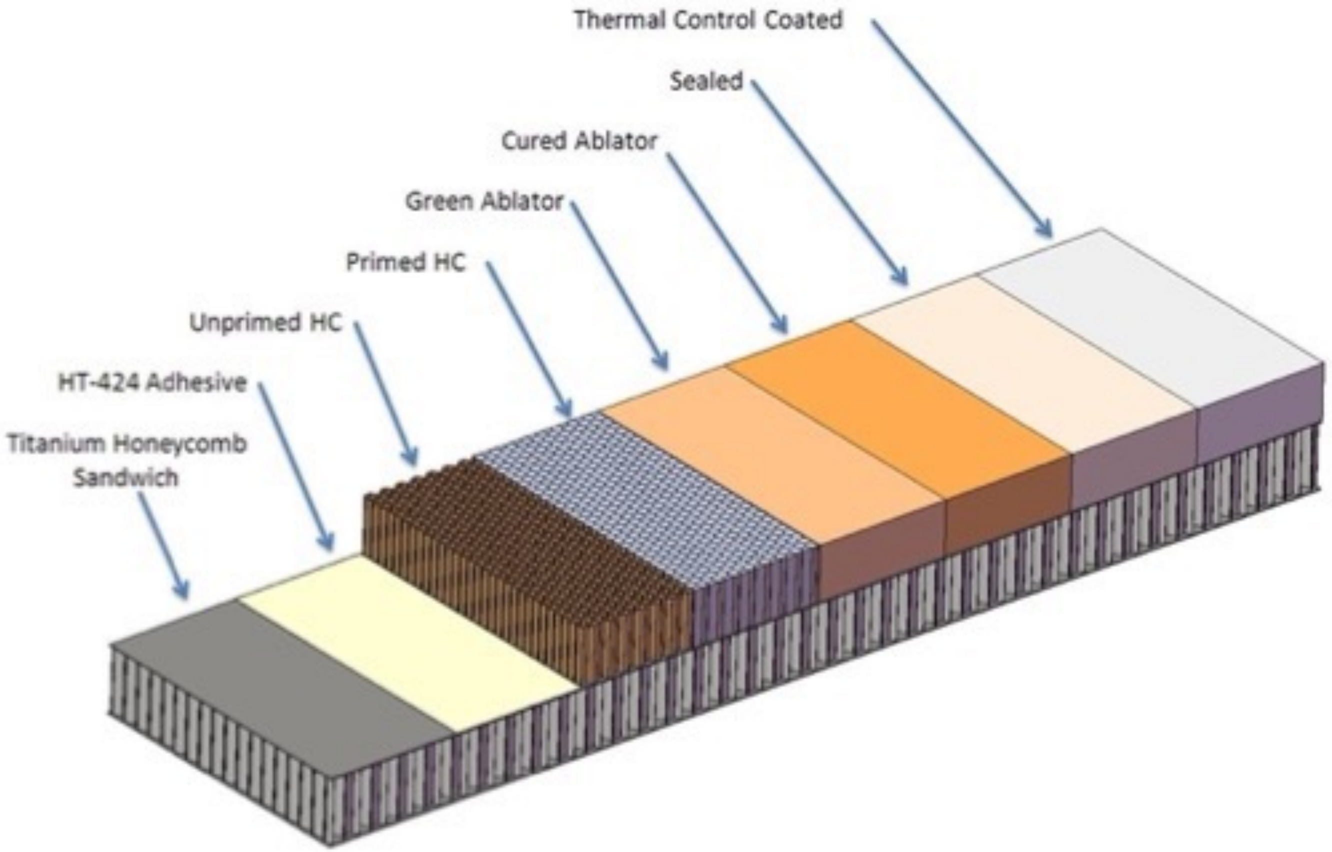
Material	Composition (Mass Fractions %)	Composition (Volume Fractions %)	Density (g/cc)
SLA-561 (LM, US Patent 4,031,059)	25 Silicone Resin 3 Silica Fibers 2 Carbon Fibers 35 Silica Microballoons 6 Phenolic Microballoons 29 Cork	5.5 Silicone Resin 0.3 Silica Fibers 0.3 Carbon Fibers 43.9 Silica Microballoons 14.4 Phenolic Microballoons 35.6 Cork	0.225
BLA (Boeing Lightweight Ablator, US Patent 6,627,697)	42 Silicone Resin 38 Silica Microballoons 4 Catalyst 16 Thinning Fluid		0.32

SLA

Honeycomb Reinforced Materials

Multiple Processing Steps – Complex Integration

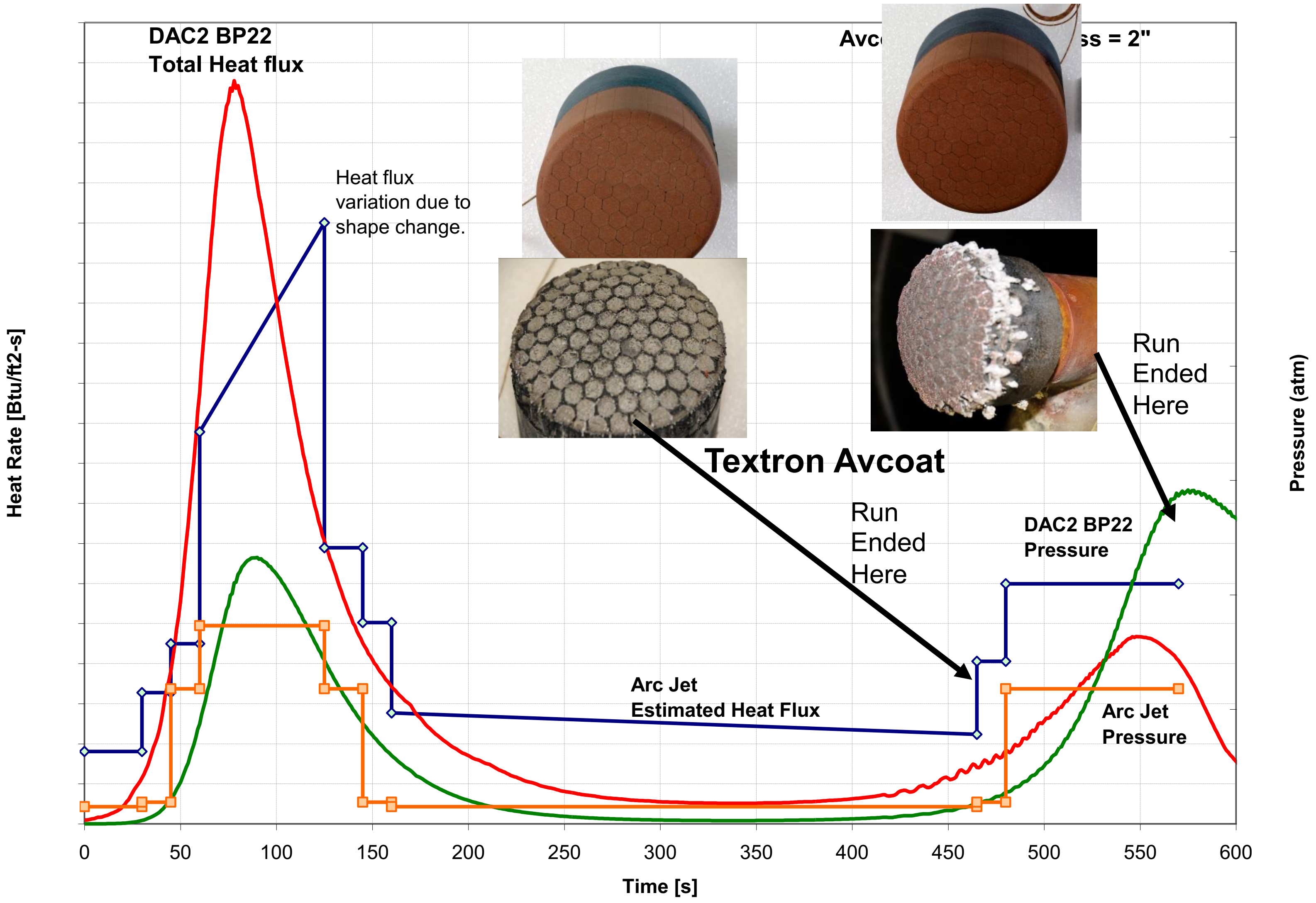
- Avcoat construction schematic showing the various steps and processes involved in building the honeycombed ablator
- Integration approach allows for bond verification of HC prior to filling
- Ablative recipe is complicated and involves several components that insulate as well as phase transition / ablate during heating pulse
- Segmented HC allows coverage of a large vehicle
- Integration approach very time consuming and subject to flaws



Nevertheless, Avcoat brought us back from the Moon successfully!

Arcjet Testing of Avcoat

- Complex recipe of material constituents resulted in varied performance at different heating conditions
- Most ablators are more effective at high heat flux / enthalpy and less effective a low heating
- Glassy component of Avcoat vaporized at high heating (effective phase transition)
- Glassy component of Avcoat melted and flowed at low heating (not effective phase transition)



Ablator Architectures

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  - Avcoat, SLA-561V, SRAMs, Phencarbs, BLA, BPA, etc…
- Resin Infiltrated Preforms
  - SIRCA, PICA, conformal PICA
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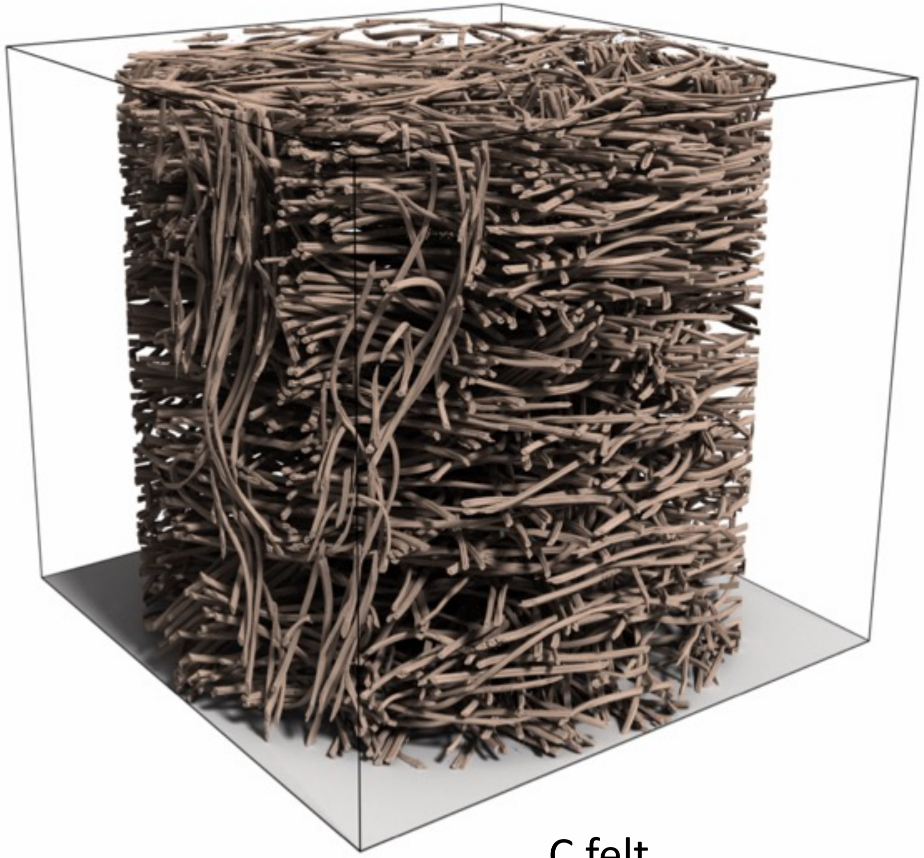


C felt

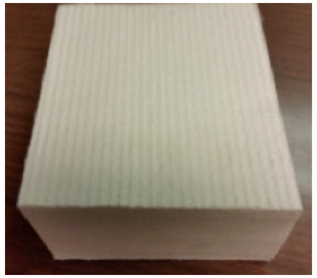
Resin Infiltrated Preforms (Low Density)

- **Begin with a porous preform (open porosity)**
  - PICA: Carbon Furnace Insulation (FiberForm)
  - SIRCA: Ceramic Shuttle Tile
  - Have some control over preform starting density and composition
- **Infiltrate with a resin**
  - PICA: Phenolic
  - SIRCA: Silicone
  - Resin is diluted in a solvent
    - Have ability to control resin to solvent ratio to control amount of resin in final product
- **Pros: Processing Flexibility**
  - Parameters that can be tailored:
    - Starting preform density (family of materials)
    - Preform to resin ratio
    - Can locally densify material with secondary application of resins
    - Resin Composition
      - Grade the resin composition within the preform from one resin composition to another
        - Phenolic at surface, lower conductivity silicone at bondline
- **Cons: Limited Part Size**
  - Starting PICA Block Size Limit: ~24” x ~42”
  - Single piece demonstrated to 1.4m max diameter (PICA)
  - Felt preforms allow more opportunity for larger block size
  - Starting SIRCA tile size ~ 12” x 12” x 6”
  - For tiled config - requires gaps between parts with development of proper gap design, gap fillers etc…
  - Verification of bond between tile and carrier structure is challenging

1.4m PICA heatshield

Extended single piece heatshield manufacturing demonstrated recently

PICA Manufacturing Overview



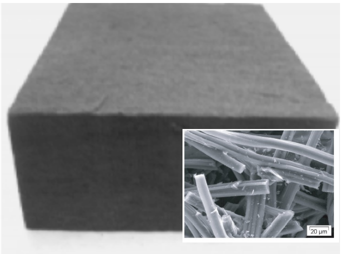
Rayon or Lyocell

Sustainability concern

Conversion to carbon

Near net shape preform

Single piece PICA heatshield (< 1.25m max diameter)



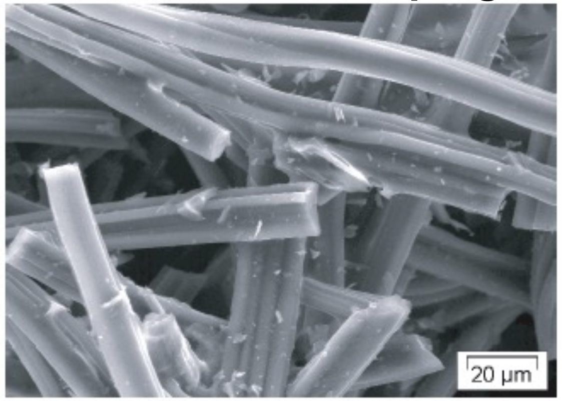
FiberForm® billet preform

Tiled PICA heat shield (> 1.25m max diameter)

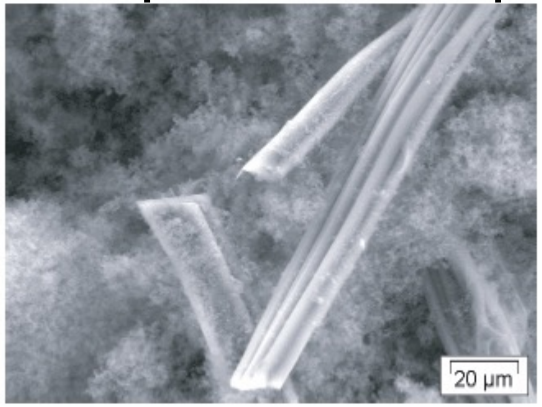
- Chopped, graphitized rayon or Lyocell - based carbon fiber slurry-cast into either block (billet) or single piece heatshield preforms
- Single piece cast heatshields have fiber oriented to optimize through-thickness thermal conductivity
- Lightweight phenolic sol-gel matrix is infiltrated into preform

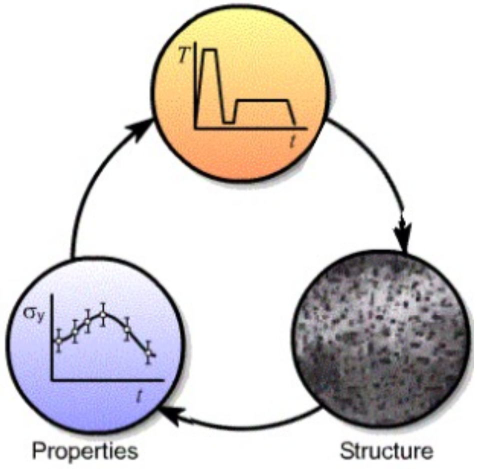
Importance of Microstructure
Importance of Gap Filler Compatibility

Fiberform before impregnation



PICA with phenolic resin impregnated





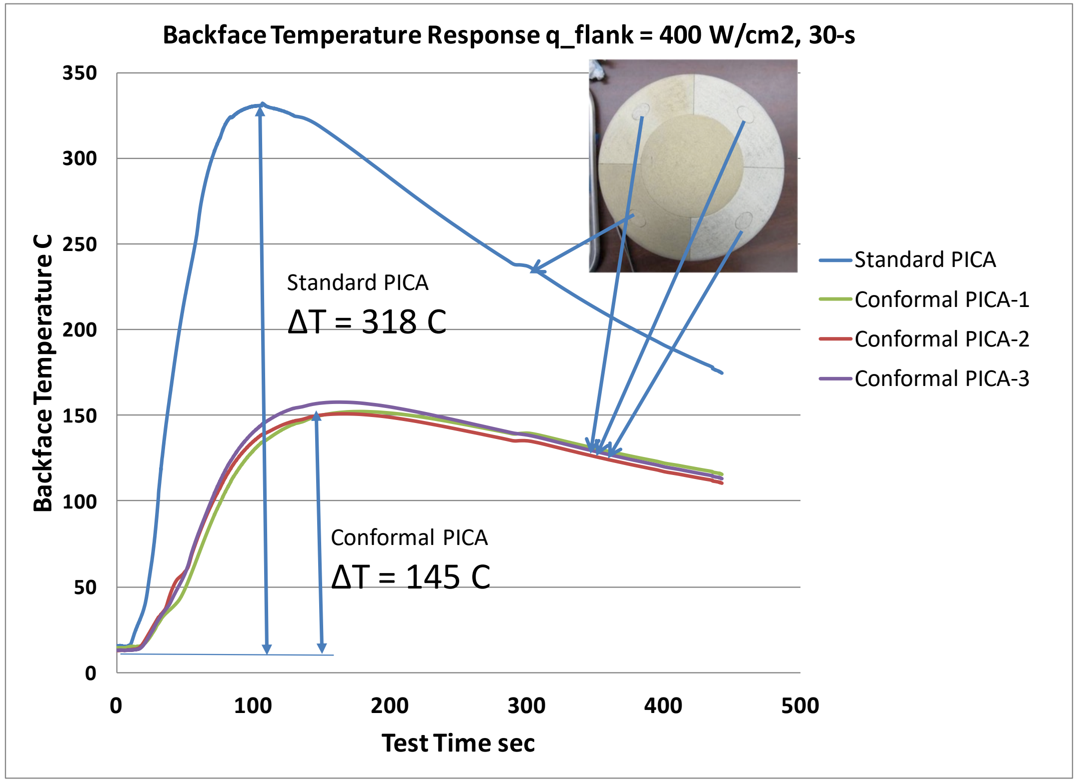
What happens when the phenolic resin is not present in PICA

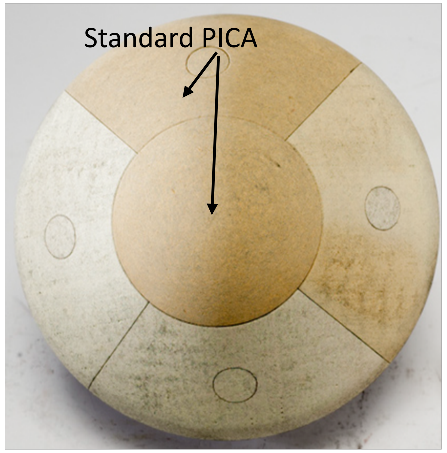
Tunneling failure mode

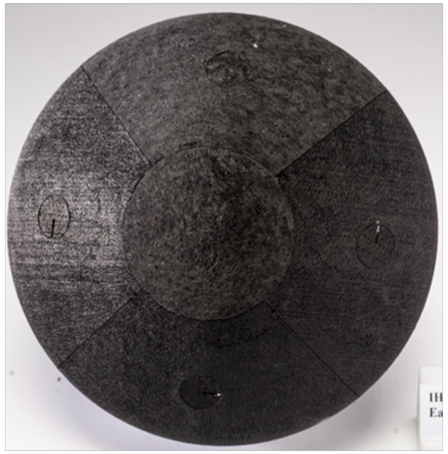
Gap filler compatibility is critical for tiled configurations

Conformal PICA

- Conformal-PICA
  - Felt Based Substrate
  - Recession comparable to PICA
  - Thermal penetration much lower







Flank heating:
~400 W/cm^2, 30 s
Shear:
~200 Pa on flank
~500 Pa at shoulder

Conformal-PICA (C-PICA) is a higher-performance alternate to PICA especially for Aerocapture missions.

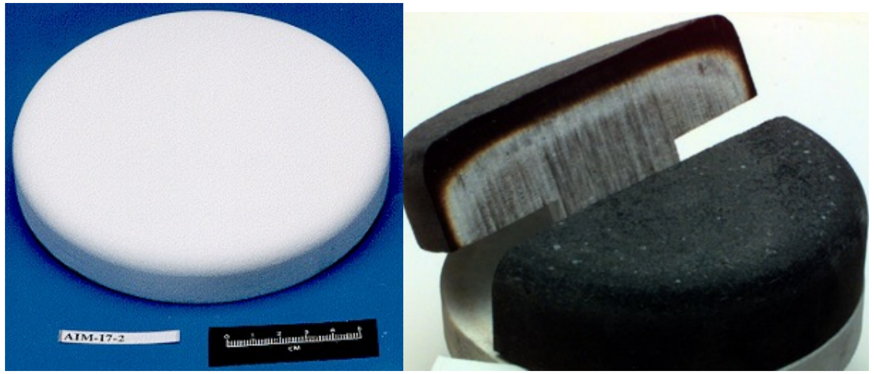
STMD Invested in C-PICA - (2012 – 2016) - Maturity at small scale TRL 5+ & larger scale TRL 4+

- Uses carbon felt instead of rigid FiberFormTM used in manufacturing PICA, otherwise processing is similar.
- Compliant, easy to integrate and mass efficient (~ 50%) compared to PICA (Backup Chart #4)
- Industry capabilities has improved considerably in the past 5 years.

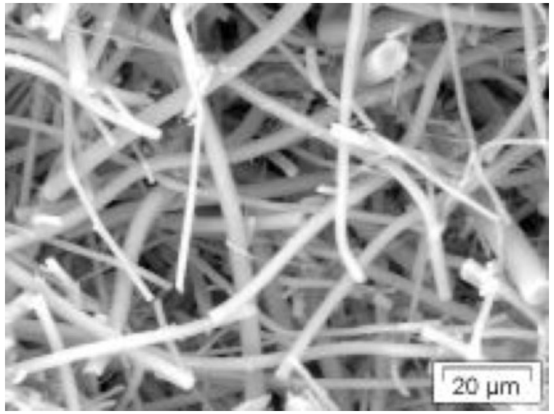
C-PICA - beneficial to future aerocapture missions and as a back-up for PICA.

Silicone Impregnated Refractory Ceramic Ablator: SIRCA

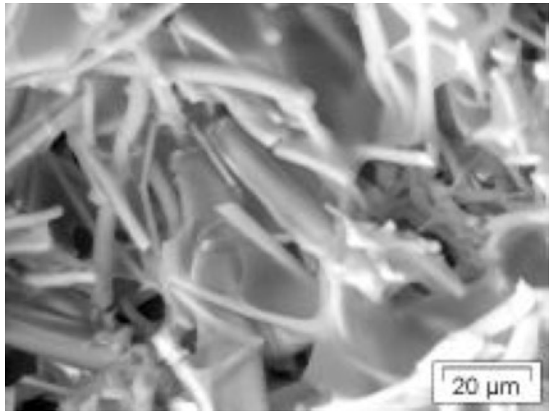
- Ceramic substrate provides good structural integrity
    - Fibrous Refractory Ceramic Insulation (FRCI-12) or LI2200 used
- Simple, uniform polymer infiltration process
- Low density (0.264 g/cc ± 0.024 g/cc or 16.5 lb/ft^3 ± 1.5 lb/ft^3)
- Easily machined to any shape
- Reusable for limited number of flights?



Un-infiltrated tile



Infiltrated tile: SIRCA



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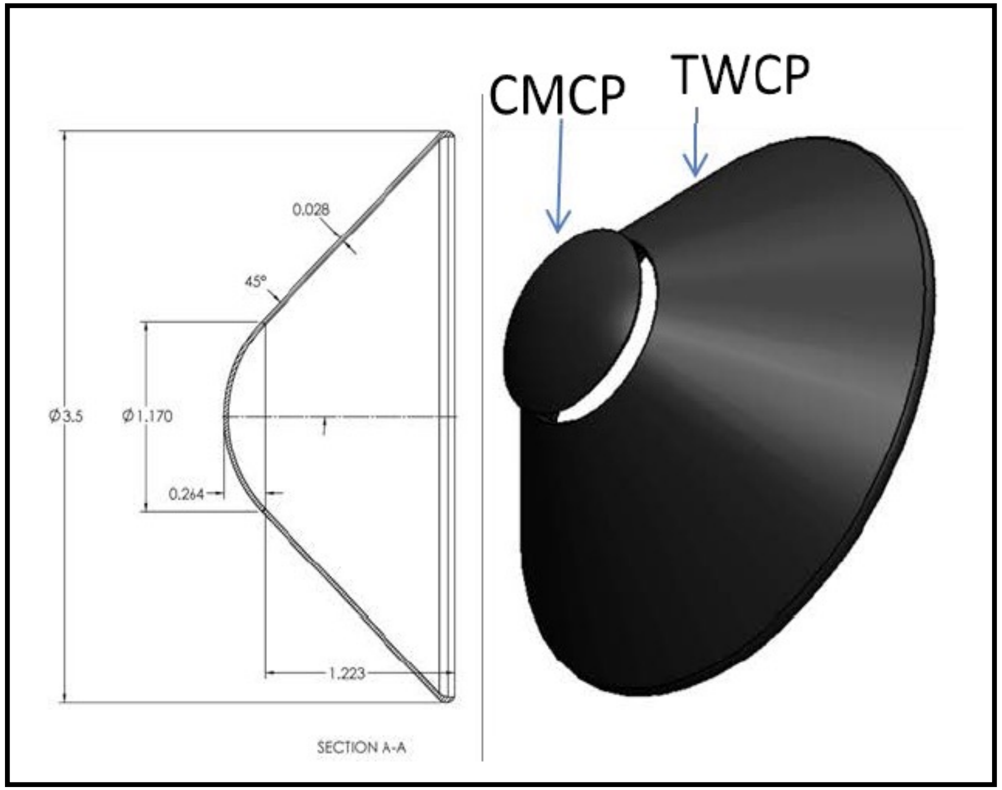
Carbon Phenolic (CP) Heat Shield for NASA Applications

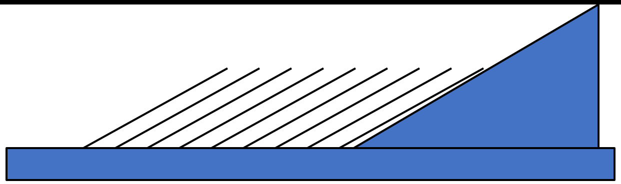


Without CMCP cannot build a blunt body heatshield. DoD uses carbon-carbon for nosetips; not a substitute for CMCP for blunt bodies (higher conductivity, mass penalty, design complexity)

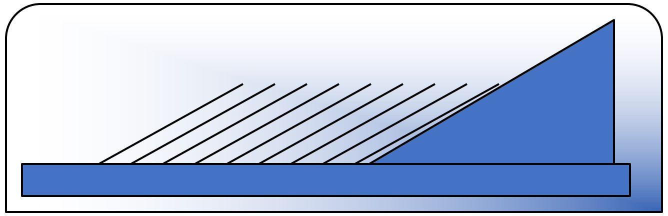
- Galileo and Pioneer-Venus leveraged DoD CP development augmented with NASA specific development.
- Avtex Rayon manufacturing ended in mid 1980's
  - Raw material supply chain issue
- Some Avtex Rayon stockpiled Avtex Rayon.
- Navy, Air Force and NASA (Shuttle Nozzle) have periodically evaluated Rayon Replacement

- **Carbon phenolic heat shield consists of Chop Molded Carbon Phenolic (CMCP) part and Tape Wrapped Carbon Phenolic (TWCP) part.**
- **NASA developed CMCP for blunt body entry geometry and leveraged DoD developed TWCP process**

Tape Wrapped vs Chopped Molded CP



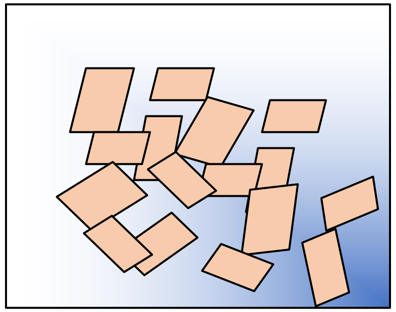
Tape Lay-up on Mandrel



Vacuum Bag

Auto-Clave

CMCP - NASA unique

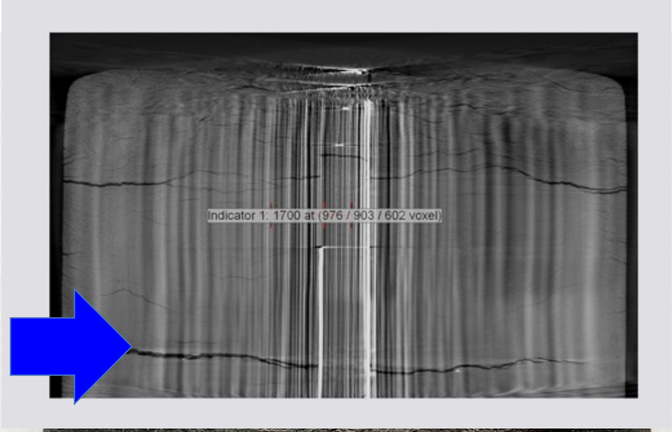


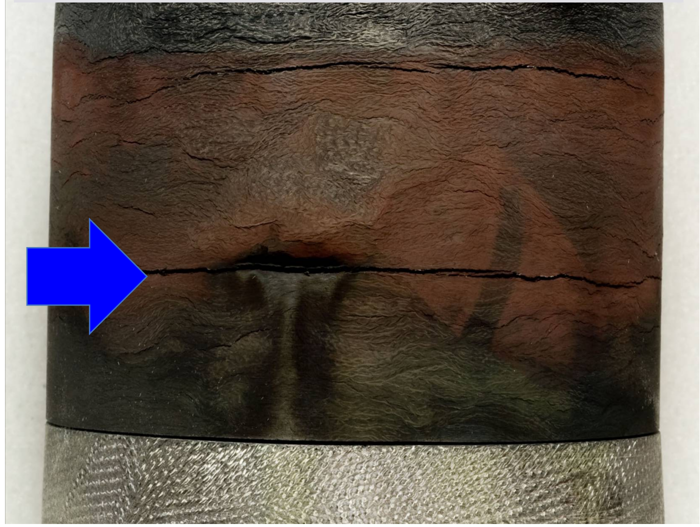
Chop in mold

Hot Press

Arcjet Testing of Carbon Phenolic

- Fully dense carbon phenolic parts must be fabricated under high pressure to eliminate ply separation and then machined from thick billets to maintain proper ply orientation
- If improperly processed, even thin sections of CP have been observed to fail as was learned during the MPCV TPS ADP initial arcjet testing of TW and CMCP for compression pad
  - Prone to delamination failure





- **Post-test arcjet model show in-plane ply separation through the thickness**
- **Sidewall heating is typically ~10% of stagnation heating**

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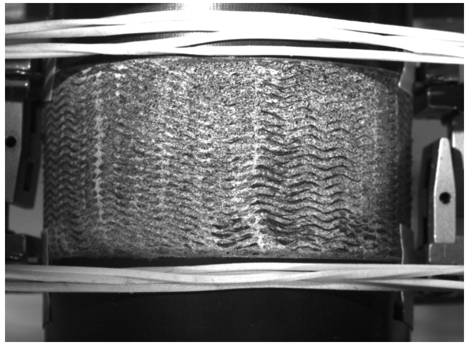
Pre-test

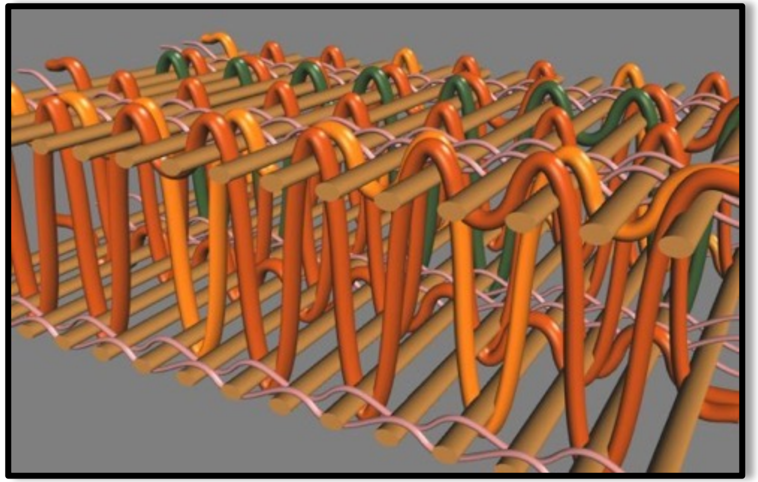


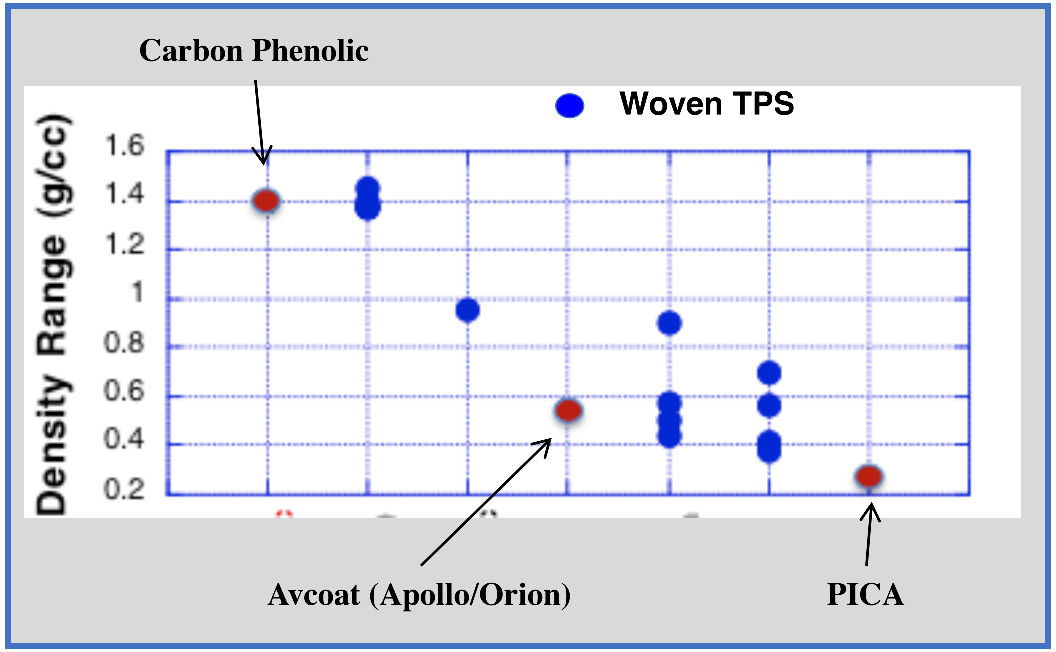
End of Test

3D Woven TPS

Woven TPS:

- Advanced weaving techniques either alone or with resin infusion used in manufacturing a family of ablative TPS.
- Current SOA in weaving allows for 3-D weaving of multi-layers with varying compositions and density.
- Ability to design TPS for a specific mission

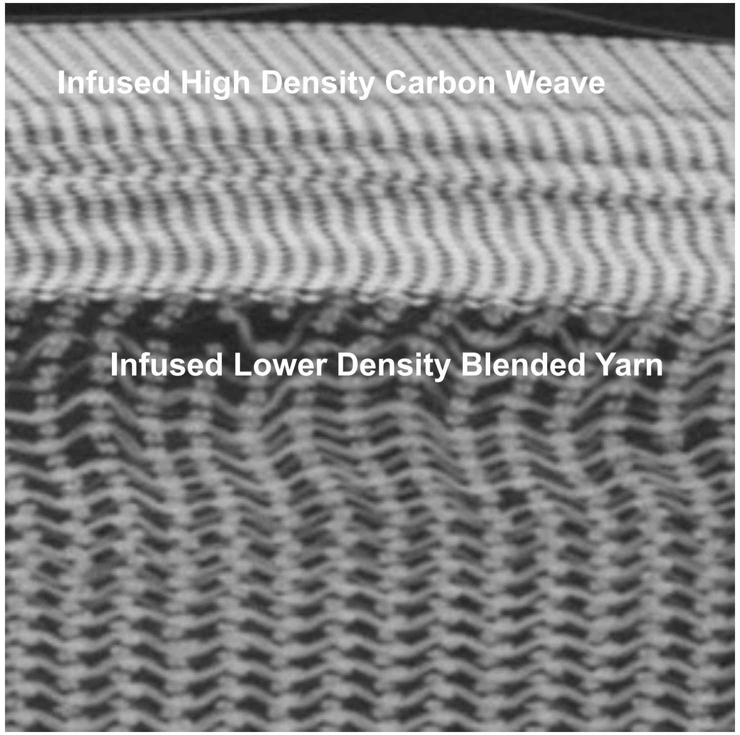




3D Woven TPS

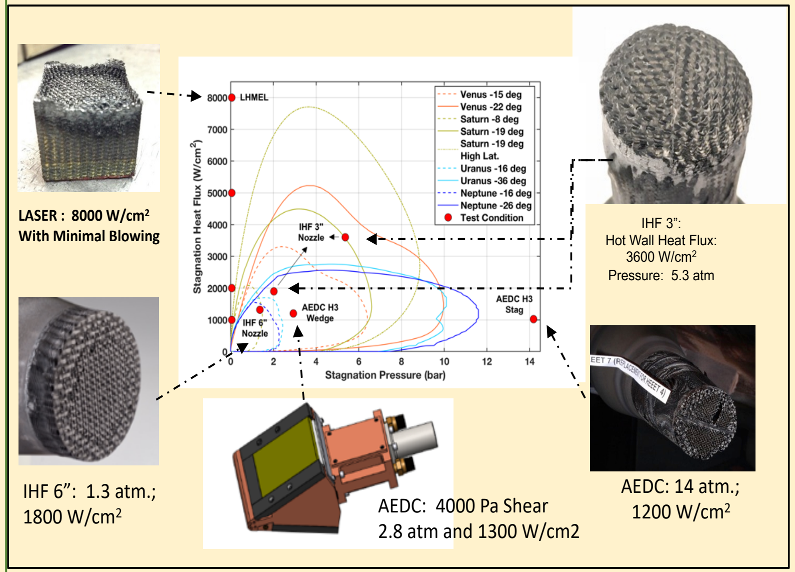
- Begin with a porous woven preform (open porosity)
  - 3D-MAT: Quartz preform
  - HEEET: Carbon or carbon/phenolic preform
  - Have control over preform starting density, number of layers and composition
- Infiltrate with a resin
  - 3D-MAT: CE – fully dense
  - HEEET: phenolic – high surface area matrix
    - Resin is diluted in a solvent
    - Have ability to control resin to solvent ratio to control amount of resin in final product
- Features leading to flaws (potentially)
  - Fiber denier
  - Interstitial spacings
- Pros: Flexibility
  - Parameters that can be tailored:
    - Starting preform density
    - Preform to resin ratio
    - Resin Composition
- Cons: Limited Part Size
  - Weaving width limitation may drive need for a tiled system
  - Single piece demonstrated to 1.2m diam (3MDCP weave for MSR EES)
  - For tiled config - require gaps between tiles with development of proper gap design, gap fillers etc…
  - Verification of bond between tile and carrier structure is challenging
    - Need for NDE

HEEET dual layer TPS

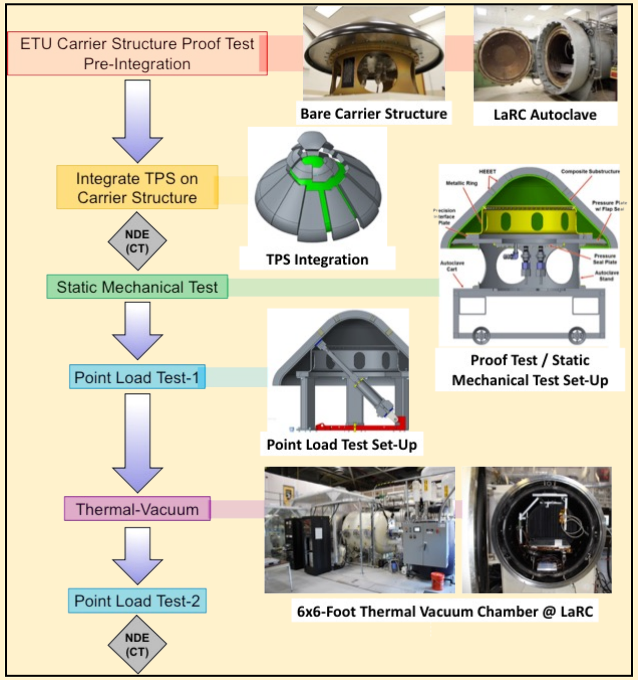


HEEET at TRL 6 Closes a Very Large (Heatshield) Gap for Venus and other Extreme Entry Missions

HEEET Project leveraged advanced 3-D weaving and resin infusion to create a robust and mass efficient ablative TPS and tested it across a range of extreme entry environments.



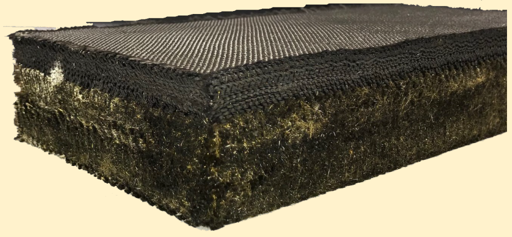
Dual layer HEEET including integrated seam have been tested at extreme conditions, without any sign of failure.

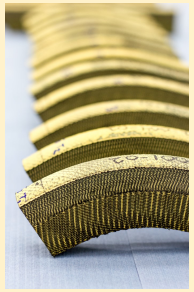


Successful Integrated Testing and Design Tools Validation

Manufacturing/Tech Transfer

3-D Woven, Dual-Layer Preform





Full Scale (1m) Engineering Test Unit

Things to Consider when Developing Ablative Materials

- Target Mission Reentry Environment:
  - Heat Flux
  - Pressure
  - Shear
  - Enthalpy
  - Heat Load
- From a Thermal/Ablation Perspective:
  - Low Density
  - Low Thermal Conductivity
  - High Emittance (Virgin and Char)
  - Char Yield
  - Blowing
    - Molecular weight of species (low)
    - At what temp does decomposition begin
  - Good mechanical integrity of char (resistant to spallation and shear)
    - Glassy material may have challenges in high shear

Material "System" Characteristics to Consider when Developing Ablative Materials

- From a design/system/manufacturing perspective:
    - Low total mass
    - Monolithic heat shield
        - No gaps/seams
    - CTE similar to carrier structure
    - Reasonable cost
    - Ease of manufacturing
        - Manufacturing robustness
            - Long Pot Life
            - Insensitive to ambient environments in green state
            - Reproducible / automated
            - Sustainable
        - Scalability of process from lab to production
    - Strength and Stiffness

Closing Thoughts

- When targeting a given application for an AM TPS system consider how the microstructure controls the performance in SOA ablators
  - Example - for a high compliance system need long continuous to semi-continuous fibers (felts, weaves etc…)
  - Microstructures/architectures control performance
    - There are reasons why we arrived at microstructures we use today
    - SOA microstructures/materials also have inherent limitations
    - When designing an AM TPS system, it is beneficial to understand SOA material performance advantages and limitations to result in a system that meets the requirements for the target application
- Leverage computational material modeling

National Aeronautics and Space Administration

Ames Research Center
Entry Systems and Technology Division