



HEEET: Innovative New TPS for Extreme Entry

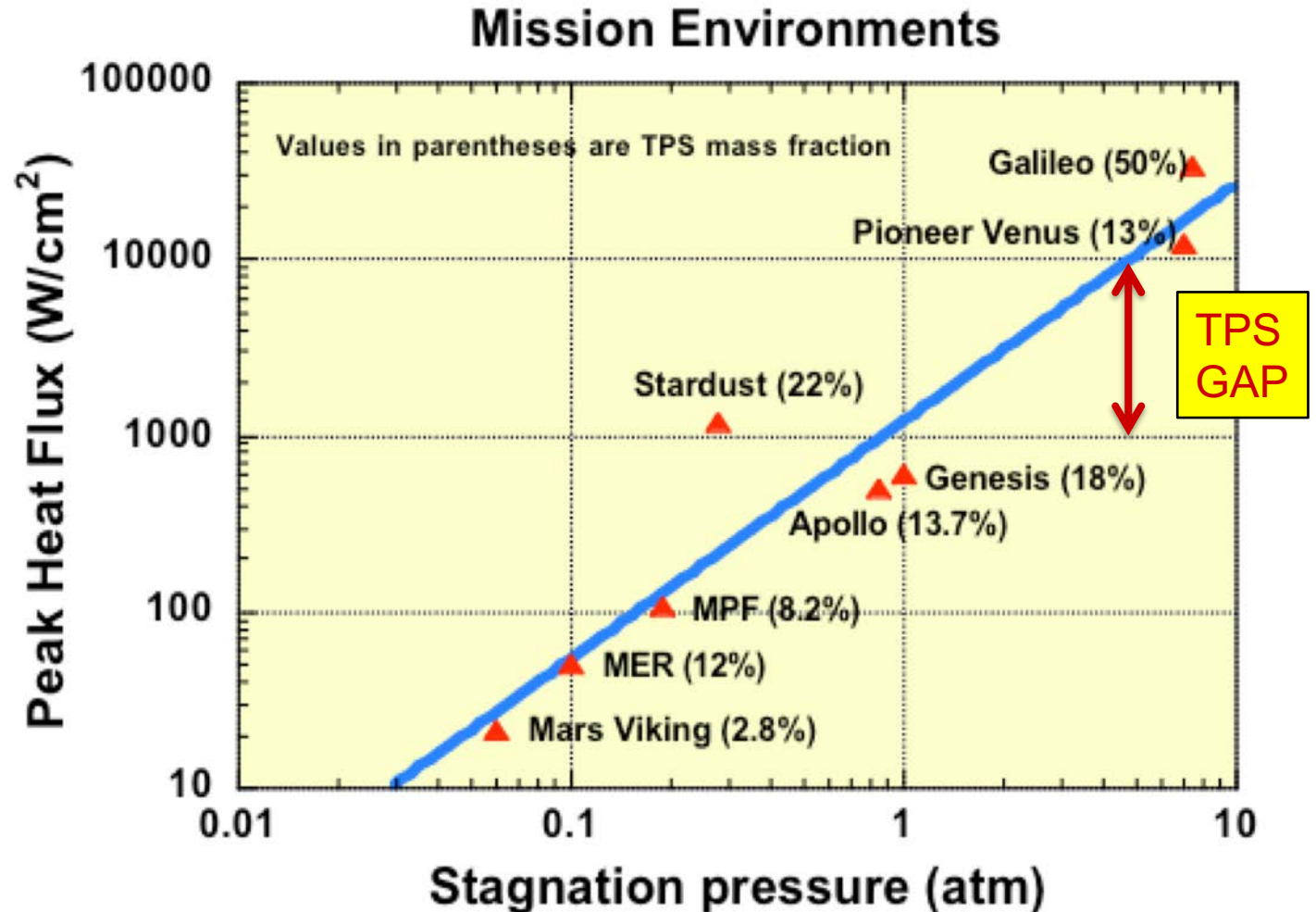
HEEET Team Accomplishments Presented by Don Ellerby 5.17.2019

Outline

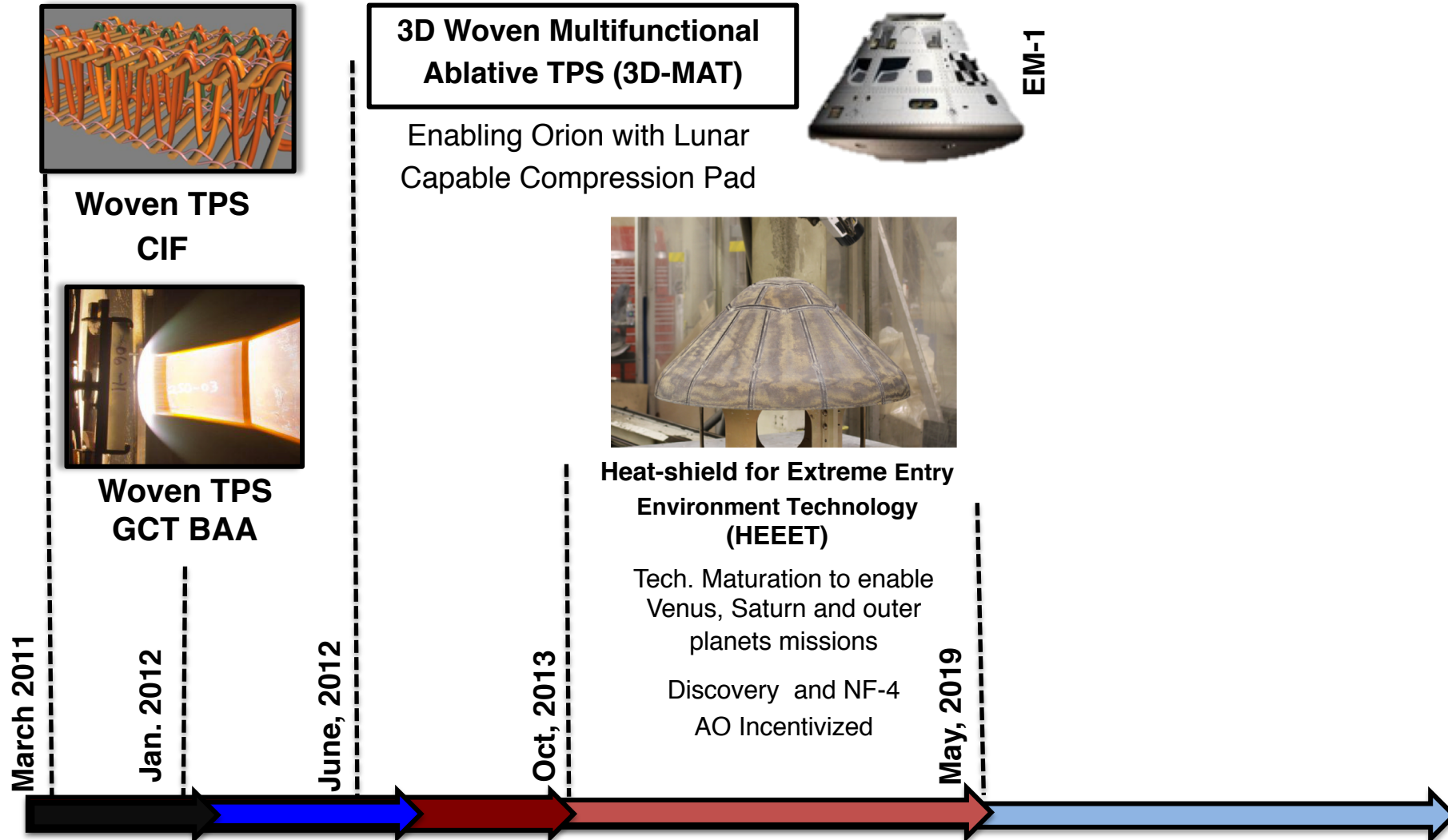
- **HEEET = Heatshield for Extreme Entry Environment Technology**
- **Motivation for HEEET**
- **Implementation (2014 – 2019)**
 - Requirements
 - Manufacturing
 - Aerothermal
 - Structures
- **Documentation**
 - Design Data Book
- **Final TRL Assessment**
- **Mission Infusion**

Motivation for HEEET

- Address a shortfall in available TPS to meet the needs for very high heating entry environments
- Desire to develop a system that would avoid some of the sustainability challenges related to “heritage” TPS (i.e. Carbon Phenolic)



3D Woven Thermal Protection System (TPS) Development



- 3D-MAT is tailoring a specific Woven TPS solution for the Orion compression pad for the 2018 Lunar Flight (EM-1)
- HEEET has been matured to TRL 6 and is ready for mission infusion.

SMD-STMD Agreement

The primary goal of the HEEET development activity is to develop a woven TPS technology to TRL 6. If successfully executed, the envisioned project will reduce the technology development risks allowing for infusion into Discovery-2014. The agreed-upon schedule for the technology development is that the TRL will be advanced to TRL 6 prior to the end of FY 2017. For the purposes of this agreement, TRL 6 is defined as the development of a *prototype system which would go well beyond ad hoc, "patch-cord", or discrete component level breadboarding and would be tested in a relevant environment* (excerpted from NPR 7123.1B Appendix E). A common understanding of the application of this definition will be required to validate reaching TRL 6. To achieve this milestone, the development team will complete the following major activities:

- Development of a mid-fidelity thermal response model.
- Completion of "coupon level" Arc Jet and Laser thermal performance tests.
- Development of a material property database.
- Completion of structural testing to validate the analytical thermal/structural models.
- A ~1 meter engineering test unit designed, fabricated, and tested under relevant environmental conditions.

Future planetary exploration missions operating in extreme environments may be enabled by the development of advanced Thermal Protection System (TPS) technologies. STMD has initiated the subject project to address the major TPS challenges associated with ambitious exploration missions. Specifically, the successful maturation of the HEEET technology has the potential to:

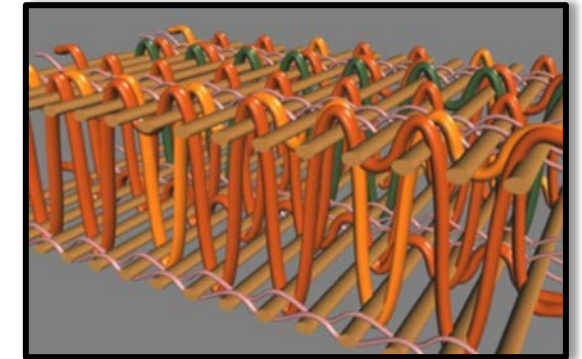
- Reduce entry g-load to less than 50 g's.
- Reduce the heatshield mass by 30% to 40% as compared to Carbon Phenolic.

These accomplishments will enable a broader range of science missions by allowing for increased flexibility of design for the critical entry phase.

What is the HEEET Material?

Mid-density 3D woven dual layer carbon phenolic

- 3D layer to layer weave
- Dual Layer:
 - OML Layer = Recession Layer (RL) – manages recession
 - Higher density all carbon fiber weave, exposed to entry environment
 - IML Layer = Insulation Layer (IL) – manages heat load
 - Lower density, lower thermal conductivity, blended carbon/phenolic yarn
 - 2 layers are integrally woven together,
 - mechanically interlocked (not bonded)
- Woven material has medium density phenolic resin infusion
 - Higher phenolic loading than PICA
 - Open porosity



3D Weave



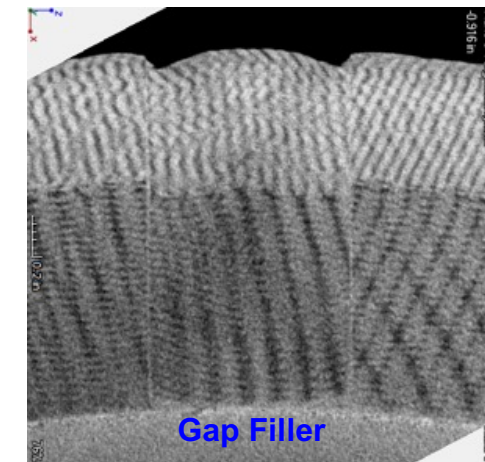
Dual Layer Weave

Project Requirements

- **Draft set of generic high level TPS requirements sent out for review:**
 - Developed with in-put from discipline experts within NASA, including folks who have supported MSL and MPCV
- **Assumption is that generally any TPS system is exposed to a common set of environments and that it's the magnitude of any loads induced by those environments that varies with the mission and point design:**
 - Ground
 - Launch
 - Transit (On-orbit)
 - Entry
- **Requirements provide a structure to discuss with mission proposing organizations our scope of work and progress towards achieving TRL 6**
 - Requirements are developed from a mission performance perspective
 - Verification written as a project technology development goal
- **Reviewed requirements during HEEET Workshop (7/30/13)**
 - Received feedback from Gov't (APL, JPL, GSFC,...), Industry (LM, Boeing,...)
 - Identified In-Scope Requirements for HEEET
 - Identified verification approach and TRL achieved

Seams in the HEEET Architecture

- **A tiled heatshield design is required due to weaving width limitations**
 - Results in seams between tiles – **the most challenging part of HEEET development**
- **The HEEET project has baselined a gap filler between tiles to perform two primary functions:**
 - Provide structural relief for all load cases by increasing compliance in the joint
 - Provide an aerothermally robust joint
- **Two factors inherent to the HEEET material and its mission applications drive requirements at the seams in the system.**
 - Aerothermal environments for HEEET mission architectures require unsupported adhesive joint widths be minimized to prevent runaway failure at the seam
 - IHF 3” nozzle testing at $\sim 3500 \text{ W/cm}^2$ and 5 atm suggest joints ≤ 0.010 ” are required
 - HEEET in-plane modulus is high
 - As the carrier structure deflects the HEEET architecture must have sufficient compliance to maintain compatibility with the carrier without inducing excessive stress in the system

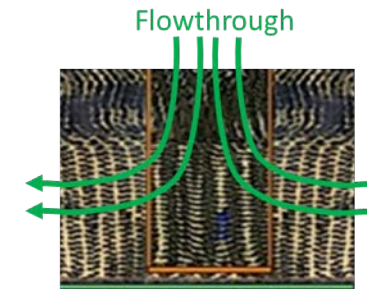
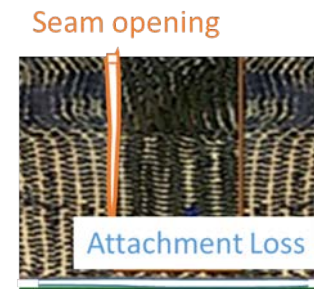
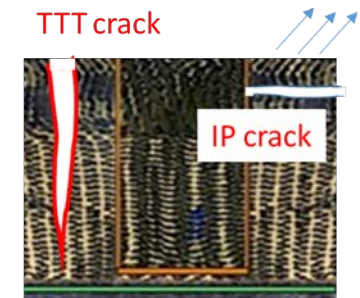


HEEET Failure Modes

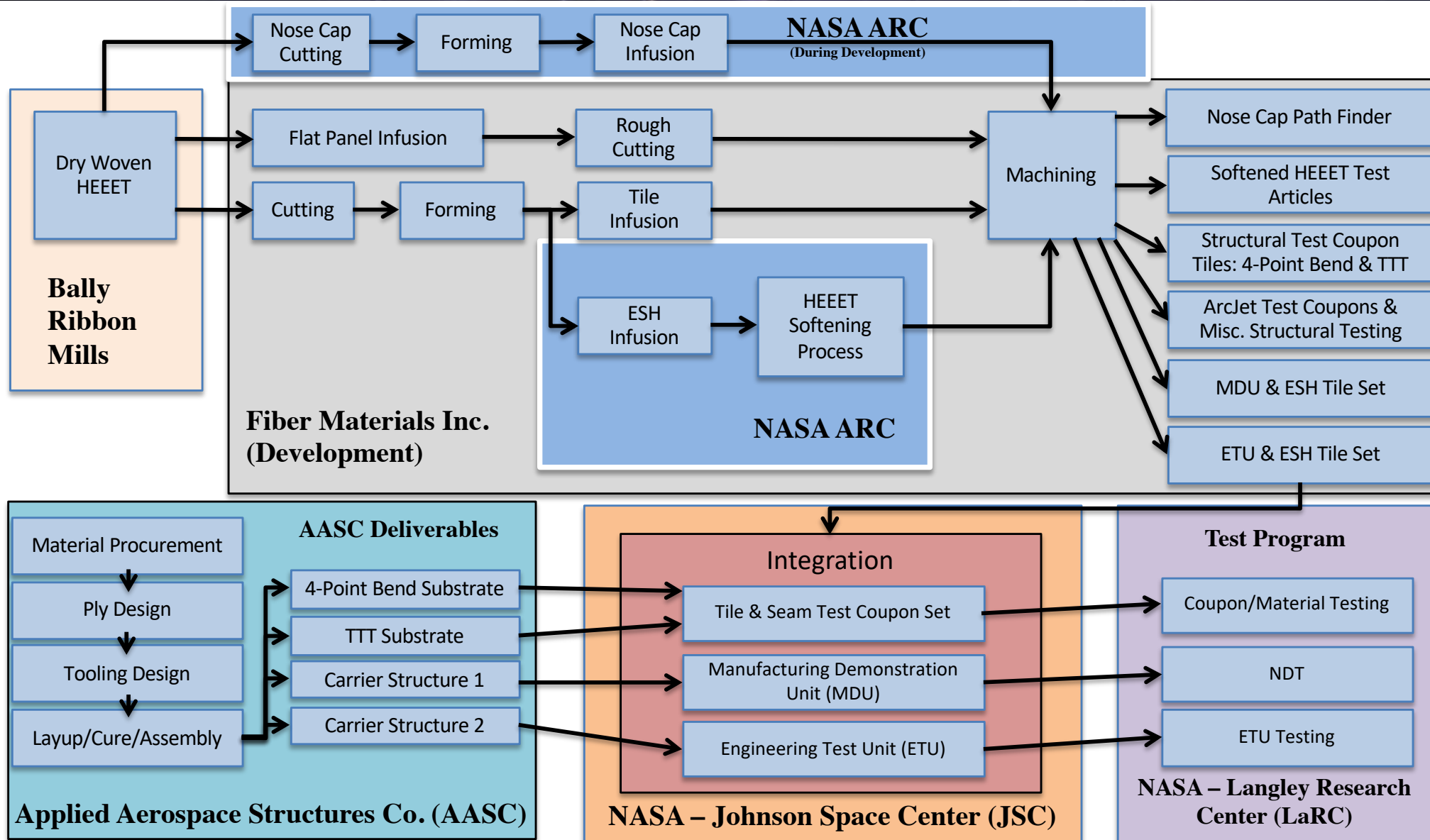
Typical failure modes of tiled systems include:

- 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

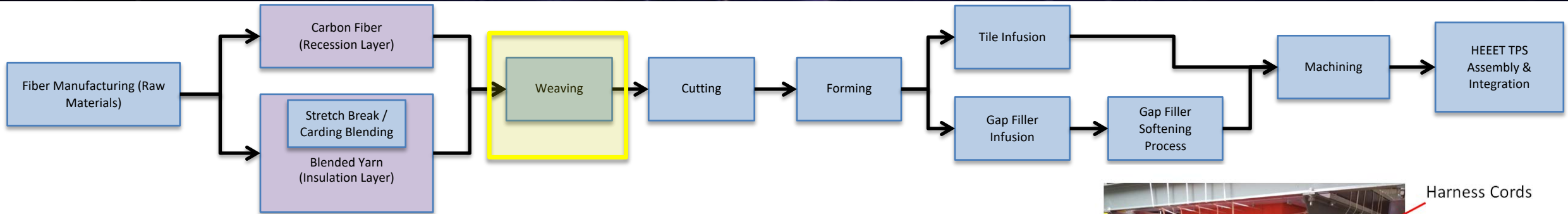
Structural Aero/Material



HEEET Manufacturing Overview

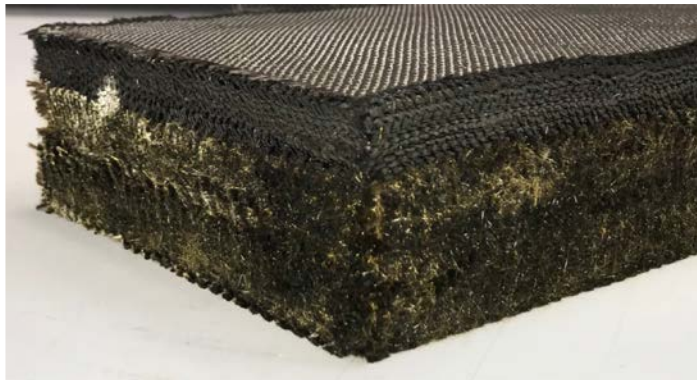


BRM Weaving

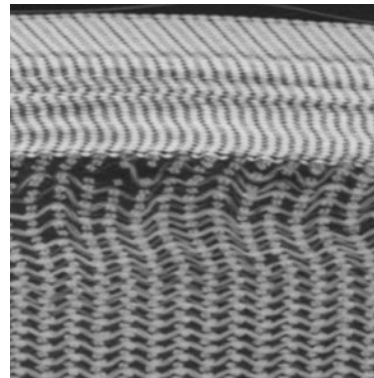


- **2 Phase scale up in weaving capability**

- Phase 1: From 1" thickness x 6" width to 2.1" thickness x 13" width
- Phase 2: Increased width to 24" (2.1" thickness)



Dual Layer HEEET Weave



CT Scan HEEET Weave



Harness Cords

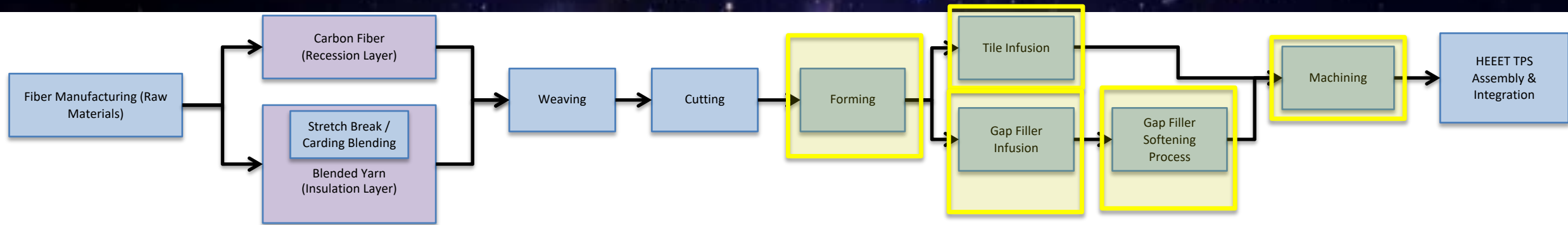
Heddles

Approx. 150 deep,
320 wide, total:
48,000 Heddles

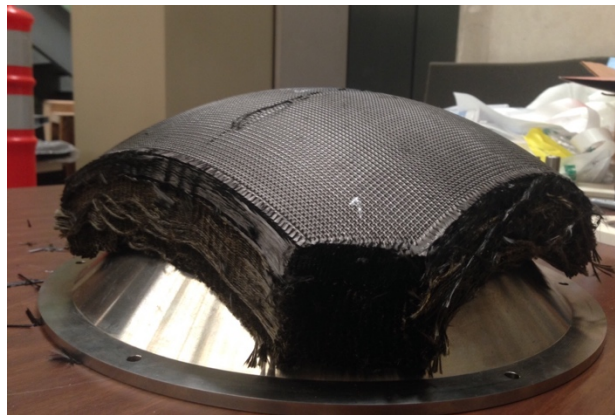
Springs (attached to
each Heddle)

24" Loom

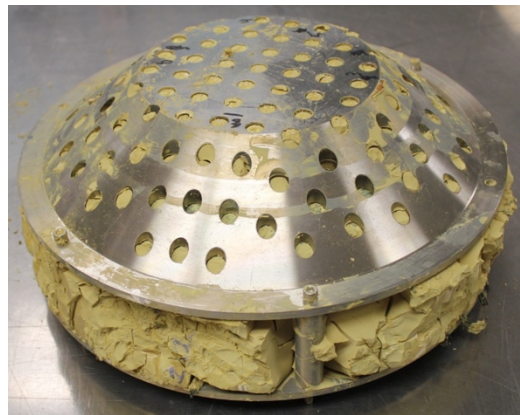
FMI Acreage Tile and Gap Filler Manufacturing



- **Forming, resin infusion and machining processes were initially developed in-house**
- **Established processes were Tech Transferred to Fiber Materials Inc. (FMI)**
- **FMI performed an upgrade to Infusion Vessel to support HEEET infusion process**
- **FMI successfully fabricated acreage tiles and gap fillers for the ETU**



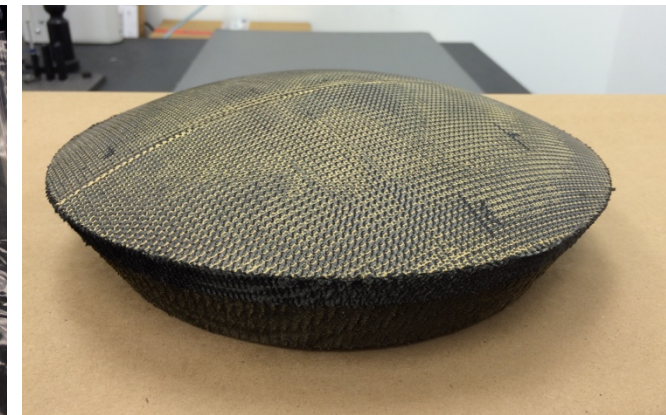
Forming



Resin Infusion: Tooling



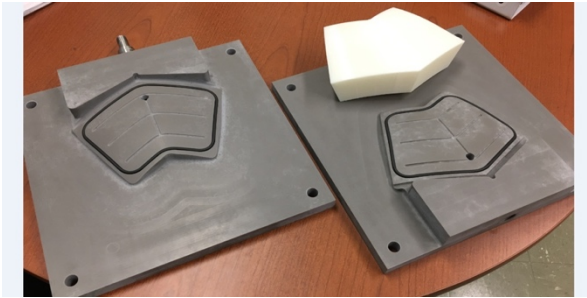
Infused Part



Machined Part

HEEET Drawings/Tooling/GSE/Carrier Structures

- 2 composite carrier structures built
- >25 ETU related GSE/Tooling Built
- 100+ ETU related drawing sheets
- >15 manufacturing/integration specifications released



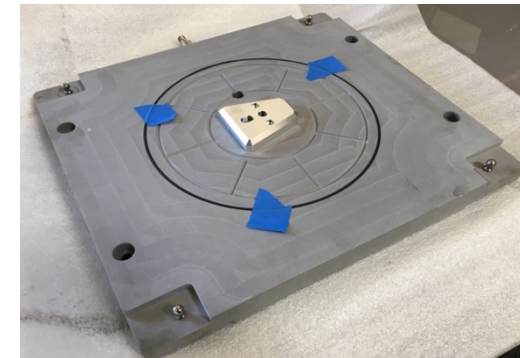
Inner Tile Vacuum Fixture



Routing Fixture



ESH Compression Tooling



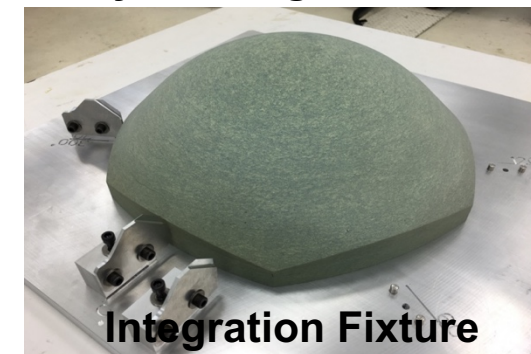
Assembly Routing Vacuum Fixture



Integration Build Stand



Composite Carrier Structures

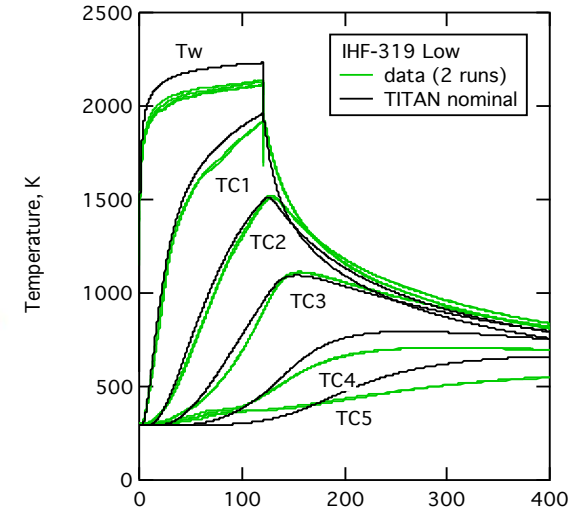
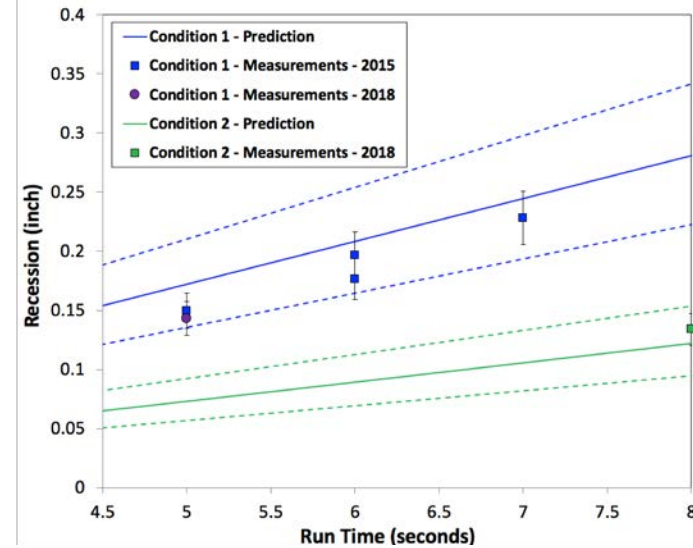


Integration Fixture

Arcjet Test Campaign

Objectives for aerothermal test campaign:

1. Support development and validation of the TPS sizing tools
 2. Exercise the system (acreage and seams) under mission relevant conditions to establish system capability
 - Looking for failure modes
- 12 arcjet test series conducted
 - >140 coupons tested
 - First testing in the IHF 3" nozzle
 - 3500 W/cm² and 5.3 atm
 - First NASA testing in AEDC H3 facility
 - 4000 Pa shear
 - FIAT code adapted to support dual layer TPS sizing
 - Novel dual layer margins policy developed



IHF 3":
Hot Wall Heat Flux: 3600 W/cm²
Pressure: 5.3 atm



AEDC Shear Testing:
Hot Wall Heat Flux: 1200 W/cm²
Pressure: 2.9 atm
Shear: ~4000Pa

Structural Test Campaign

- **Element Level Testing**

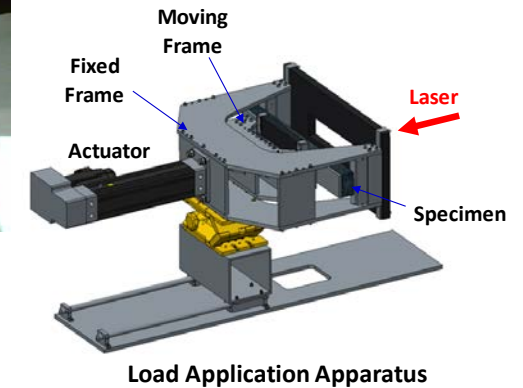
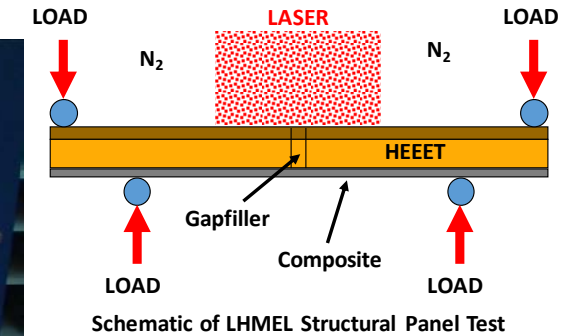
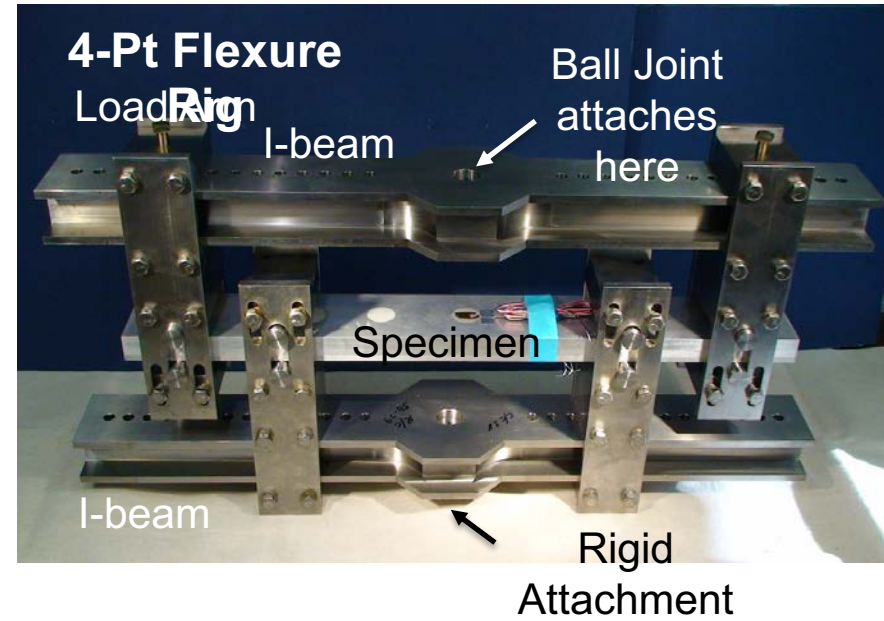
- Material Properties and allowables
 - Different Layers
 - Gap Filler
 - Adhesives
 - Composite structure

- **Component Level Testing**

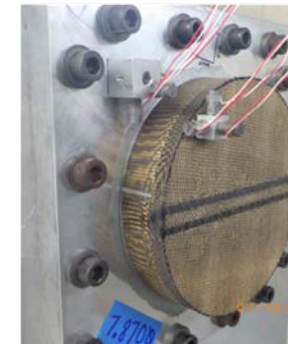
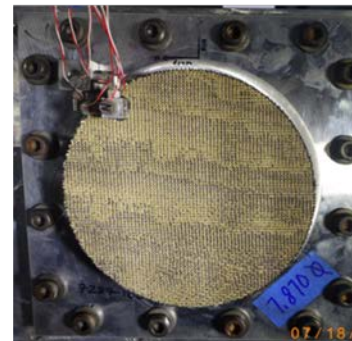
- 4-pt Bend (LaRC)
- LHMEEL 4pt-Bend
 - Developed novel test approach
 - Adopted by Orion
- Shock Testing (NTS)

- **Subsystem Testing (LaRC)**

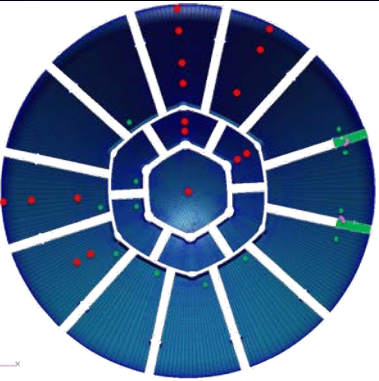
- 1m Engineering Test Uniut (ETU)



Shock Testing

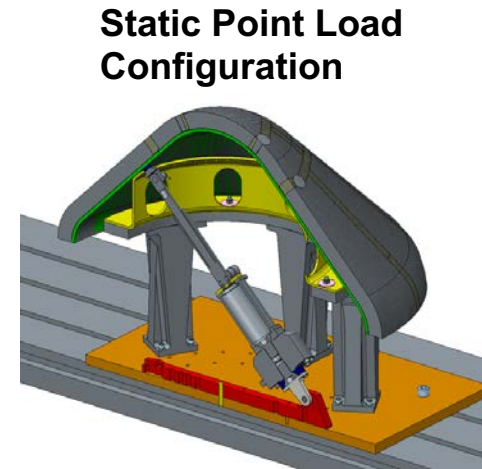
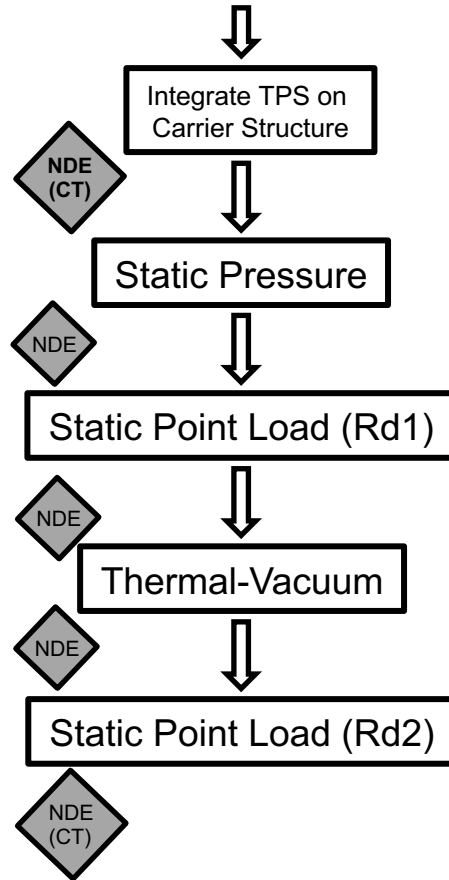


Subsystem (ETU) Testing Overview



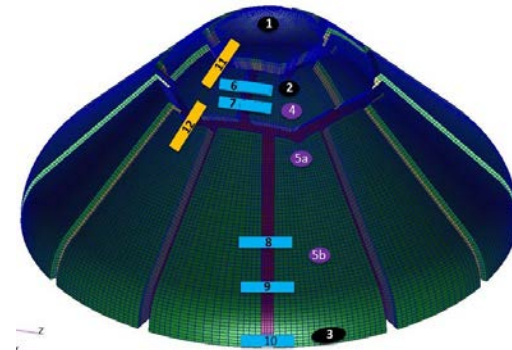
- 79 Total Strain Gages**
For Test:
- 24 Biaxial
 - 17 on Recession layer
 - 7 on Composite
 - 17 Uniaxial
 - 14 on Composite
 - 3 on Ring
- For Defect Tracking: 14 Uniaxial**

MDU Carrier Structure Proof Test
 ETU Carrier Structure Proof Test
 Pre-Integration



Static Point Load Configuration

Point Load Locations

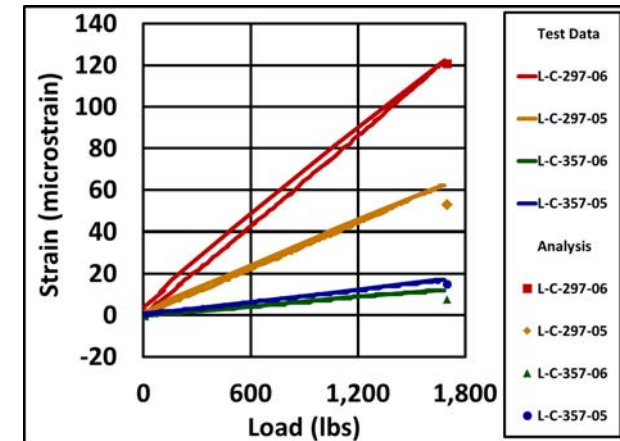
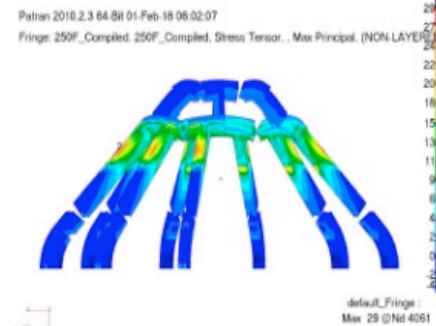
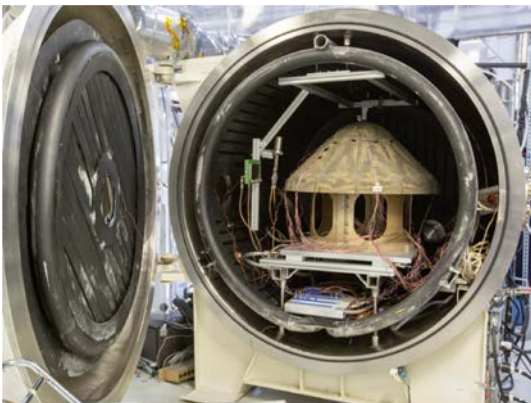


12 load locations are shown
 23 total tests, 2 at each location
 minus nose cap

Static Pressure Test in Autoclave



ETU in Thermal Vac Chamber



Pt 12: Under Closeout Plug

Documentation: Multi-Volume Design Data Book

Executive Summary

- **Need for TPS for Extreme Environments**
- **Woven TPS concept**
- **Requirements for HEEET Development Project**
- **Scope of Development Effort**
- **Summary of Other Volumes**
 - HEEET System Manufacturing Guide
 - Design Development
 - Aerothermal Testing
 - Structural and Thermostructural Testing
- **Status and Recommendations**

System Manufacturing Guide

- **System Architecture**
- **System Implementation Requirements**
- **Manufacturing and Integration Overview**
- **Individual Processes**
 - ◆ Verification of Inputs
 - ◆ Process
 - ◆ Verification of Product
- **Appendix: Process Specs**

Design Development

- **Failure Modes and Margin Policy**
- **Selection of Weave**
- **Selection of Infusion**
- **Forming**
- **Panel to Panel Attachment**
- **Substrate Attachment**
- **Machining**
- **Selection of Adhesives**
- **Gap-filler**
- **Selection of Adhesive Thickness**
- **Assembly**
- **Repair**
- **Acceptance Policy**
 - ◆ Process Controls
 - ◆ Inspection
 - ◆ Acceptance Test
- **Aerothermal Response Model Development**
- **Structural Model Development**
- **Material Properties**

Adds Why

Aerothermal Characterization

- **Overview**
- **Properties Testing**
- **Failure Modes**
 - ◆ Acreage
 - ◆ Gap-filler
 - ◆ Adhesive
 - ◆ System Architecture Features
- **Aerothermal Response Modeling**
 - ◆ Acreage
 - ◆ Gap-filler
- **Findings**
- **Appendices: Individual Test Series Reports**

Structural Characterization

- **Overview**
- **Properties Testing**
- **Failure Modes**
 - ◆ Acreage
 - ◆ Gap-filler
 - ◆ Adhesive
 - ◆ System Architecture Features
- **Structural Response Modeling**
 - ◆ Acreage
 - ◆ Gap-filler
- **Findings**
- **Appendices: Individual Test Series Reports**

Independent Review Board

- **HEEET established an Independent Review Board at the start of project**
 - Self imposed requirement
 - Membership included TPS developers, TPS flight hardware integrators, and mission-proposing community
 - Regular insight and feedback on TRL progress and requirements verification
 - IRB provided a TRL assessment at the end of the project: **HEEET achieved TRL 6**
- **HEEET Standing Review Board members:**
 - Bobby Braun (UC-Boulder, IRB Chair), Micheal Amato (GSFC), Stan Bouslog (JSC), Robin Beck (ARC), Anthony Calomino (LaRC), Steve Gayle (LaRC), Ken Hibbard (APL), Pam Hoffman (JPL), Joy Huff (KSC), Michelle Munk (LaRC), Christine Szalai (JPL)
- **13 IRB Reviews:**
 - Baseline Architecture Downselect: Nov 2013
 - Project Plan Review: June 2014
 - ETU System Requirements Review: Sept 2014
 - Design Review #1: Feb 2015
 - Thermal Test Plan Review: June 2015
 - Structural Test Plan Review: Feb 2016
 - Manufacturing & Integration Review: Mar 2016
 - Failure Modes & Margins Review: Dec 2016
 - Manufacturing Schedule & Forward Work: Feb 2017
 - ETU Manufacturing Readiness Review: Aug 2017
 - End of FY18 Status and FY19 Planning: Sept 2018
 - Design Data Book Review: May 2019
 - TRL Assessment: May 2019
- IRB has proven to be extremely valuable, providing insights from a mission implementation perspective as well as project implementation

Final TRL Self Assessment

Have we built high-fidelity prototypes that address scaling issues? Yes

Have we operated in relevant environments?

- Aerothermal (arc-jets) **Yes**
- Thermostructural (combined loading of flexures at LHMEEL) **Yes**
- Structural (pressure, thermal-vacuum and point loads on 1 m ETU) **Yes**

Have we documented test performance demonstrating agreement with analytic predictions? Yes

HEEET system is assessed to be at **TRL 6**

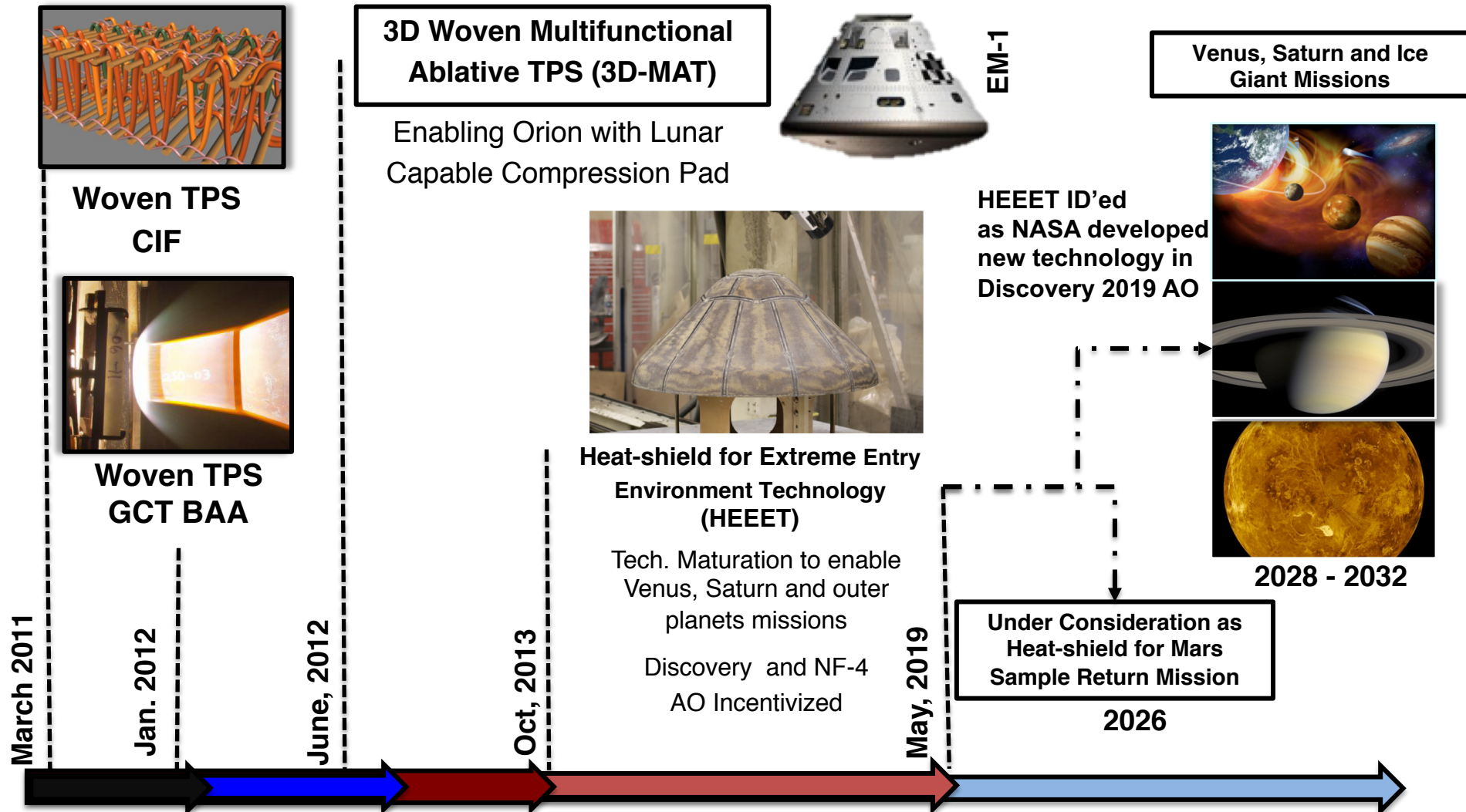
Limitations

- Not at TRL 6 for thickness much greater than 2"
- Not at TRL 6 for applied environments above 5 atm and 3600 W/cm²
- No mission opportunity (except Jupiter) appears to require these levels

Mission Infusion

- **HEEET called out as GFE with incentives for Discovery 2014 and NF-4**
- **NF-4:**
 - Incentive:
 - HEEET team provided as GFE for consulting and technology transfer through the mission lifetime
 - \$20M above cost cap
 - NASA committed to delivering HEEET at TRL 6
 - Risk of technology development to TRL 6 did not impact evaluation of mission risk
 - Risk of technology implementation was assessed as part of mission risk evaluation
 - **Be careful what you wish for!**
 - HEEET was baselined by 4 proposal teams for NF-4
 - Conducted TPS Sizing for 55 scenarios
 - More than 250 sizing runs
 - Excellent exercise for future proposal team support

3D Woven Thermal Protection System (TPS) Development



- 3D-MAT is tailoring a specific Woven TPS solution for the Orion compression pad for the 2018 Lunar Flight (EM-1)
- HEET has been matured to TRL 6 and is ready for mission infusion.

HEEET Team

NASA ARC:

- Dave Driver (Retired)
- Marianne Shelley (Retired)
- Ron Chinnapongse (Retired)
- Don Ellerby
- Matt Gasch
- Cole Kazemba
- Milad Mahzari
- Frank Milos
- Owen Nishioka
- Keith Peterson
- Margaret Stackpoole
- Ethiraj Venkatapathy
- Zion Young
- Peter Gage
- Tane Boghozian
- Jose Chavez-garcia
- Greg Gonzales
- Ben Libben
- Ruth Miller
- Grant Palmer
- Dinesh Prabhu
- Joseph Williams
- Alexander Murphy

NASA JSC:

- Mike Fowler
- Charles Kellermann

NASA LaRC:

- Carl Poteet
- Scott Splinter
- Sarah Langston
- Kevin Mclain
- Gregory Shanks
- Jacob Tury
- Stewart Walker

NASA Facilities:

- Ames:
 - Arcjet Complex
 - STAR Lab
 - EEL
 - Main Shop
- JSC:
 - ES4/Manufacturing
- LaRC
 - James H. Starnes, Jr., Structures and Materials Laboratory
 - Light Alloy Lab
 - Materials Research Lab
 - Model Shop
 - Systems Integration and Test Branch Laboratory

External Partners:

- Bally Ribbon Mills
- Fiber Materials Inc.

External Test Facilities:

- Laser Hardened Materials Evaluation Laboratory (LHMEL)
- Arnold Engineering Development Center (AEDC)
- NTS

External NDE:

- Hadland
- NSI
- VJ Technologies

Carrier Structures:

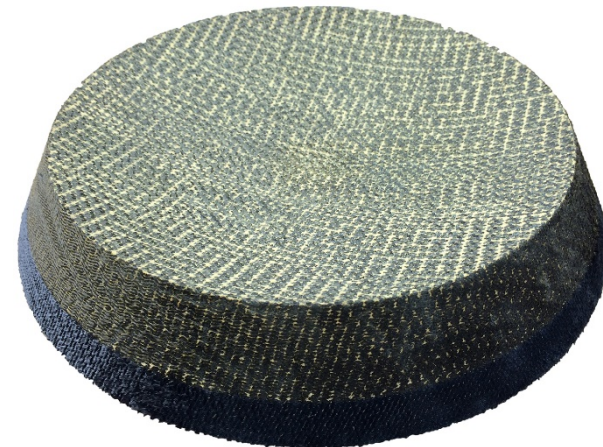
- AASC



**NASA Ames
Research Center**
Mountain View, CA

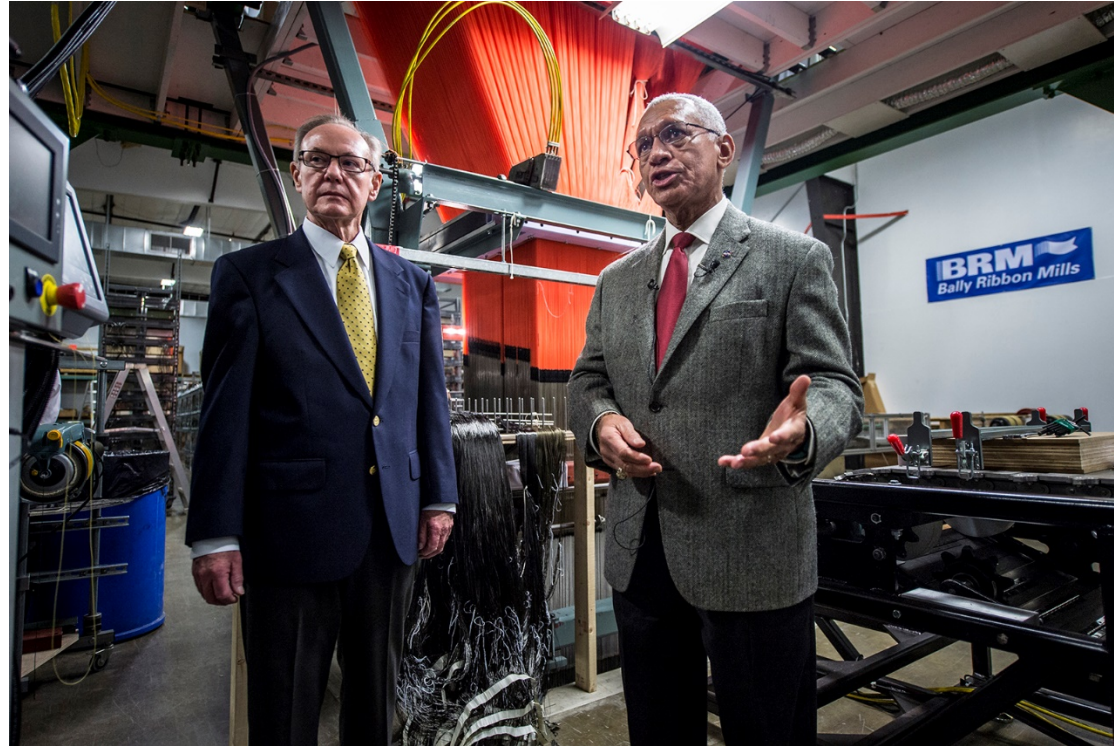
Bally Ribbon Mills
Bally, PA







The Path to Mars Goes Through Bally, Pennsylvania



With HEEET, it might just come back to Earth too!



**HEEET TPS DEVELOPMENT SUPPORT AND MANUFACTURING
SCALE UP**

Fiber Materials Inc., Biddeford, Maine U.S.A.

May 18, 2019

HEEET Manufacturing at FMI: Program Summary

- 2014-2018 project to support NASA Ames Research Center TPS manufacturing development of HEEET
- Design/installation of automated multi-component infusion system equipment: 2014-2015
- Densification qualification runs and test material fabrication: 1" then 2" HEEET: 2015
- Testing: thermal conductivity & density, panels for flexure/laser tests: 2015-2016
- Machining process development: 2015 & 2017
- Forming tiles: tooling design/fabrication & forming process development: 2015-2016
- ETU densification tooling design/fabrication: 2015-2016
- ETU panel densification: 2016
- ETU tile machining and inspection: 2016-2017
- Gap filler softening equipment upgrades, process trials and demonstration: 2017
- ETU Gap filler machining: 2017
- Fabrication of more test materials: 2018

HEEET Manufacturing at FMI: Lessons Learned

- Lessons learned in every step of process:
 - How to change PICA infusion process for HEEET: blind process
 - How to machine: on a mill, locating features, tools, speeds & feeds, inspection techniques
 - Forming process: how to make the preforms fit the tooling with no gaps and no wrinkles
 - Densification tooling design iterations: CTE mismatches and how to make it affordable
 - Tile densification: shrinkage not stress relaxation!
 - Knowing what you have versus what your supposed to have: laser inspections everywhere!!
 - Gap fillers: hydraulic capacitance was a pressing problem
 - Gap filler machining: have we mentioned laser inspections everywhere?
- Lots of learning (& lots of fun)

Any Questions?

