TPS Architectures and the Influence of Material and Architecture on Failure Mode Evolution

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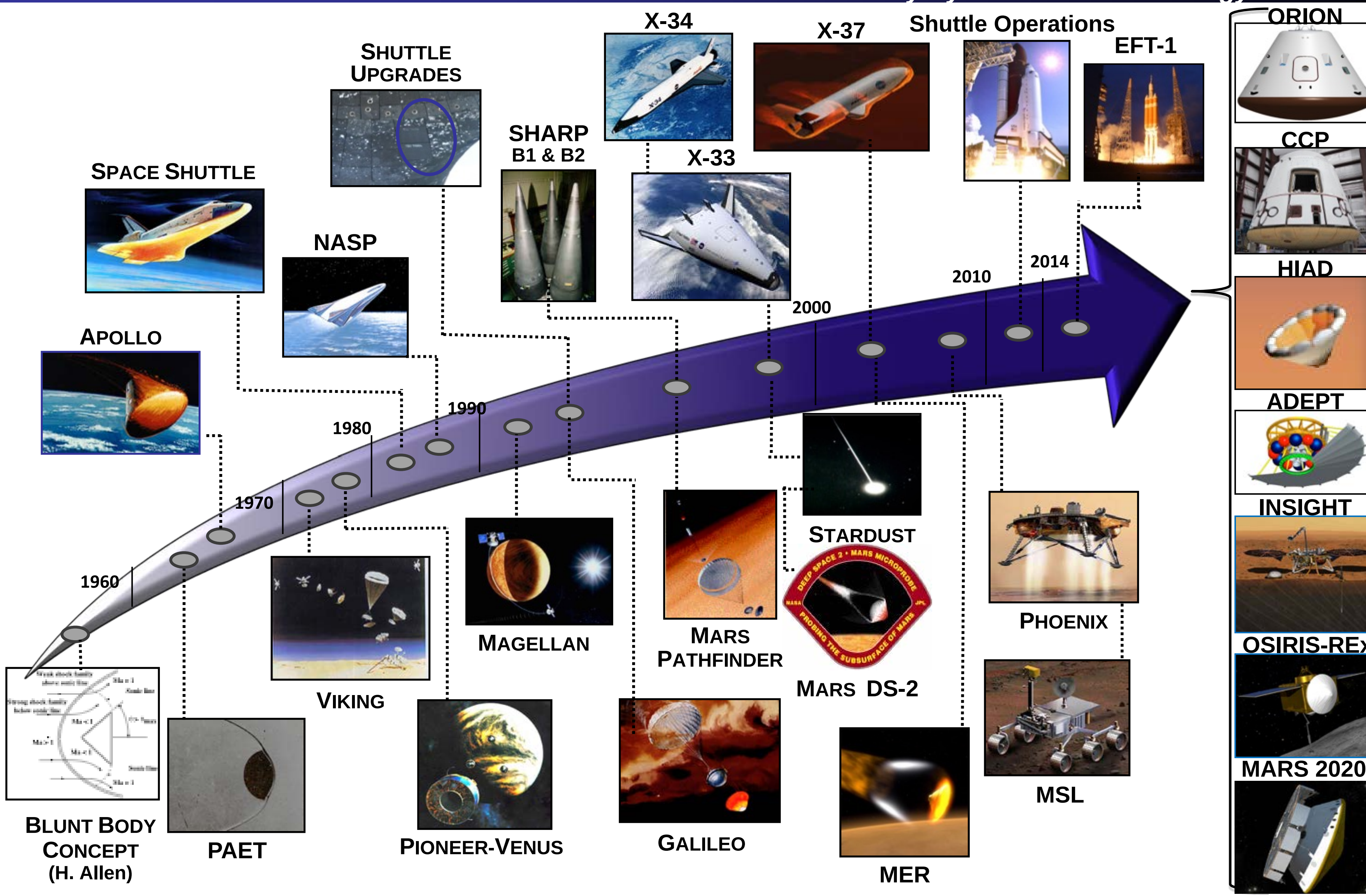


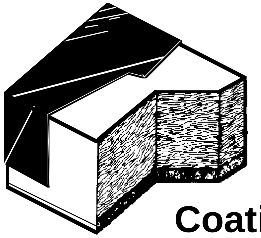
Thermal Protection Materials Development

Vision: Apply materials science and engineering in a complete process including basic research, material development, fabrication, analytical predictions and application, to support NASA mission goals.

- TPS Materials Development
  - Ablative TPS
    - PICA and SIRCA
    - Conformal PICA
    - 3D Woven TPS (HEEET and 3D MAT)
  - Reusable acreage insulation
    - Advanced ceramic tile – AETB (Alumina Enhanced Thermal Barrier)
    - Advanced coatings – TUFI (Toughened Uni-Piece Fiborous Insulation)
  - High-temperature reusable materials
    - TUFROC (Toughened Uni-piece Fibrous Reinforced Oxidation- resistant Composite)
- TPS Materials Characterization and Testing
  - Material property testing
  - Composition testing
  - Arc-jet testing (unique)
- Flight Hardware
  - SIRCA for MER (Mars Exploration Rover)
  - Orion Developmental Flight Instrumentation (DFI)
    - EFT-1, EM-1
  - EDL Instrumentation: MSL/Mars 2020
- TPS modeling, databases
  - Thermal/mechanical finite element modeling
  - Computational Materials Modeling
  - TPSX material properties database
  - Aerothermal Materials Response Modelling (TPS Sizing)

TUFROC

PICA tiles



Coatings

NASA ARC TPS Materials Roles/SME/Expertise

- Materials Development:
  - Low TRL through Mission Infusion and Sustainment
    - Current Development:
      - HEEET - STMD
      - CA-TPS - STMD
      - ADEPT Carbon Fabric - STMD
      - PICA Sustainability - SMD
    - Mission Infusion:
      - PICA: Stardust, MSL, OSIRIS-Rex, Mars 2020
      - SIRCA: MER
      - 3D-MAT: ORION EM-1
      - TUFROC: X-37, various COTS
      - TUFI Coating/AETB Tile: Orion Backshell
  - Technology Transfer:
    - PICA: Fiber Materials Inc. (FMI)
    - TUFROC: Boeing
  - Sustainment
    - PICA
    - Carbon Phenolic
- Material Response Model Development
  - Ablative TPS Sizing (thickness)
  - Tool development (FIAT, TITAN, 3D-FIAT, Icarus…)
  - Models for Specific Materials (PICA, 3D-MAT, SLA, etc...)
- Mission Support (SMD and HEOMD):
  - SMD: Flagship, New Frontiers, Discovery
    - Proposal Development through Flight
    - TPS Material SME's [MSL, Mars 2020, OSIRIS-Rex, In-Sight]
  - Orion:
    - TPS Deputy Subsystem Manager. Backshell Lead
  - TPS Material Sizing
  - TPS Material Testing: Arcjet testing, etc…
- EDL Instrumentation:
  - Orion DFI:
    - EFT-1, EM-1
  - SMD:
    - MSL (MEDLI), Mars 2020 (MEDLI-2)
    - Support to meet Future Engineering Science Instrumentation Requirements for Missions with an Entry Phase
    - Collaboration with ESA on COMARS backshell instrumentation suite

A Perspective On Failure Mode Evolution in Ablators

- From Raj – “Feature to Flaw to Failure”
- TPS failure is strongly influenced by the class of TPS material and corresponding architecture
- Failure mode is dependent on the TPS architecture
- Hopefully this overview will inform on the generic types of TPS architectures and help guide failure mode evolution modeling effort

Ablator Material Architectures

- Honeycomb Materials
  - Avcoat, SLA, SRAMs, Phencarbs, BLA, BPA, etc…
  - NASA does not have a H/C ablator in our TPS portfolio
- Resin Infiltrated Preforms
  - Silicone Impregnated Refractory Ceramic Ablator(SIRCA: NASA ARC),
  - Phenolic Impregnated Carbon Ablator (PICA: NASA ARC, Fiber Materials Inc (FMI))
- Dual Layer Materials (not integrally woven)
  - Carbon/Carbon-FiberForm (Genesis: LM)
  - 3-Dimensional Quartz Phenolic HD/LD (3DQP: Textron)
- 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 (ortho weave like 3D-MAT)
  - Single to Multi layer integrally woven layers (HEEET)
  - 3-D C-C
- Others:
  - Chop Molded Carbon/Phenolic
  - Sprayable SLA
  - Syntactic foams (Acusil)

Honeycomb Materials

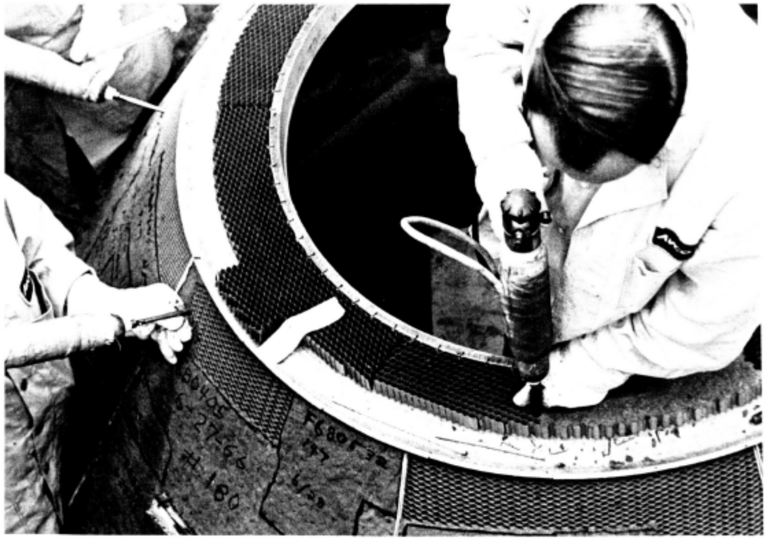
- Honeycomb Benefits
  - Stabilizes the char, preventing/reducing char spallation
  - Monolithic approach
  - Provides a method to verify bond to carrier structure
- Resins
  - Phenolic Resins: Higher Heat Fluxes
    - PhenCarbs(ARA), Boeing Phenolic Ablator(BPA)
  - Epoxy / phenolic Resins: Higher Heat Fluxes
    - Avcoat (Textron: Apollo)
  - Silicone Resins: Lower Heat Fluxes
    - Super Lightweight Ablator(SLA: LM)), SRAMs(ARA), Boeing Lightweight Ablator(BLA)
- Features leading to flaws (potentially)
  - Touch labor leading to density variability
  - Separation at ablator to H/C interface

Honeycomb Materials

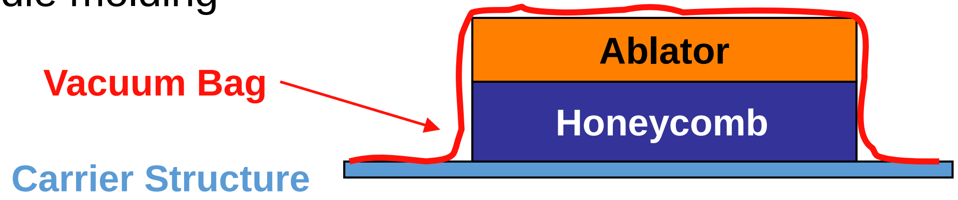
- Fillers:
  - Microballoons:
    - Silica/Glass and Phenolic
  - Fibers:
    - Silica/Glass, Ceramic and Carbon
  - Others:
    - Cork, etc…
- Constituent Pre-Treatments
  - Thermal
  - Chemical
  - Improve adhesion with honeycomb
  - Improve adhesion between fillers and resin
  - Remove sizings, remove contaminants, etc…

Honeycomb Materials

- Honeycomb:
  - Composition:
    - Silica/Ph, Glass/Ph, Carbon/Ph…
  - Cell Shape:
    - Hexagonal, Flexcore,…
  - Cell Size
  - Cell Wall Thickness
- Manufacturing Techniques:
  - Hand Packing
  - Hand Injecting (Avcoat)
    - Caulking gun
  - Press Ablator Preform into Honeycomb (or vice versa)
    - Vacuum bagging or closed die molding



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



Compositions of SLA-561 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

Resin Infiltrated Preforms (Low Density)

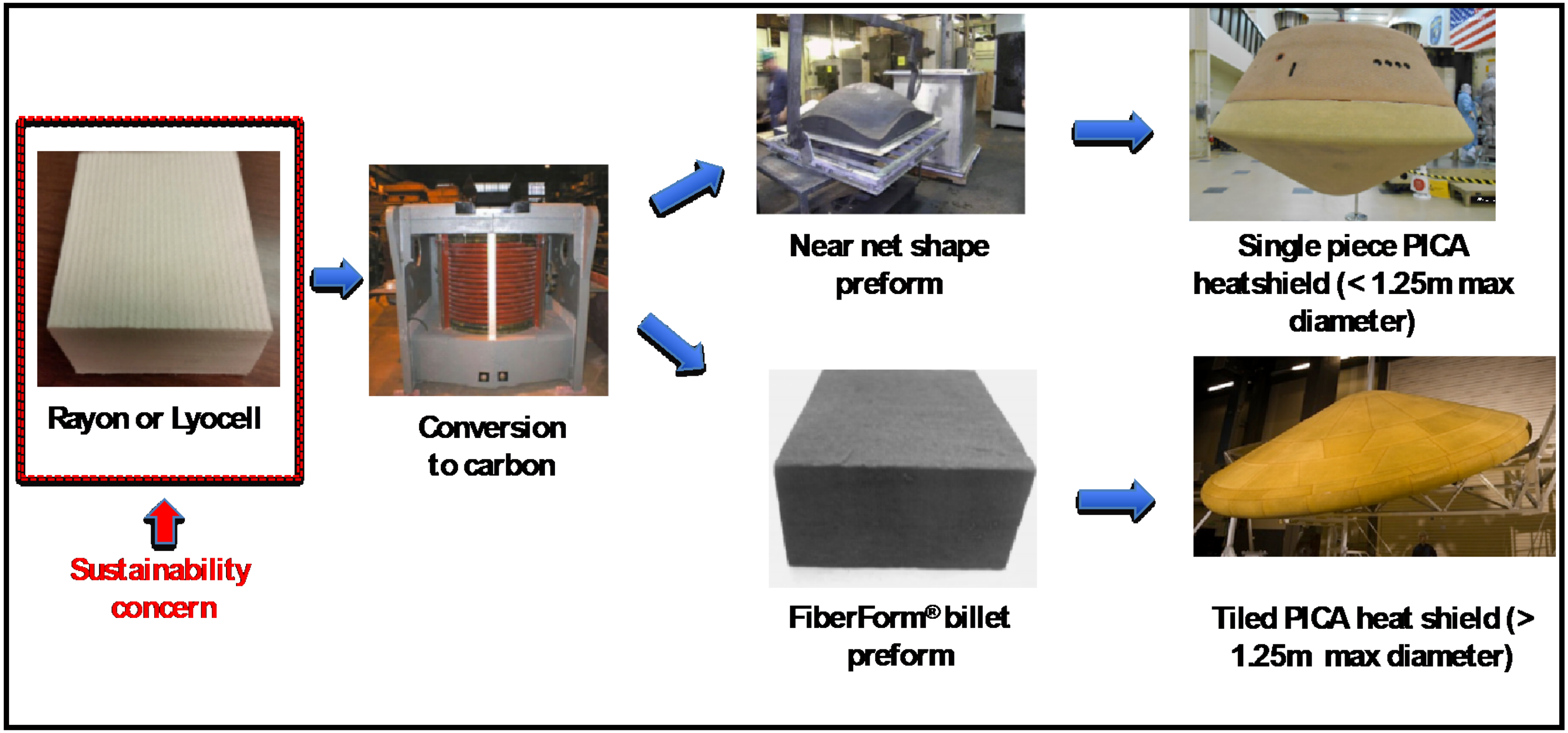
- Begin with a porous preform (open porosity)
  - PICA: Carbon Furnace Insulation (FiberForm)
  - SIRCA: Ceramic Shuttle Tile
  - Have some control over preform starting density and composition
- Infiltrate with a resin
  - PICA: Phenolic
  - SIRCA: Silicone
  - Resin is diluted in a solvent
    - Have ability to control resin to solvent ratio to control amount of resin in final product

Resin Infiltrated Preforms (Low Density)

- Pros: Flexibility
  - Parameters that can be tailored:
    - Starting preform density
    - 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 0.87m max diameter
  - Requires gaps between parts with development of proper gap design, gap fillers etc…
  - Verification of bond between tile and carrier structure is challenging

PICA Manufacturing Overview

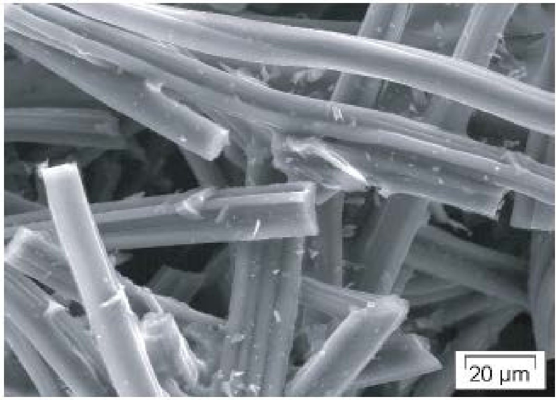
Role of Rayon/Lyocell in PICA Manufacturing



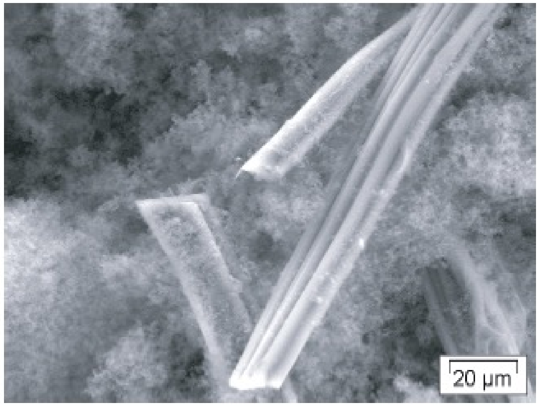
- Chopped, graphitized rayon or Lyocell - based carbon fiber slurry-cast into either block (billet) or single piece heatshield preforms
- Single piece cast heatshields have fiber oriented to optimize through-thickness thermal conductivity
- Lightweight phenolic sol-gel matrix is infiltrated into preform

Importance of PICA Microstructure / Gap Filler

Fiberform before impregnation



PICA with phenolic resin impregnated



What happens when the phenolic resin is not present in PICA

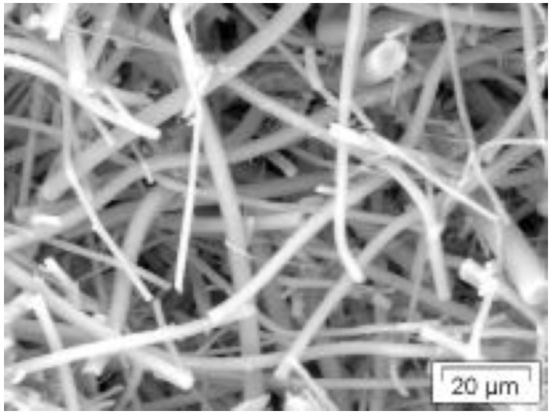
Tunneling failure mode

Gap filler compatibility is critical

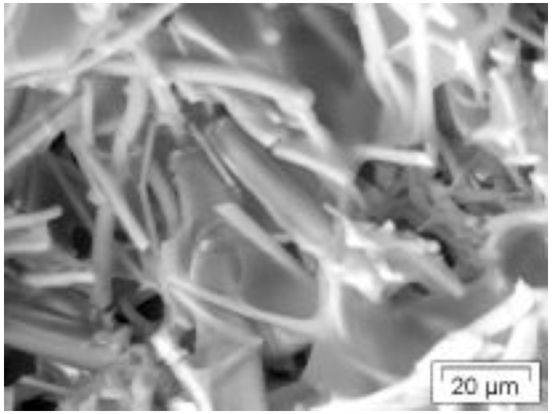
Silicone Impregnated Refractory Ceramic Ablator: SIRCA

- Ceramic substrate provides good structural integrity
  - Fibrous Refractory Ceramic Insulation (FRCI-12) 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 and compatible with Computer Aided Machining (CAM)

Uninfiltrated LI-2200



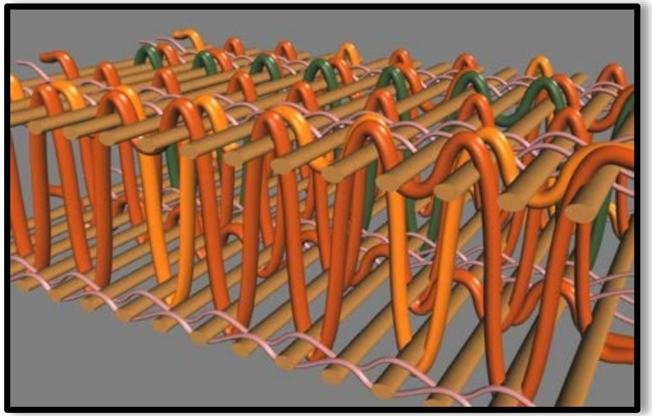
Infiltrated LI-2200: SIRCA

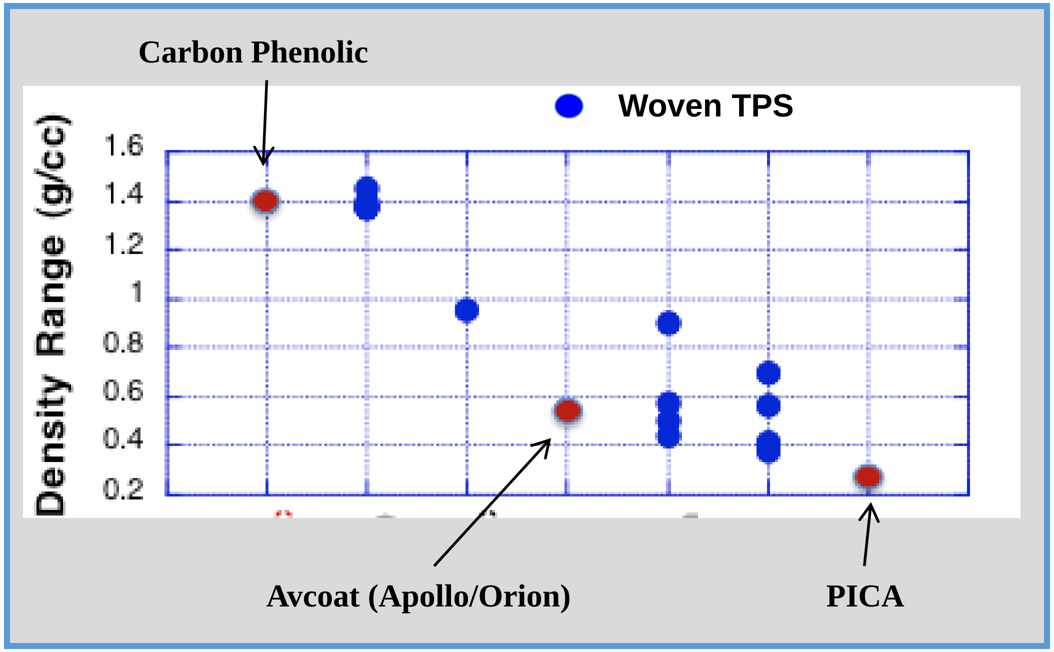


Woven TPS: What is it?

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.





Woven TPS

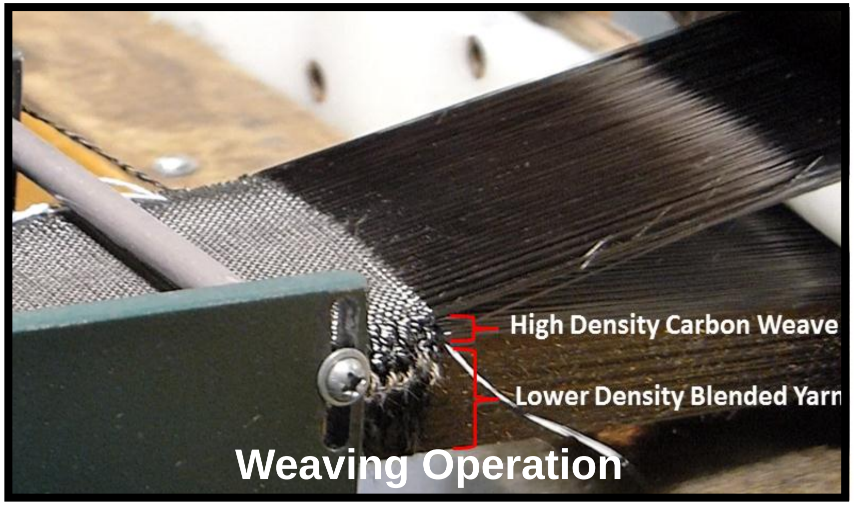
- Begin with a porous woven preform (open porosity)
  - 3D-MAT: Quartz preform
  - HEEET: Carbon or carbon/phenolic preform
  - Have control over preform starting density, number of layers and composition
- Infiltrate with a resin
  - 3D-MAT: CE – fully dense
  - HEEET: phenolic – high surface area matrix
    - 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

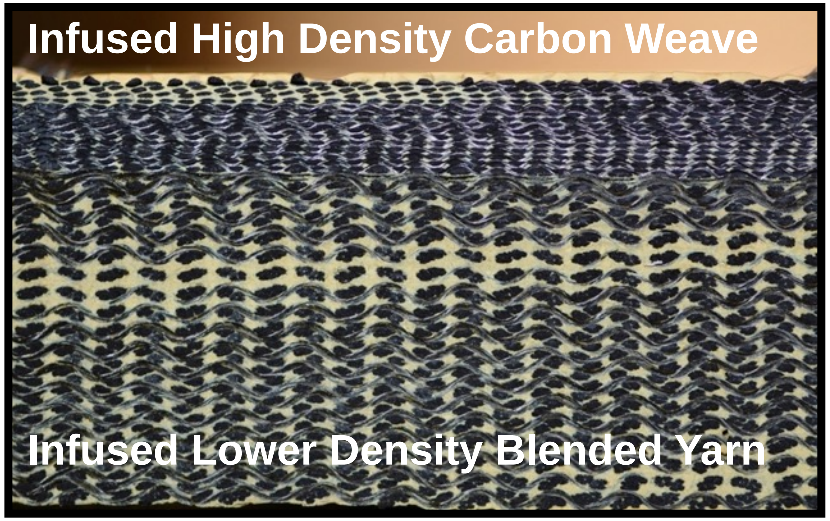
Woven TPS

- Pros: Flexibility
  - Parameters that can be tailored:
    - Starting preform density
    - Preform to resin ratio
    - Resin Composition
- Cons: Limited Part Size
  - Weaving width limitation drives need for a tiled system
  - Single piece demonstrated to 24” width (HEEET type weave)
  - Requires gaps between parts with development of proper gap design, gap fillers etc…
  - Verification of bond between tile and carrier structure is challenging
    - Need for NDE

Woven TPS - HEEET Weaving: Bally Ribbon Mills

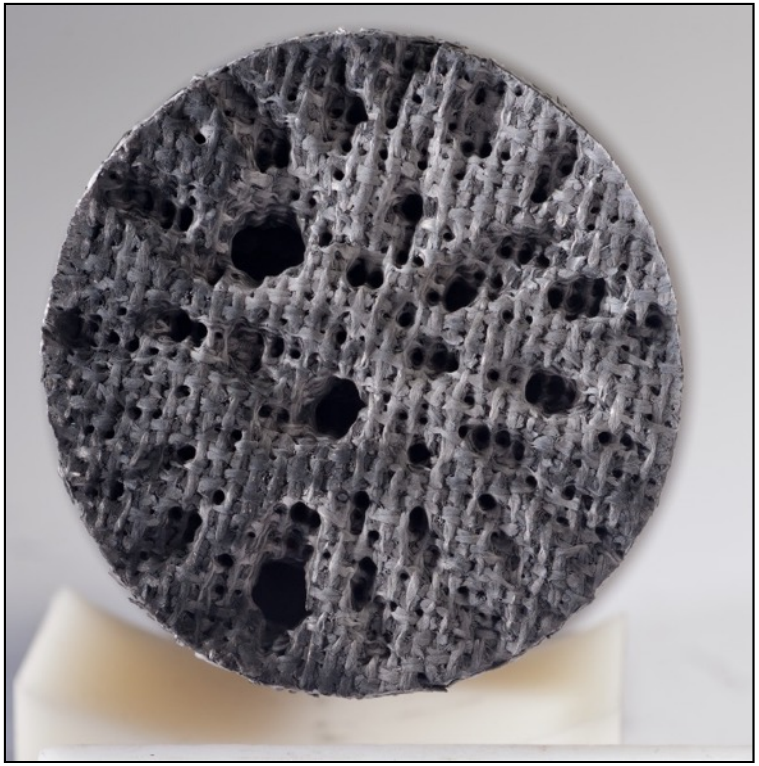
- **Dual-Layer 3-D woven material infused with low density phenolic resin matrix**
  - Recession layer
    - Layer-to-layer weave using fine carbon fiber - high density for recession performance
  - Insulating layer
    - Layer-to-layer weave: blended yarn - lower density/lower conductivity for insulative performance
- **Material Thickness:**
  - 2in (5.3 cm) thick material [0.6in (1.5cm) recession layer, 1.4in (3.8cm) insulating layer)]
- **Material Width:**
  - Initial weave capability was 6in width x 1in thickness
  - Completed weaving 13in (33cm) wide material
  - Currently weaving 24in (61cm) wide material
  - **Weaving width limitation drives need for a tiled system**
    - **Gap filler approach required**





Weave Features

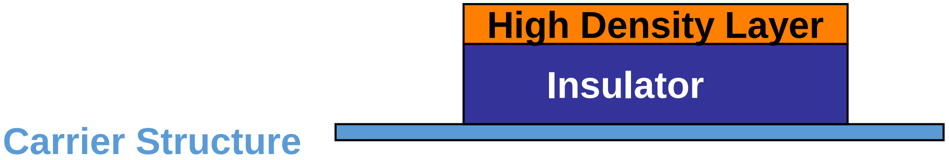
- Interstitial size drives flaw/failure
  - Permeability / scale of porosity



Tunneling in very low density woven material with large interstitial spaces

Other Dual Layer Materials (3DQP, Genesis)

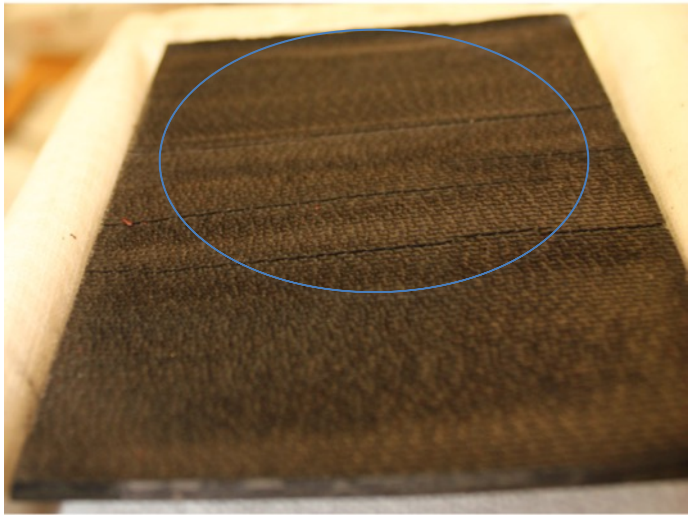
- High Density Surface Layer
  - Low recession
  - Examples:
    - C/C for LM Genesis heat shield concept
    - Si/Ph for Textron 3DQP Dual Layer
- Insulating Second Layer
  - Low thermal conductivity
  - Low density
  - Chemically and/or mechanically attach/bond layers together
  - Examples:
    - FiberForm for LM Genesis heat shield concept
    - Mod 58 Phenolic Syntactic Foam for Textron 3DQP



- Bond between surface layer and insulating layer

2-D Continuous Fiber Composites

- Used in most extreme reentry environments
- Higher Density
- Lower Recession
- Higher Thermal Conductivity
- Long Heritage
- Manufacturing:
  - Tape Wrapped
  - Chop Molded
  - Compression Molding
- Examples:
  - C/C
    - High Density Layer on Genesis Heat Shield
    - BRV Nosetips
  - C/Ph
    - Galileo Heat Shield
    - Pioneer Venus
    - DoD Reentry Vehicles
    - Rocket Nozzles



Prone to delamination failure

Factors That Influence TPS Design

- Aerothermal Environment
  - Peak conditions (heat flux, shear, pressure) maybe used to screen suitability of a given material
  - Total heat load will be used to size the thickness and therefore total mass of the heat shield
- Strength/Stiffness (Airloads/Vibroacoustic)
  - Limits of ablator material will drive things such as carrier structure design(stiffness) and block layout for segmented approaches
- Outgassing
- Space Environment
  - LEO: Atomic Oxygen
  - UV
  - Long Term Space Exposure
- Damage Tolerance/Impact Resistance
- Repairability
- Refurbishment
- ***Reliability requirements***

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
    - May want high char yield for
  - 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

Materials 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

Other Considerations

- Gap Design in Segment Approaches
  - Aerothermal Testing
  - Structural Testing
  - Ease of integration
- Transparency of material to shock layer radiation
  - Currently no ground based facility that combines convective and radiative heating
- Impact resistance to Micro Meteoroid and Orbital Debris (MMOD)
  - So concepts will be inherently more impact resistant
- Bond Verification
  - Ability to verify good bond between ablator and carrier structure
- Non-Destructive Evaluation (NDE)
  - Ability to find critical defects within material
- Waterproofing
  - Is waterproofing required and if so finding a compatible waterproofing agent.
- Atomic Oxygen
  - Is material susceptible to oxidation by atomic oxygen and if so finding a compatible coating.

Questions?

National Aeronautics and
Space Administration

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