Three Dimensionally Woven Mid-Density Carbon Phenolic (3MDCP) is a Novel Single Piece Ablative TPS for Extreme Entry Environments

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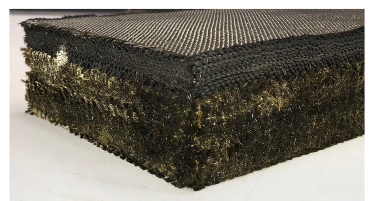
Peter Gage: Neerim Corporation

1. Background – HEEET and 3MDCP

Heatshield for Extreme Entry Environment Technology (HEEET)

- NASA's Space Mission Directorate (SMD) and Space Technology Mission Directorate (STMD) co-funded the HEEET development project
- HEEET was matured to TRL 6 as a Tiled Thermal Protection System (TPS) targeted for the most demanding planetary science entry missions at destination such as Venus, Saturn and the Ice Giants (Uranus, Neptune)
- HEEET utilizes a novel dual layer weave as the preform which is infused with a mid-density phenolic resin
- The dual layer weave has an outer high density Recession Layer, composed of all carbon yarns (exposed to the entry environment) and an inner lower density Insulation Layer, composed of a blended carbon/phenolic yarn (manages the heat load)
- Seam between tiles is the weak link structurally and aerothermally

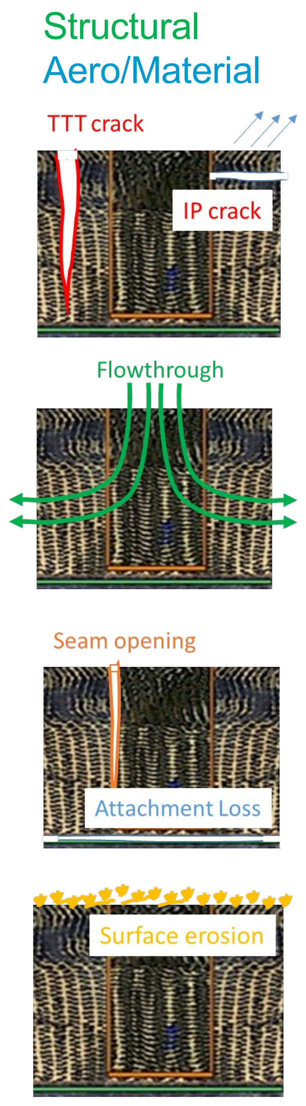


HEEET Dual Layer Weave

HEEET 1m diameter, 45° sphere cone Engineering Test Unit

Typical failure modes of tiled systems include:

- Tile and gap-filler failure
  - Through Thickness cracks causing "heat leaks"
  - In plane cracks causing reduced thickness
  - Surface erosion (mechanical failure causing spallation or accelerated layer loss)
  - Flowthrough (permeability permits interior flow)
- Loss of attachment of tiles or gap fillers, causing complete loss of thermal material over the full tile area
  - Adhesive mechanical failure
    - Substrate failure adjacent to adhesive
  - Adhesive thermal failure
- Cracking and opening of seams, permitting a "heat leak" in the gaps between tiles
  - Adhesive mechanical failure
    - Tile failure adjacent to adhesive
  - Adhesive char and erosion
- Material response prediction error
  - Recession rate error
    - Differential recession at seam
  - Conduction

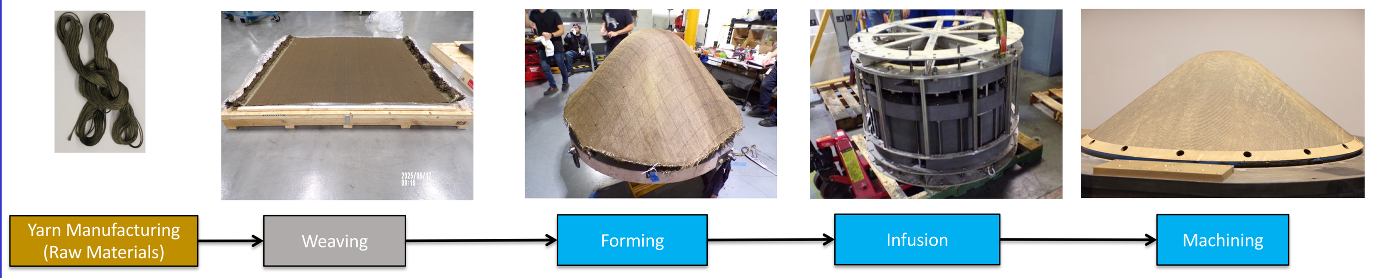


Mars Sample Return (MSR) Earth Entry System (EES)

- Required a robust, high reliability heat shield
- Desired a single piece heat shield that would enhance system reliability by eliminating seams between tiles (eliminate purple failure modes above)
- Infused insulation layer (0.83 g/cc) was shown to have aerothermal performance capability that met MSR requirements
- Insulation layer had potential to be:
  - Formed into sphere cone shape
    - HEEET RL is too stiff to form into sphere cone shape
  - Woven at the width needed for a single piece heat shield
    - HEEET RL is too fine a weave to be practically woven at scale required
- **3MDCP** was baselined as the forebody heatshield for MSR EES
  - Targeted HEEET IL weave design but at much greater width (80" vs 24")
    - Weave density slightly reduced to enable wider woven material
  - Required:
    - Installation of new weaving infrastructure
    - Development of methods to form full scale sphere cone shape from a flat panel
    - Scale up infusion tooling and processes

2. 3MDCP Manufacturing

Manufacturing Overview



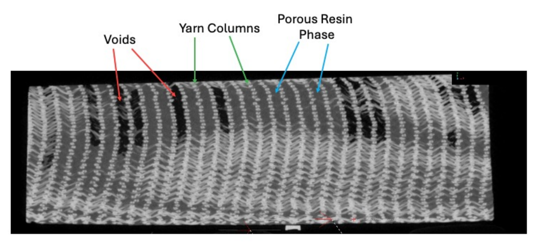
Industry	Blends carbon/phenolic yarn Schappe Techniques	Installed new 80" loom, weaves preforms TEAM Inc.	Forms preforms FMI	Infuses formed preforms FMI	Machines infused blanks into flight part FMI
MSR Status	Complete: 6400 kg	Complete: Qty 16. full scale preforms	Full-scale Forming Demonstrated	Full-scale Infusion Demonstrated	Full-scale Machining Demonstrated

MSR EES Flight Ready Heat Shields

- MSR EES TPS project completed production of two flight ready heatshields prior to termination of the MSR program.
- Heat shields are stored at NASA Ames in climate controlled environment for future use.

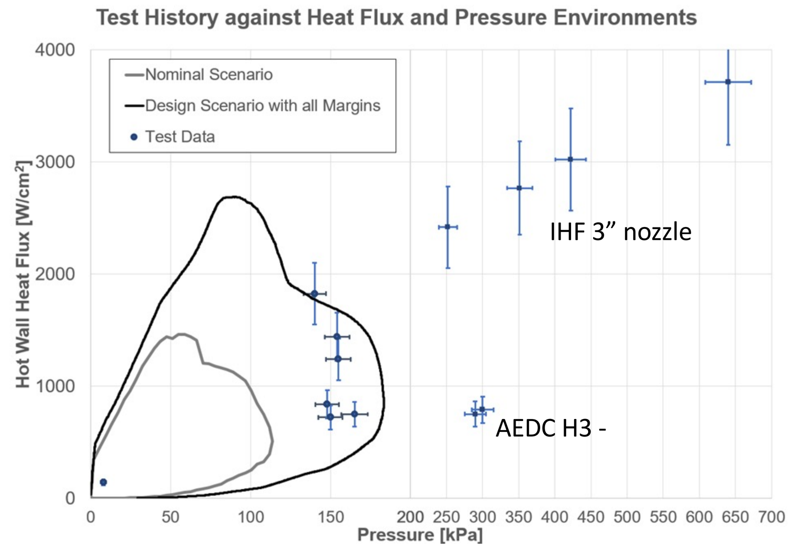
MRL	Description (from MRL Deskbook)	3MDCP Hardware Produced	3MDCP Success Criteria
1	Basic manufacturing implications identified		
2	Manufacturing concepts identified	HEEET IL basis for weave (at narrow with, 24"), infusion (at low part volume), machining, low curvature forming (at tile scale)	Entry point for forming and weaving
3	Manufacturing proof of concept developed	Formed 60° cone angle forebody, sub-scale surrogate weave Formed 45° cone angle, full scale flight representative weave Flight part is 52.5° cone angle	Entry maturity for 3D weave. Need to increase weave span for single piece. Entry maturity for infusion. Need to demonstrate infusion at full scale. Full-scale forming at 45 deg is critical milestone for MRL 3
4	Capability to produce the technology prototype in a laboratory environment	Sub-scale Development Unit (S-DEV)	Forming, infusion and machining demonstrated at sub-scale with surrogate weave.
5	Capability to produce prototype components in a production-relevant environment	Flight Manufacturing Demonstration Unit #1 (F-MDU-1) – full scale with flight weave Flight Infusion Demonstration Unit (FIDU) – full scale with flight weave	Infusion processes/procedures were updated after F-MDU-1. Infusion updates successfully demonstrated with flight weave on FIDU. Machining processes/procedures updated after F-MDU-1. Updates were not demonstrated on FIDU.
6	Capability to produce a prototype system or subsystem in a production-relevant environment	Flight Production Unit #1 (FPU-1)	Forming and infusion using updated procedures, demonstrated on FPU-1 Additional refinement to machining process implemented after FPU-1. NDE for full heat shield in work.
7	Capability to produce systems, subsystems, or components in a production-representative environment	FPU-2	Forming, infusion and updated machining executed on FPU-2. After a production hiatus, expect one "production-representative" build before committing to flight production at pilot line maturity.
8	Pilot line capability demonstrated; ready to begin LRIP	Given NASA's science mission cadence, production unlikely to mature beyond pilot line.	
9	LRIP demonstrated; capability in-place to begin FRP	N/A	
10	FRP demonstrated and lean manufacturing practices in-place	N/A	

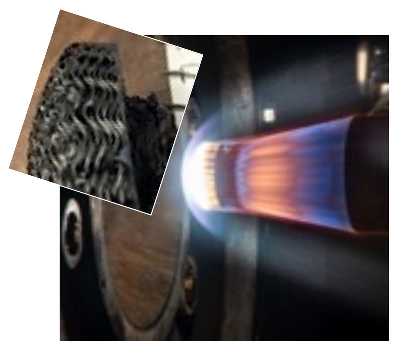
3. Full Scale CT Scanning



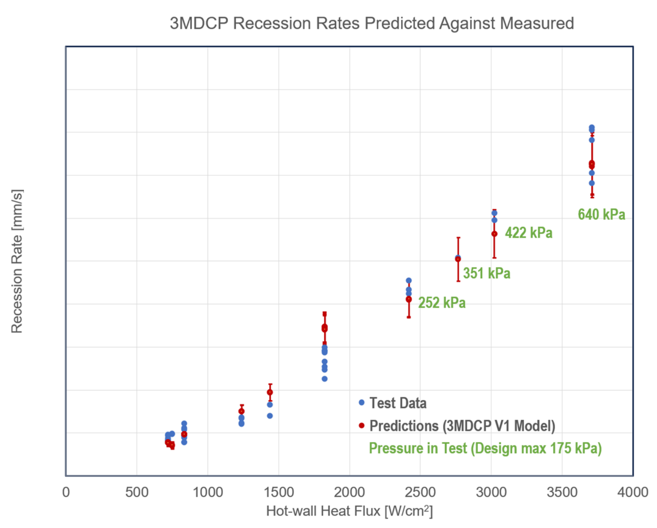
- NASA Langley is developing capability to perform full scale CT scanning of the heat shield
- NASA Ames is developing tools to extract spatially resolved void fraction maps, including uncertainty quantification
- Given the resin infusion process the phenolic phase is inherently porous (sub-micron scale porosity)
- In this case voids refer to the absence of the phenolic phase between weave columns

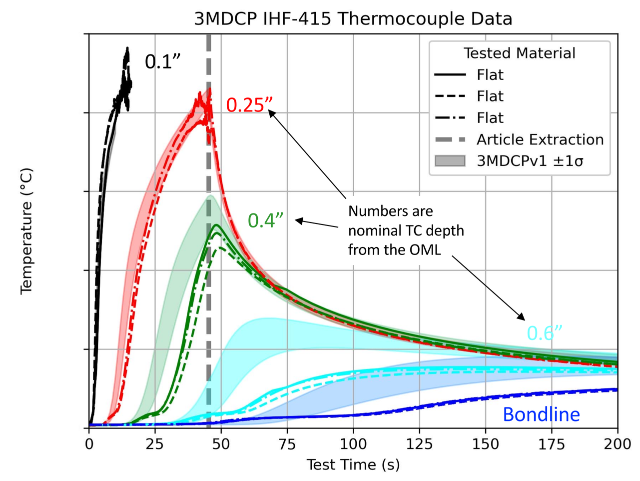
4. Aerothermal Performance Testing/Material Response Model





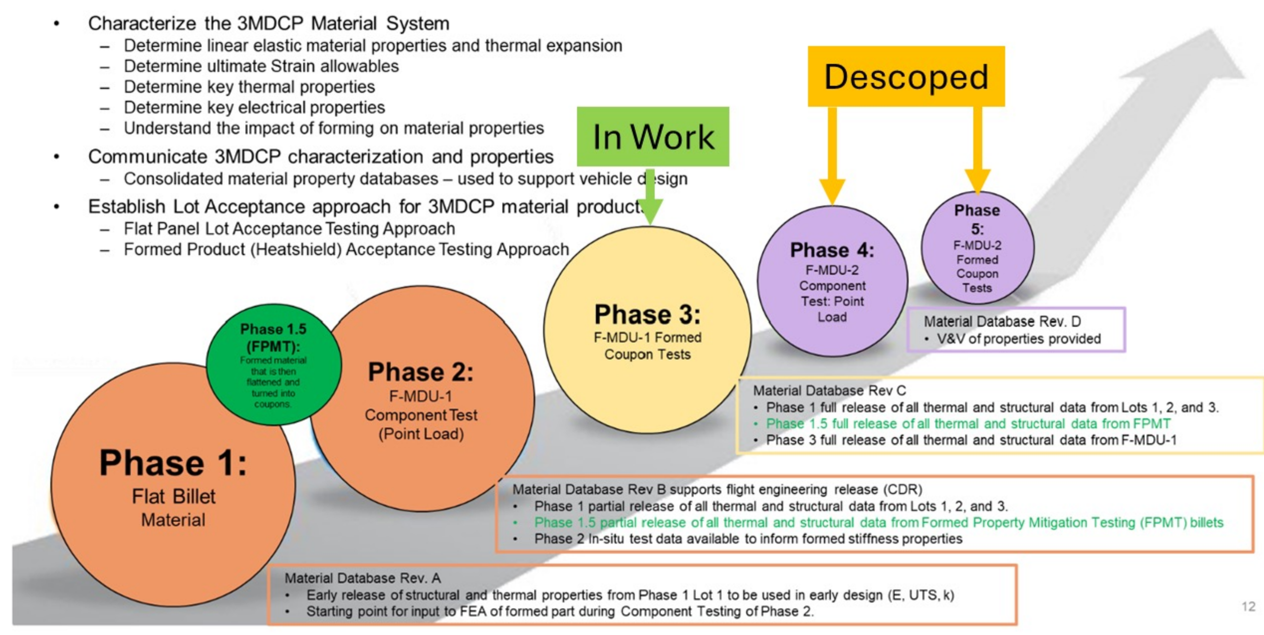
- 3MDCP tested over a broad range of environments
- To bound margined heat flux requires substantial over test in pressure



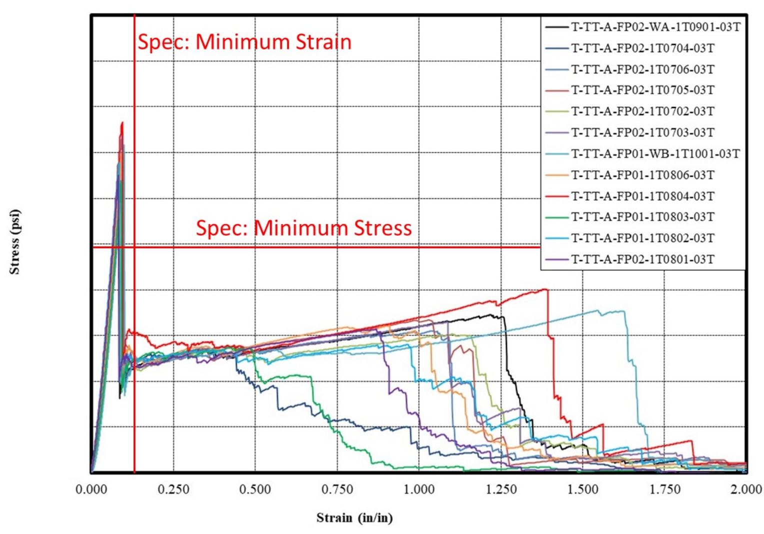


- 3MDCP FIAT version 1 material response model:
  - Faithfully predicts recession rates over broad range of conditions
  - Accurately predicts near surface TC response
  - Conservatively predicts deeper and bond line TC response
    - Opportunity to update response model to pull out conservatism

5. Material Property Testing

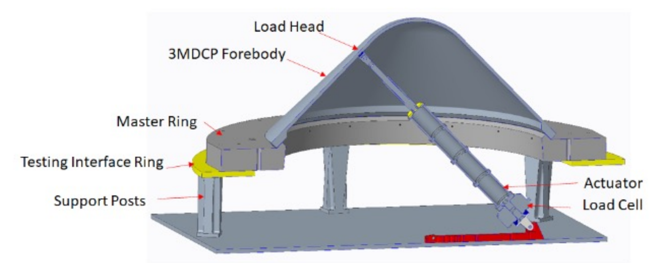


Through Thickness Tensile Tests

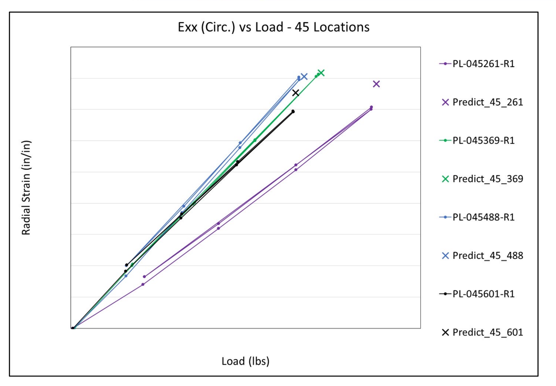


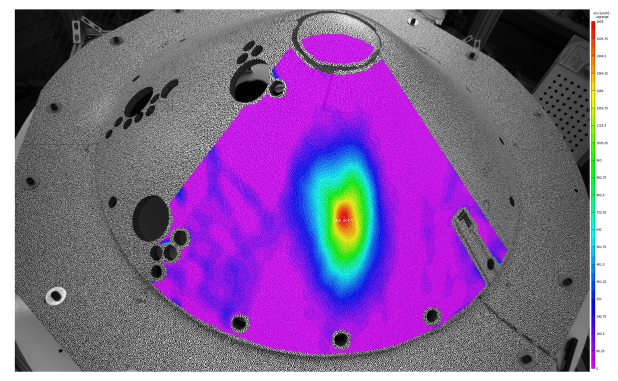
- 3D weave enables material to carry load, post ultimate stress, for significant strain
- Heat shield design utilized strain based allowables
- Resin microcracks but fibers are not broken

Point Load Tests: F-MDU-1



- Series of point load tests conducted across the F-MDU-1 heat shield
- Strain measured using photogrammetry
- Predictions based on correlated material properties (stiffness), match measured strains well





6. Summary

- Two flight ready 52.5° sphere cone, 1.25m diameter heat shields were manufactured that meet MSR mission requirements
- Manufacturing processes and procedures are mature and demonstrated, achieving MRL 7, from blended yarn production through final machining
- Material performs predictably at a broad range of aerothermal conditions, up to ~3700 W/cm² and 6 atm
- 3MDCP FIAT v1, 1-D material response and sizing tool, model faithfully predicts recession rates and conservatively predicts bond line temperatures
- Correlated material properties provide good predictions of strain response during point load testing
- 3MDCP has been matured and capable of supporting future missions

Acknowledgements

- Schappe Technique for manufacturing the blended yarn
- FMI Textiles (formerly TEAM Inc.) for installation of new loom and weaving flight scale preforms
- FMI for working with NASA to develop forming, infusion and machining processes