Heatshield for Extreme Entry Environment Technology (HEEET) Thermal Protection System (TPS)

Presented by Matt Gasch

MS&T19 Technical Meeting and Exhibition, 9/29 – 10/3/2019, Portland OR

HEEET Team

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HEEET Independent Review Board (IRB)

- 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)

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:

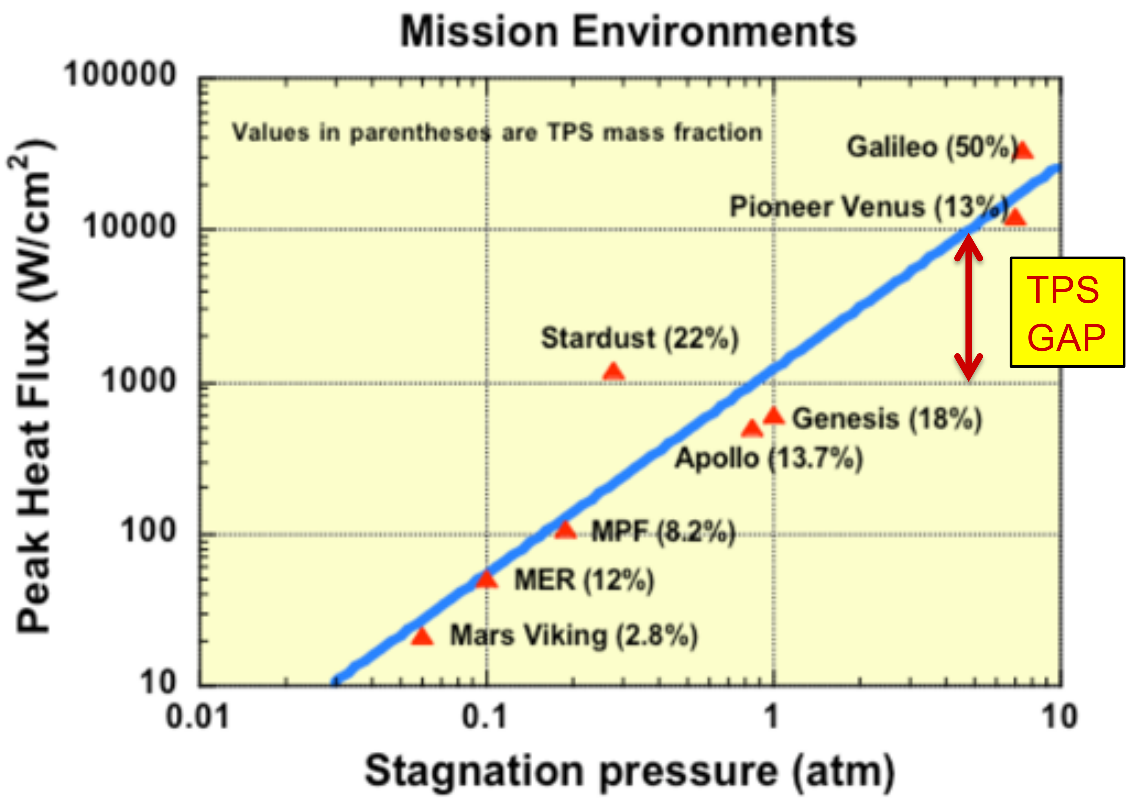
- AASC

Outline

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

Motivation for HEEET

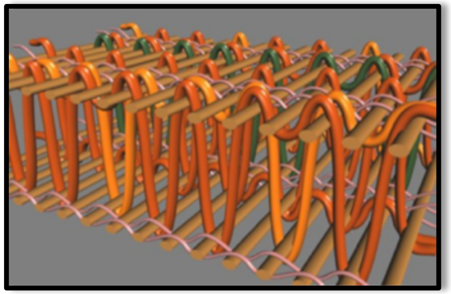
- **Address a shortfall in available TPS to meet NASA's needs for planetary science missions with very high heating entry environments**
- **Desire to develop a system that would avoid some of the sustainability challenges related to "heritage" TPS (i.e. Carbon Phenolic)**



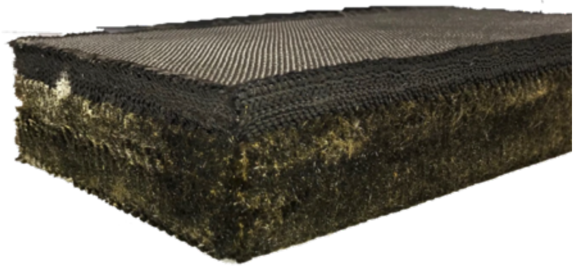
What is the HEEET Material?

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



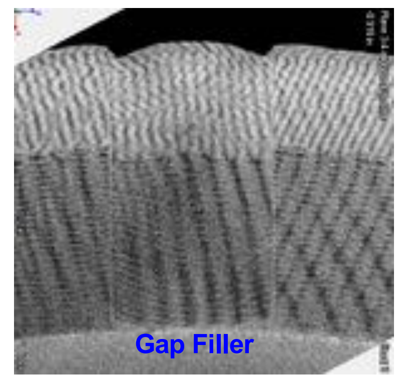
Dual Layer Weave

Project Objectives Formulation Process

- **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

- **Target vehicle sizes range from <1m – >3.5m base diameter**
- **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 ~3500 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

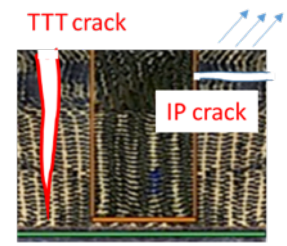


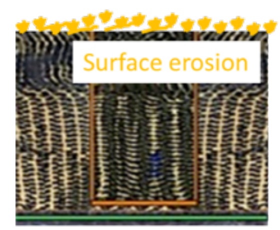
HEEET Failure Modes

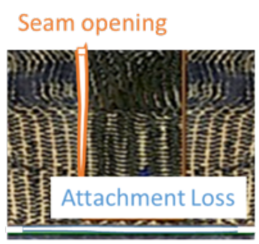
Typical failure modes of tiled systems include:

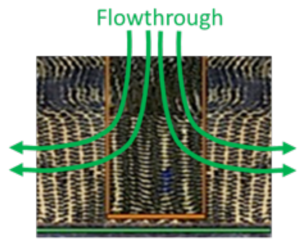
- Tile and gap-filler failure
  - Through Thickness cracks causing “heat leaks”
  - In plane cracks causing reduced thickness
  - Surface erosion (mechanical failure causing spallation or accelerated layer loss)
  - Flowthrough (permeability permits interior flow)
- Loss of attachment of tiles or gap 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

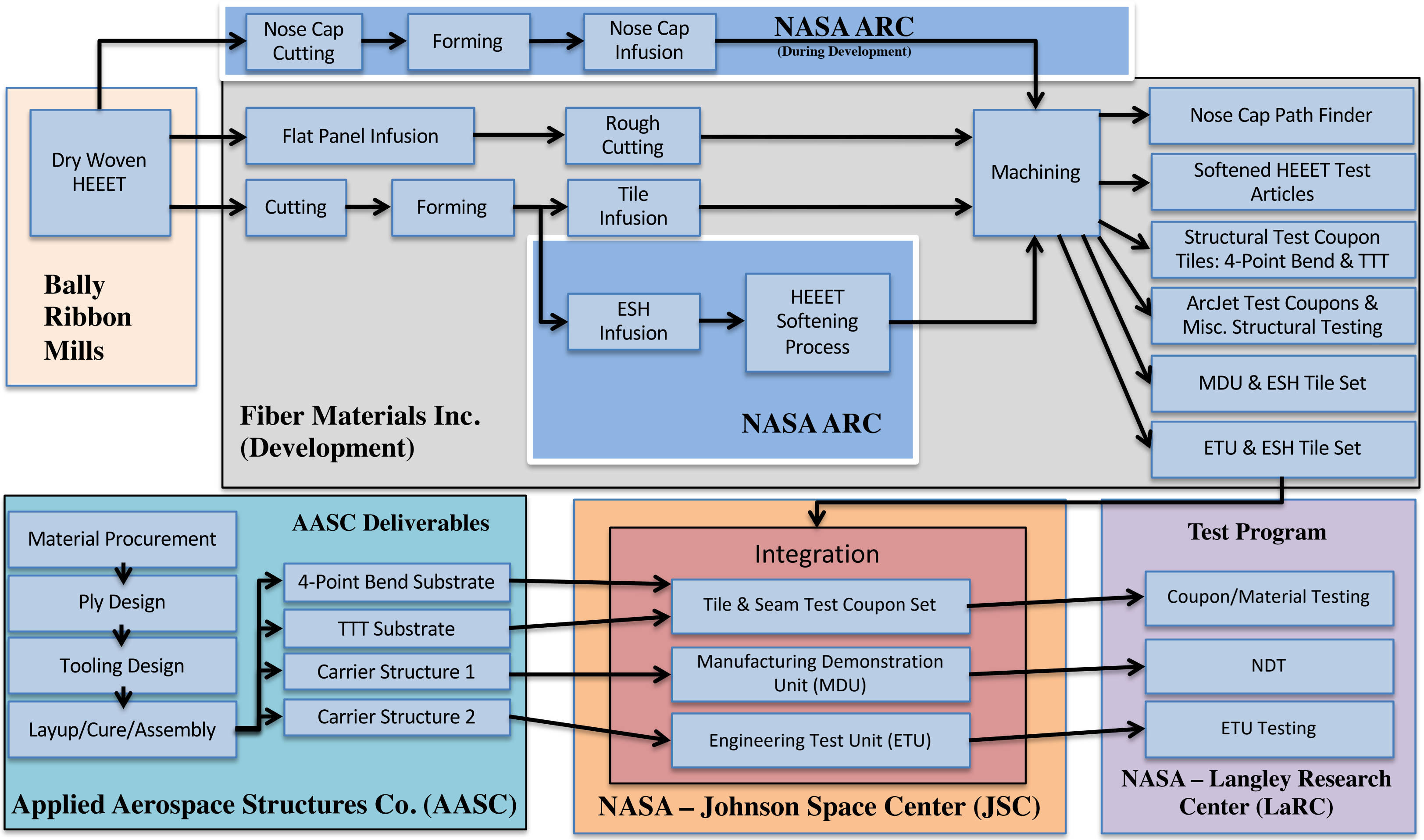




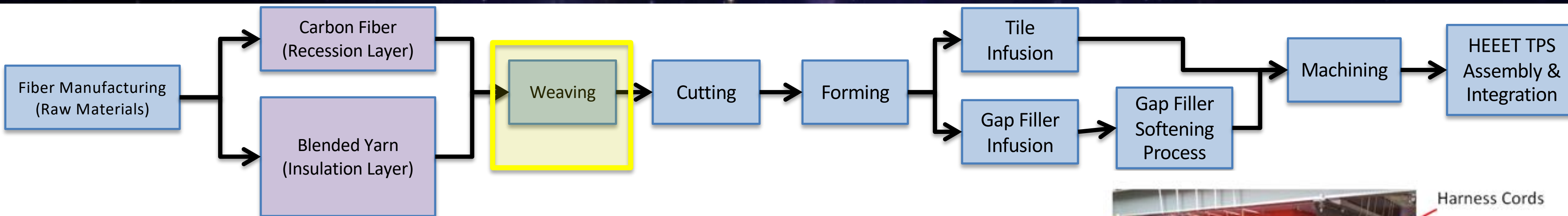




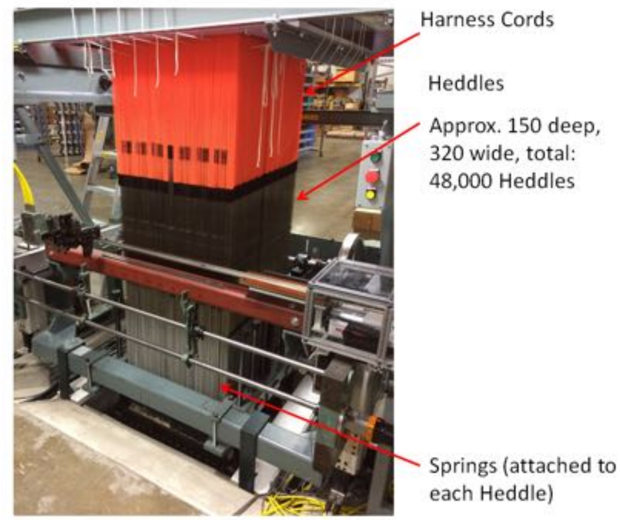
HEEET Manufacturing Overview



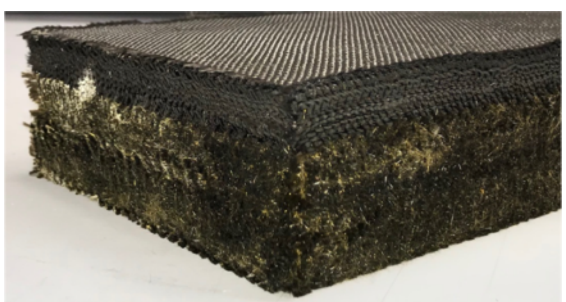
BRM Weaving



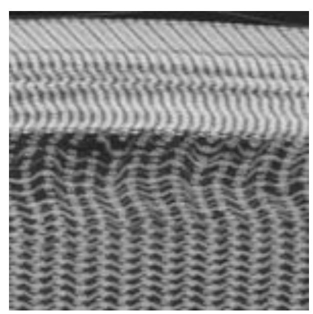
- **2 Phase scale up in weaving capability**
  - Phase 1: From 1” thickness x 6” width to 2.1” thickness x 13” width
  - Phase 2: Increased width to 24” (2.1” thickness)



24” Loom

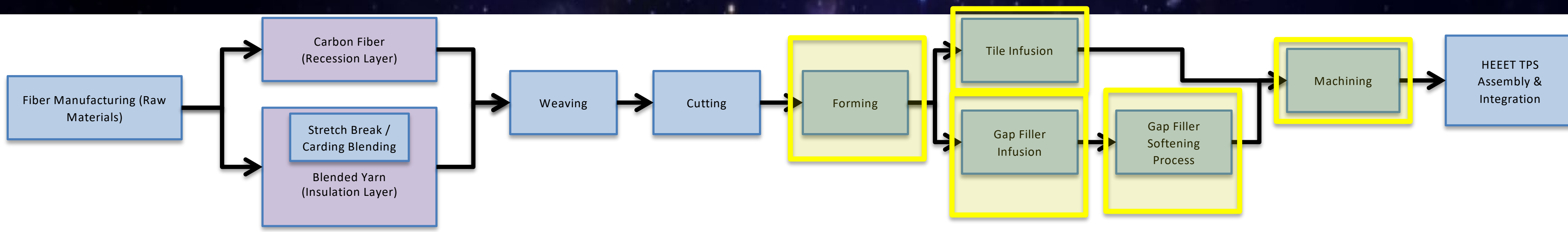


Dual Layer HEEET Weave



CT Scan HEEET Weave

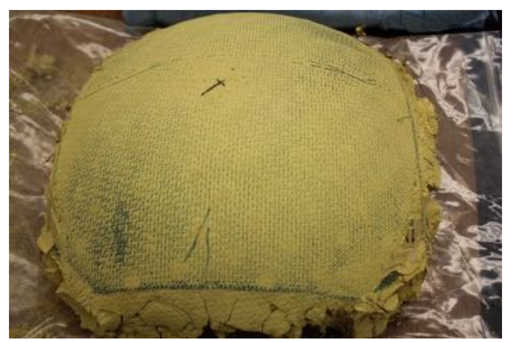
FMI Acreage Tile and Gap Filler Manufacturing

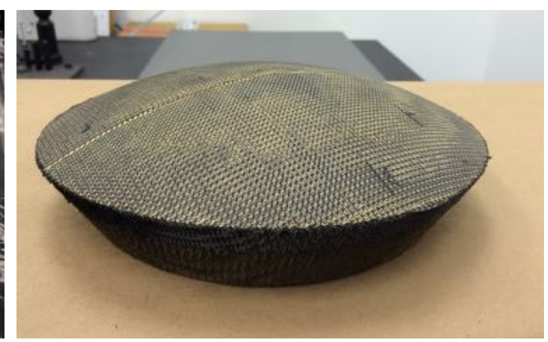


- Forming, resin infusion and machining processes were initially developed in-house
- Established processes were Tech Transferred to Fiber Materials Inc. (FMI)
- FMI performed an upgrade to Infusion Vessel to support HEEET infusion process
- FMI successfully fabricated acreage tiles and gap fillers for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


Forming


Resin Infusion: Tooling


Infused Part


Machined Part

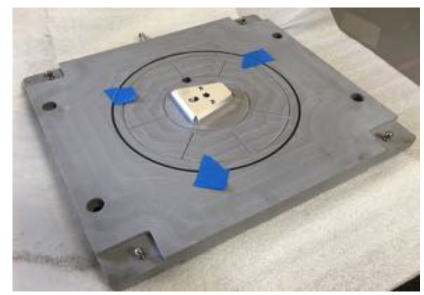
HEEET Drawings/Tooling/GSE/Carrier Structures

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

ESH Compression Tooling

Inner Tile Vacuum Fixture

Routing Fixture



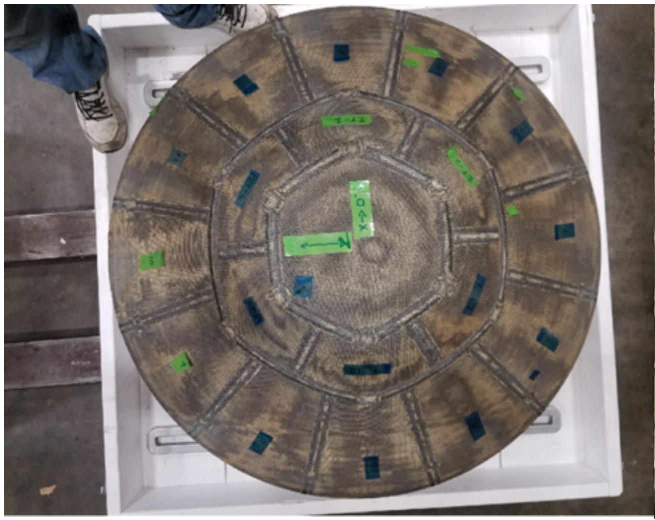
Assembly Routing Vacuum Fixture

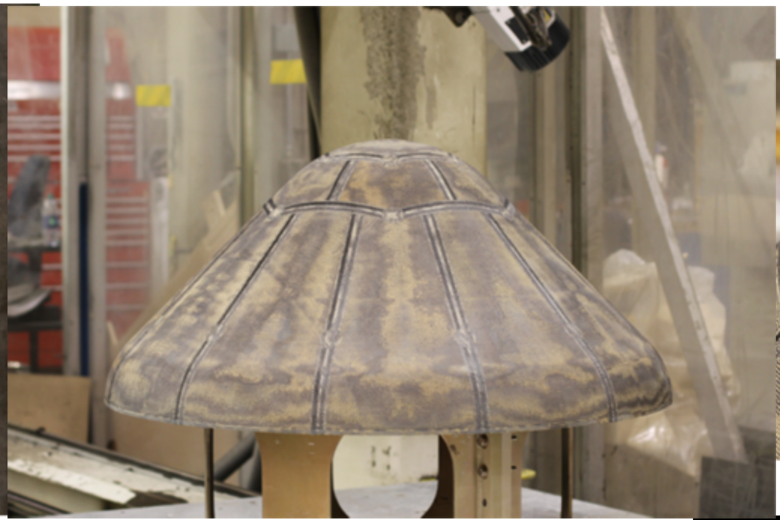
Integration Build Stand

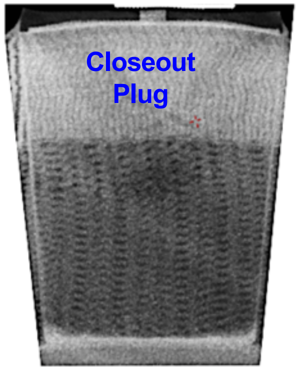
Composite Carrier Structures

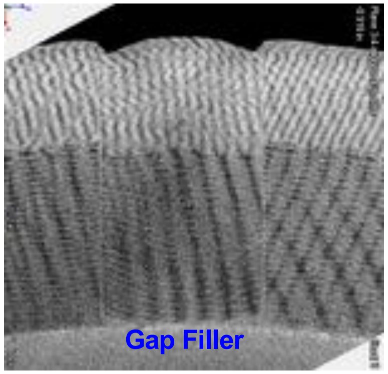
Integration Fixture

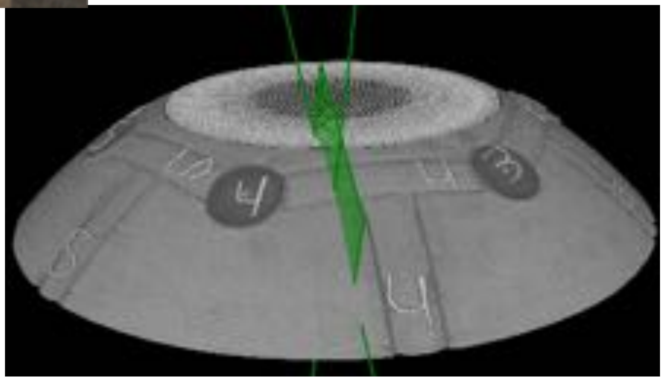
1m ETU Successfully Built and Inspected by CT Scan









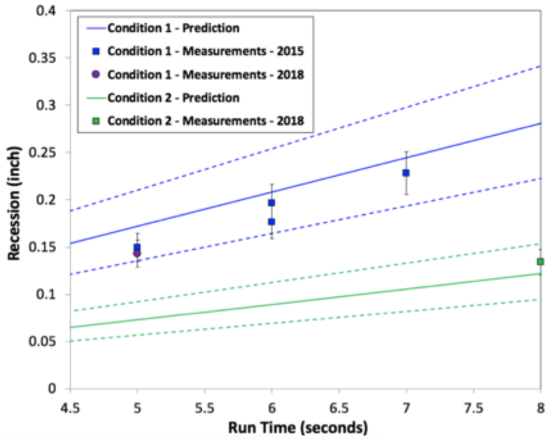


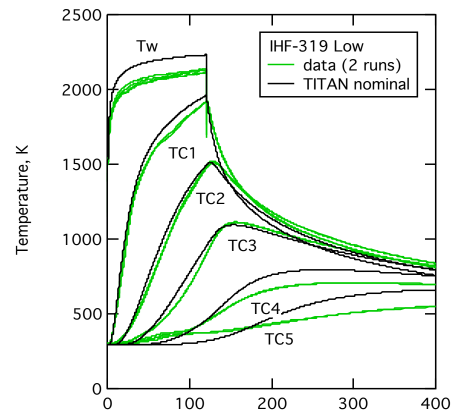
Arcjet Test Campaign

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/cm^2 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

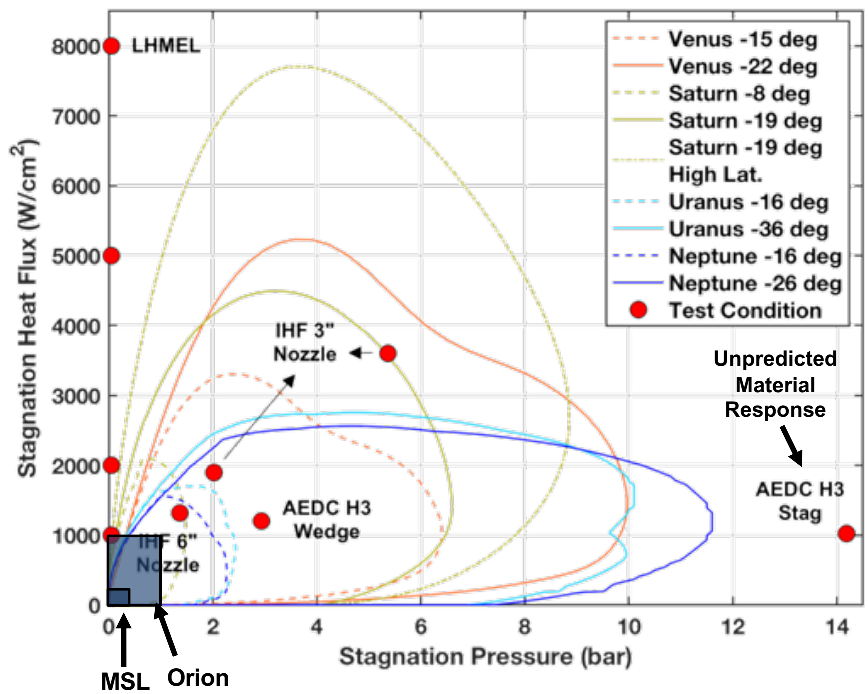




IHF 3”:
Hot Wall Heat Flux: 3600 W/cm^2
Pressure: 5.3 atm

AEDC Shear Testing:
Hot Wall Heat Flux: 1200 W/cm^2
Pressure: 2.9 atm
Shear: ~4000Pa

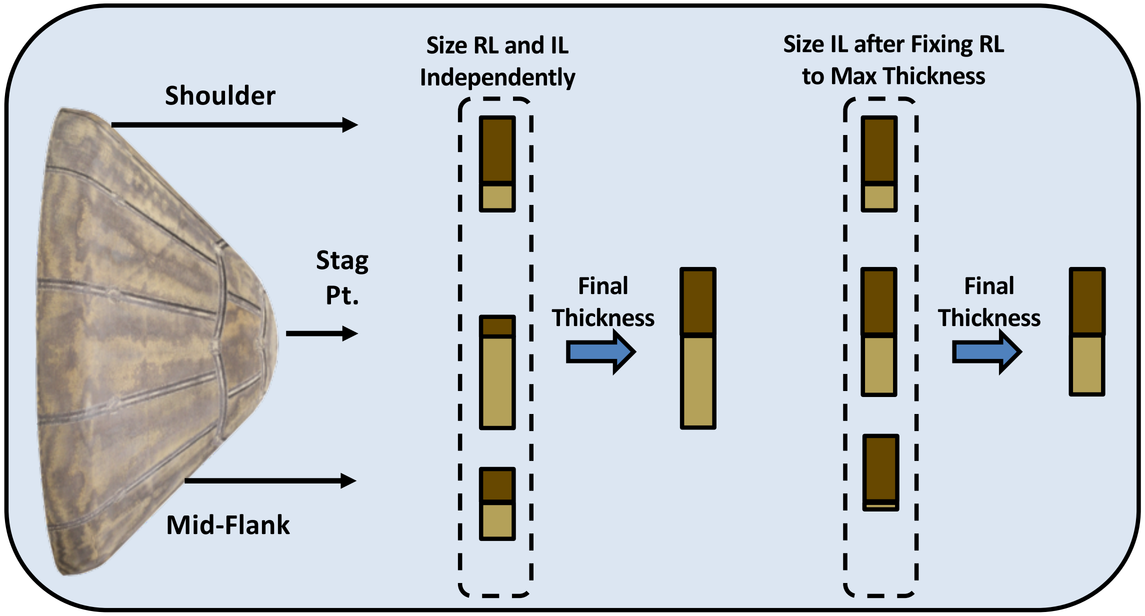
HEEET Arcjet Testing Covers Some Mission Options for All Target Destinations



Limits in ground based test facilities to achieve relevant conditions for some steep and high latitude entries. This issue applies to any TPS concept, not just HEEET.

Dual Layer TPS Sizing

- **TPS sizing is the process for determining the thickness of the TPS**
- **Bondline is the interface between the inner surface of the TPS (IML) and the structure to which it is typically adhesively bonded**
- **For single layer TPS the constraint is not to allow the bondline, to exceed temperature limit of adhesive or structure**
- **Dual Layer TPS introduces a new constraint, not to allow the insulation layer to be exposed**
- **Current HEEET implementation requires uniform TPS thickness for both layers**
- **Max thickness for each layer may occur at different body points and trajectories**
- **Sizing RL and IL independently and then stacking max RL thickness from one location on max IL thickness from another location is not mass efficient**
  - Excess RL at some locations can serve as insulation
- **More mass efficient to size IL after fixing RL to max sized thickness across all locations**



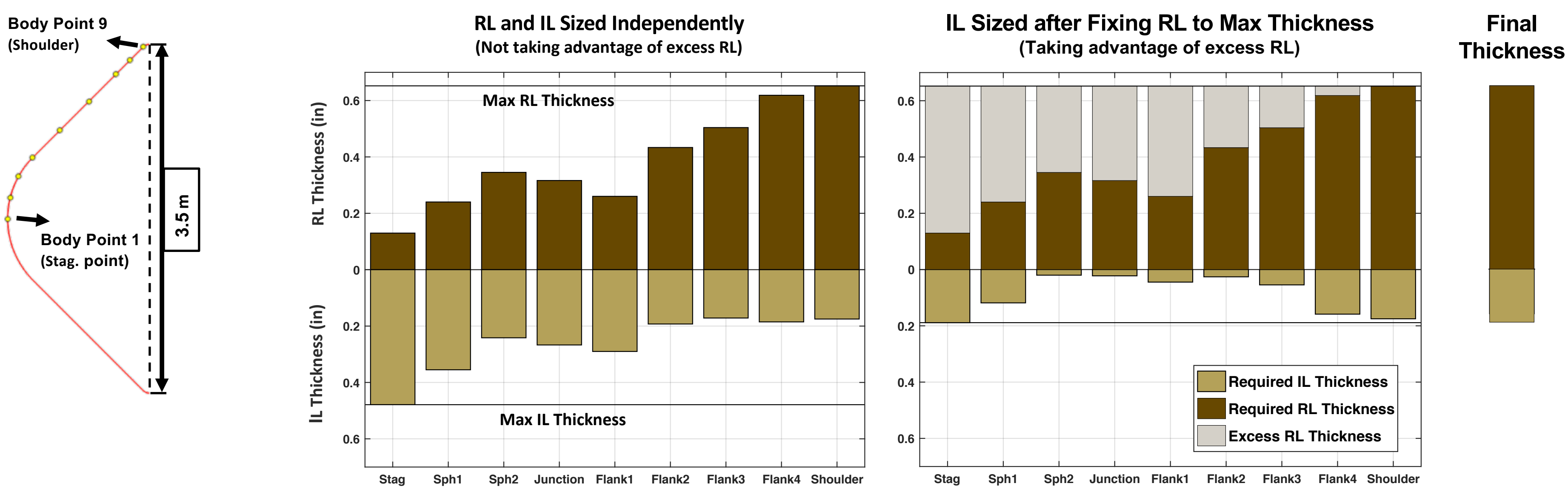
Example Sizing from a Venus Reference Mission

Sizing done at 9 locations on the heatshield

- Figure on left: RL and IL sized independently
- Figure on right: RL sized first; then IL sized while for fixed RL thickness

Taking advantage of the nonessential portion of RL thickness at locations that don't drive RL sizing provides mass benefits

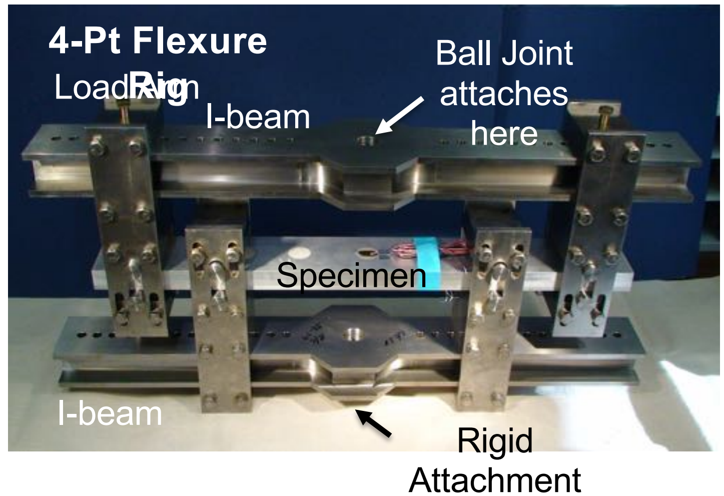
- 62% reduction in IL thickness, 19% reduction in areal mass

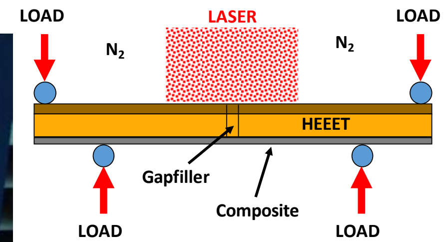


*Sizing and Margin Methodology for Dual-Layer Thermal Protection Systems, Mahzari and Milos, 15th International Planetary Probe Workshop

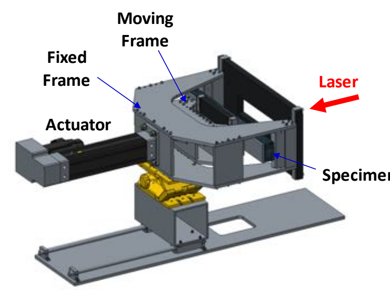
Structural Test Campaign

- **Element Level Testing**
  - Material Properties and allowables
    - Different Layers
    - Gap Filler
    - Adhesives
    - Composite structure
- **Component Level Testing**
  - 4-pt Bend (LaRC)
  - LHMEL 4pt-Bend
    - Developed novel test approach
    - Adopted by Orion
  - Shock Testing (NTS)
- **Subsystem Testing (LaRC)**
  - 1m Engineering Test Uniut (ETU)



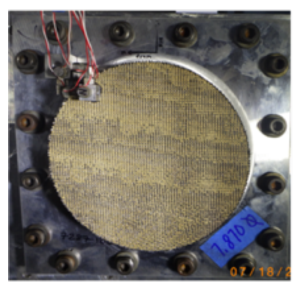


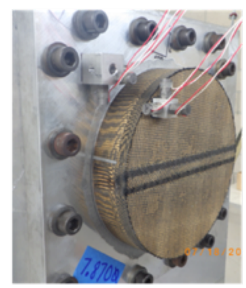
Schematic of LHMEL Structural Panel Test



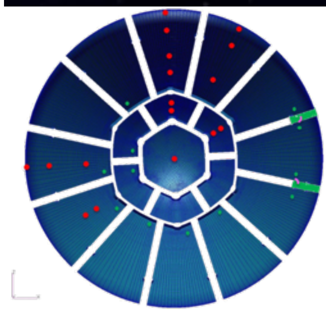
Load Application Apparatus

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

⇩

Integrate TPS on Carrier Structure

NDE (CT)

⇩

Static Pressure

NDE

⇩

Static Point Load (Rd1)

NDE

⇩

Thermal-Vacuum

NDE

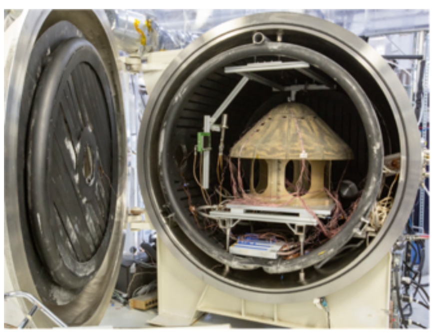
⇩

Static Point Load (Rd2)

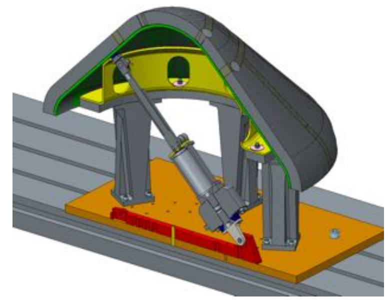
NDE (CT)

Static Pressure Test in Autoclave

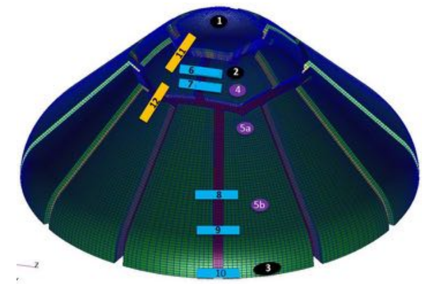
ETU in Thermal Vac Chamber



Static Point Load Configuration

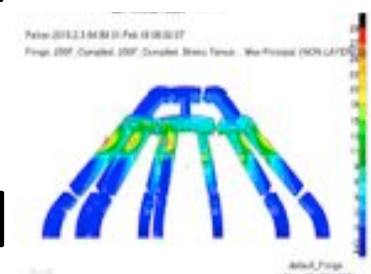


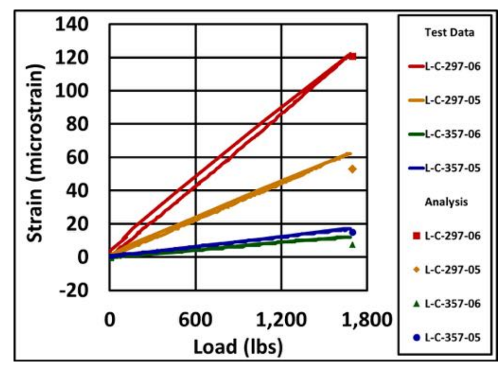
Point Load Locations



12 load locations are shown

23 total tests, 2 at each location minus nosecap





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

What is Technology Readiness Level (TRL) and Why is it Important?

TRL is a way that NASA assesses the readiness of a new technology for infusion into a mission.

TRL Levels:

- TRL 1 Basic principles observed and reported
- TRL 2 Technology concept and/or application formulated
- TRL 3 Analytical and experimental critical function and/or characteristic proof of concept
- TRL 4 Component/subsystem validation in laboratory environment
- TRL 5 System/subsystem/component validation in relevant environment
- **TRL 6 System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space)**
- TRL 7 System prototyping demonstration in an operational environment (ground or space)
- TRL 8 Actual system completed and "mission qualified" through test and demonstration in an operational environment (ground or space)
- TRL 9 Actual system "mission proven" through successful mission operations (ground or space)

Why is TRL 6 important for HEEET?

- Primary missions HEEET is targeted for are NASA Science Mission Directorate entry probe missions to other planets (ex. Venus, Saturn, Neptune, Uranus)
- Missions are often competitively selected (ex. Discovery and New Frontiers Announcement of Opportunities)
- New technologies in such proposals are required to be at TRL 6 by Preliminary Design Review (PDR)
- If HEEET at TRL 6 it is easier to infuse into proposals (mission is not burdened with cost of maturing technology)

Final Technical Readiness Level (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 LHMEL) 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

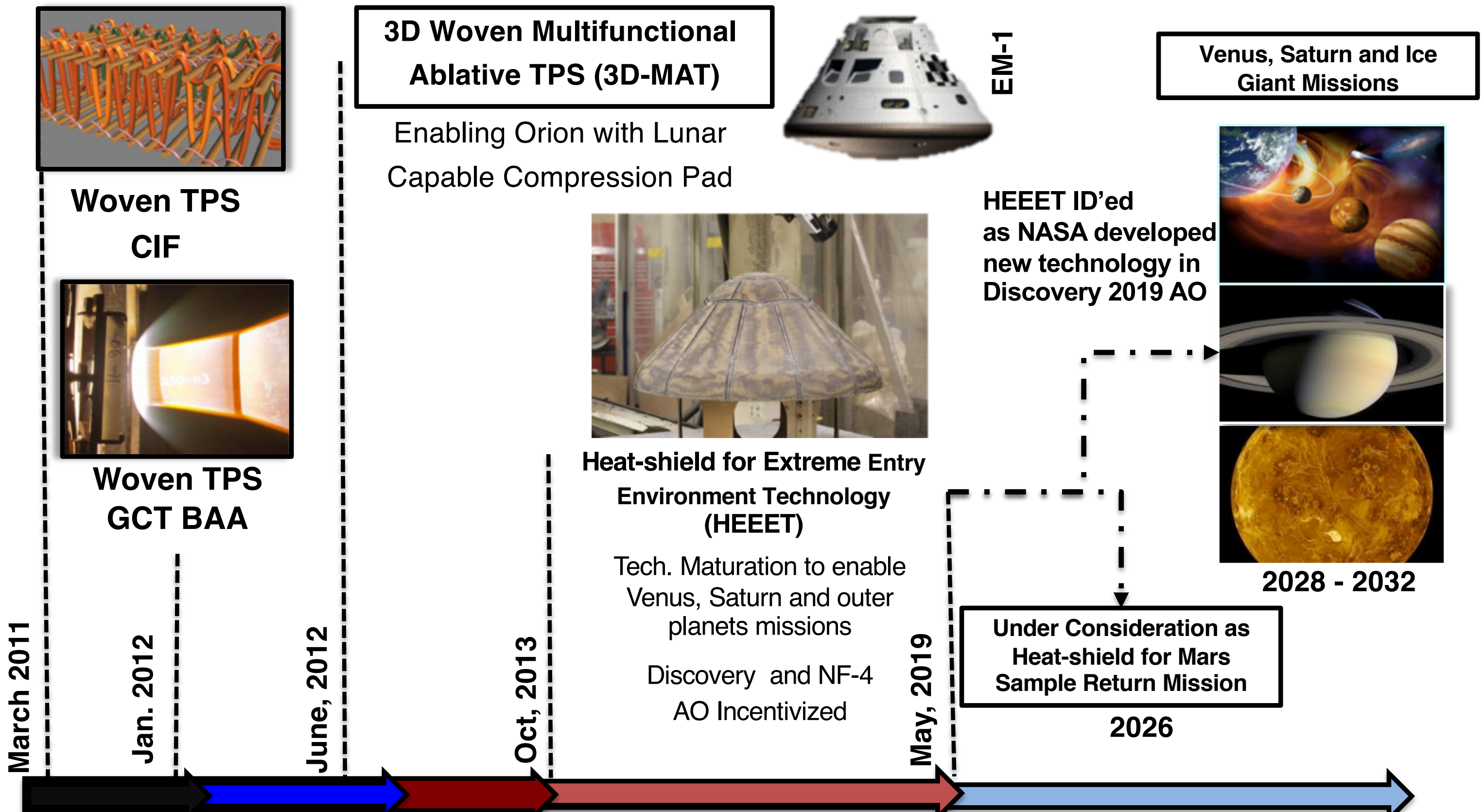
Limitations

- 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

But don’t just take our word for it - HEEET Independent Review Board (IRB) Assessment:

- “The IRB concurs […] that the overall objective of achieving TRL 6 has been completed

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.**

Any Questions?