Challenges and Opportunities for Ensuring Entry System Technology Readiness for Ice Giants Probe Missions

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The Ice Giants represent a distinct class of planets within our solar system, and appear to be similar to most exoplanets that have been detected thus far. Exploring Ice Giants in our Solar System would allow us to better understand their formation and evolution processes, and thus help establish scientific links to exoplanets. *In situ* exploration using probes similar to Galileo, along with an orbiter or a relay spacecraft, will require entry followed by deployment of the descent probe containing science instruments into Uranus or Neptune atmosphere. The challenge is not in the deployment of the probe, but in the atmospheric entry prior to deployment. The entry system has to have a capable, robust and efficient ablative thermal protection system (TPS) designed to protect the descent probe from the thermal and mechanical entry loads. Although entries into Ice Giants may not be as demanding as the Galileo entry at Jupiter, the entry environments will be more severe than environments for Mars, Sample Return missions, and Venus, and will therefore require robust TPS.

While Galileo Probe's success, nearly 25 years ago, should give us confidence, the recession data from the Galileo entry informs us that the entry environment was underpredicted and the design thickness was barely adequate. The lesson learned from Galileo probe for future Ice Giant missions will require us to be cautious and demand a more robust design. The TPS technology used on Galileo entry system no longer exists due to atrophy of manufacturing processes. Instead of attempting to revive Galileo-legacy TPS technology, NASA invested in a new and innovative TPS called HEEET (Heat-shield for Extreme Entry Environment Technology). HEEET has been matured, and is now ready to support future missions not only to the Ice Giants but also for Venus, high-speed sample return, and Saturn probe missions.

This lead talk, intended for the technology section of the workshop, will cover entry, descent, and deployment (EDD), with an emphasis on entry. A brief history of the TPS challenges for extreme entry missions will be given along with a quick overview of the concept of operations for EDD. The development and maturation of HEEET system capability will be described. Data gathered in ground-test facilities in the US will be highlighted to show that the technology is mature and ready for Ice Giant missions. All thermal protection systems carry some risk as a result of ground test limitations and Ice Giant missions present some unique challenges. These challenges are not only technical, but also due to limitations in the currently established manufacturing and integration. In addition, the concerns that arise due to potential for atrophy for future Ice Giant mission a decade or more from now will be analyzed. Plausible avenues for mitigation will be presented. There are two companion planned presentations by Dr. Prabhu and Dr. Hwang will dive deeper in the challenges and opportunities. This intended talk will set the stage for their presentations.

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[2] Neerim Corp.,

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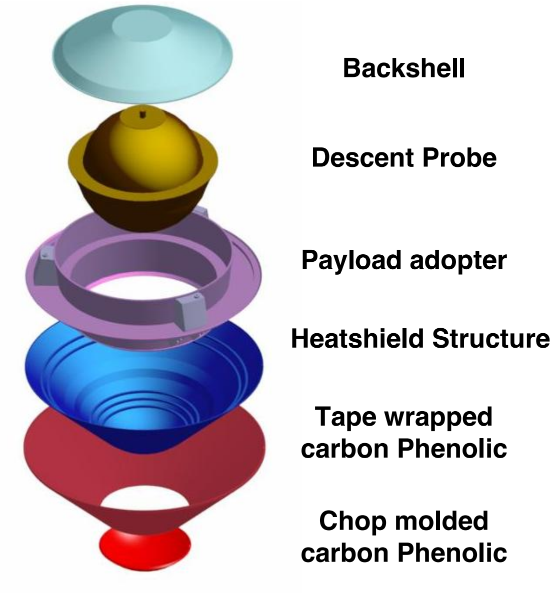
Background and Objectives

- Ice Giant probe missions will demand high confidence in the entry/thermal protection system due to extreme entry environment.
- Entry System Technology to enable Ice Giant Probe missions is mature as a result of recent NASA's investments.
  - ***HEEET is at TRL 6 for missions to many destinations including Ice Giants***.

This lead talk, along with two other companion talks by Dr. Prabhu and Dr. Hwang, will provide insight into:

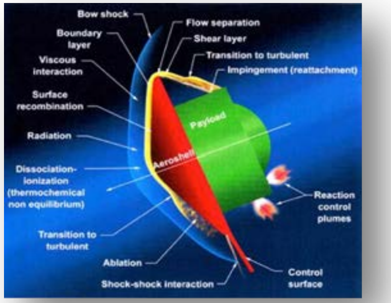
- Technology readiness of HEEET for Ice Giant Missions
- Mission/design constraints imposed by current HEEET capability and how to maximize science (Dr. Prabhu).
  - Opportunities for robust V&V if mission risk posture demands
- Approaches to sustaining the technology –
  - A common probe for broader set of missions vs optimal efficiency for a specific mission (Dr. Hwang) .

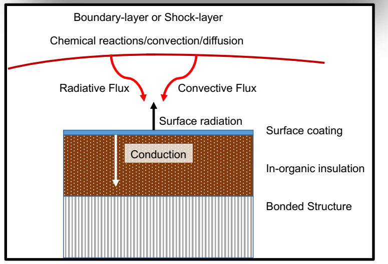
Galileo Probe Entry System

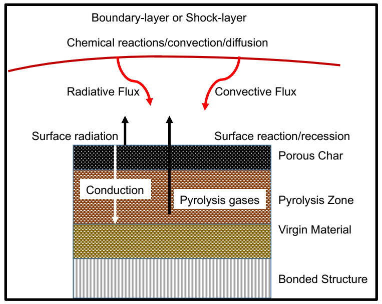


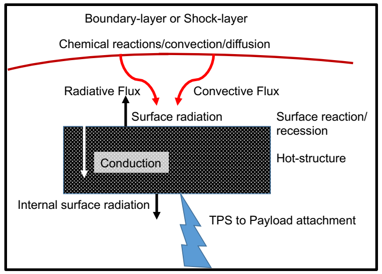
Entry/Thermal Protection System 101

- Deceleration during hypervelocity atmospheric entry causes substantial heating
  - Entry vehicle shape manages deceleration rate
  - TPS manages heat transfer to payload by rejecting most of the energy to the atmosphere
- Types of TPS
  - Reusable or Non-ablative TPS (Shuttle Tiles)
  - Hot Structures
  - Ablative TPS
    - Material consumption (ablation) in addition to re-radiation to manage heat conduction to payload
- TPS robustness
  - Mass-prohibitive to provide redundancy or back-up
  - Challenging to verify the thermal protection material/system behaves in predictable manner
    - Ground test facilities limitation

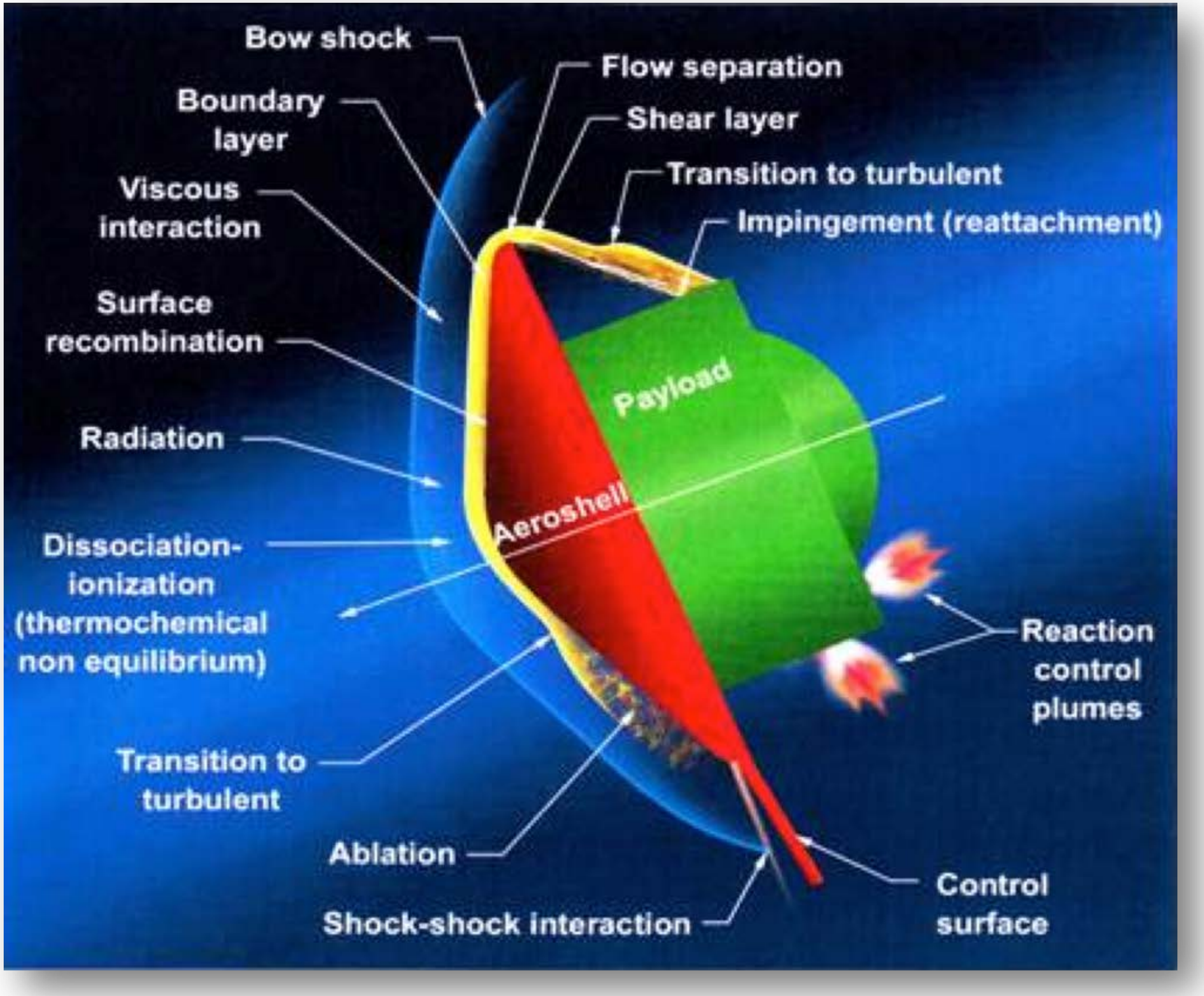




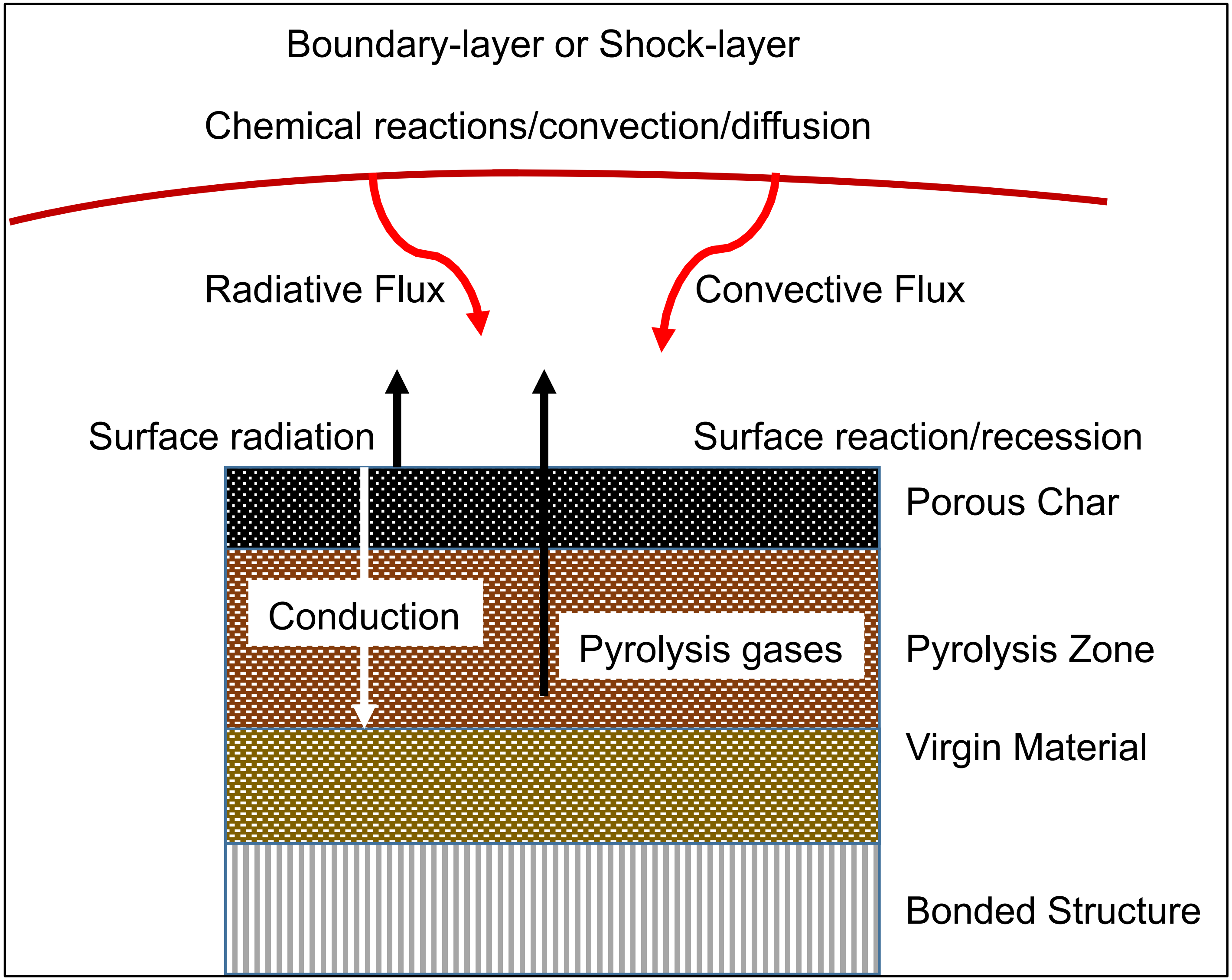




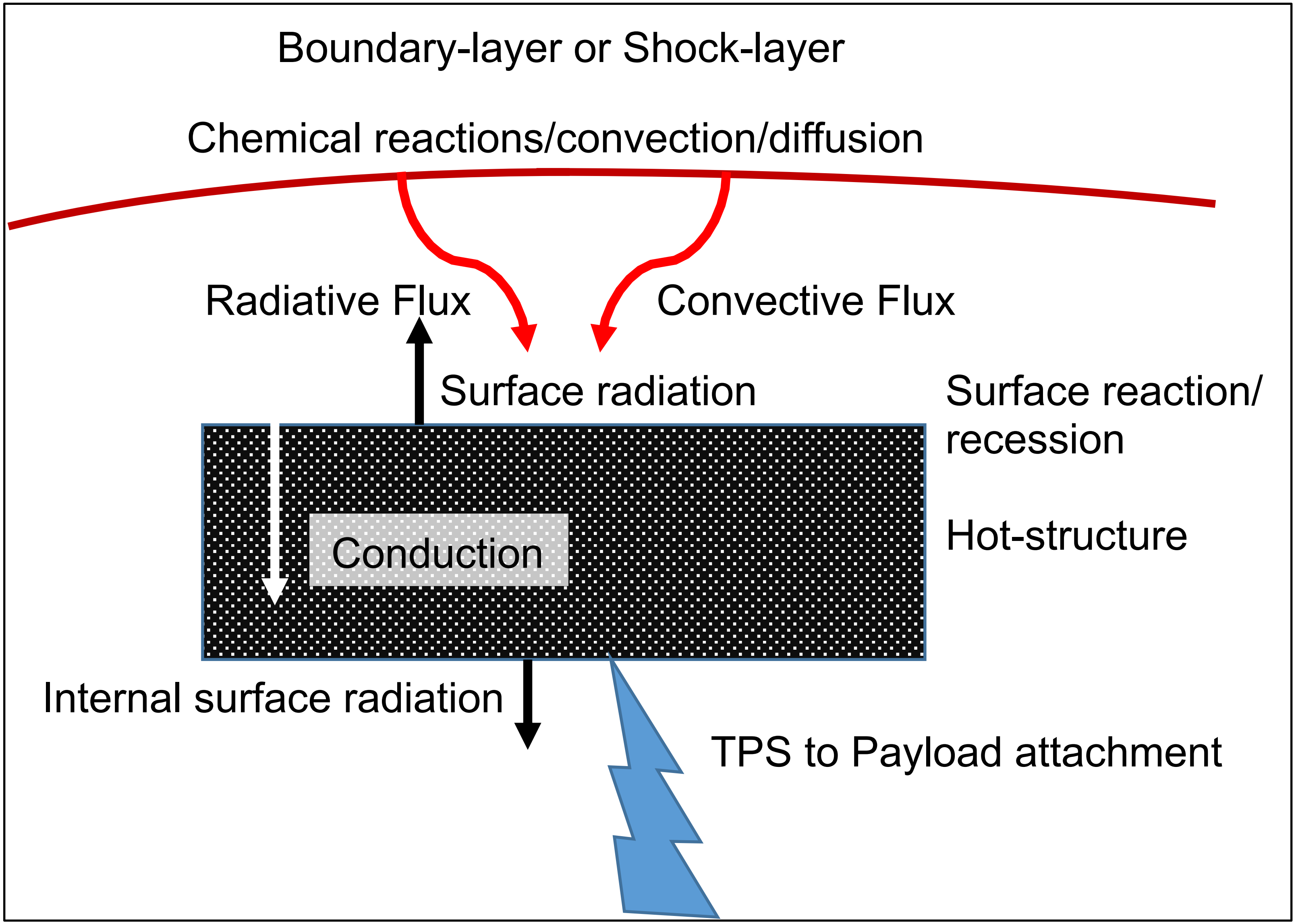
The Physics, Chemistry and the Aerothermodynamics of Entry



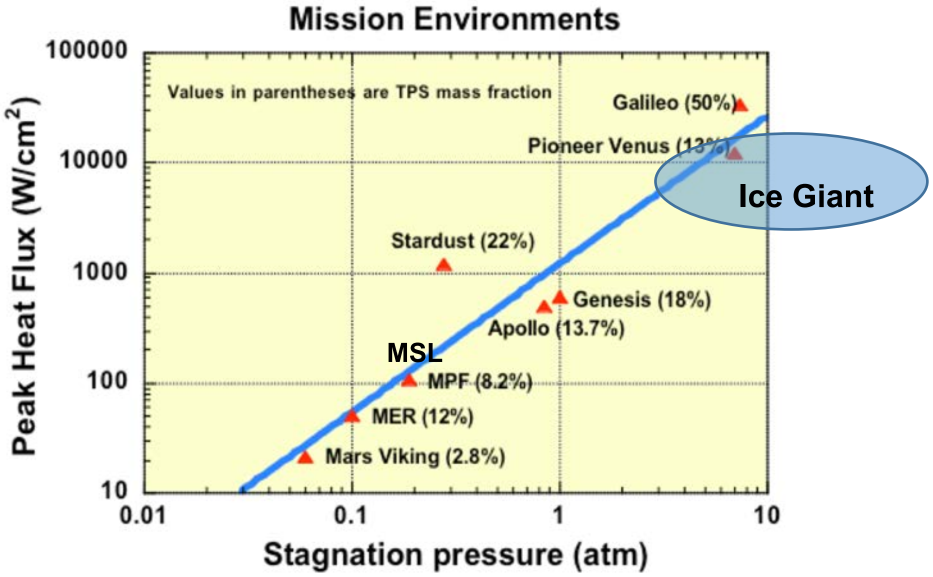
TPS –Ablative TPS



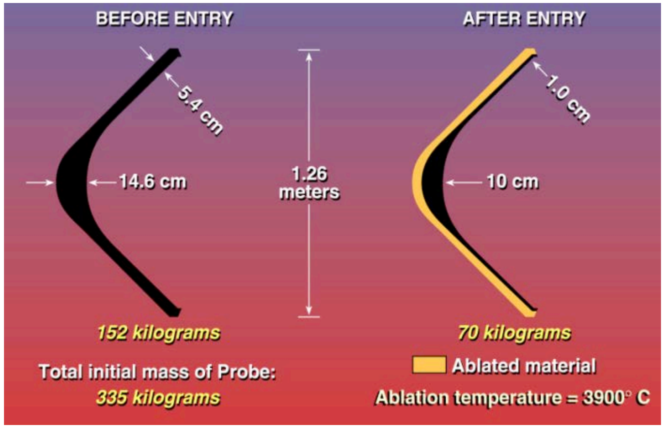
Hot-structure (Multifunctional)



TPS - Historical Perspective and Lessons Learned

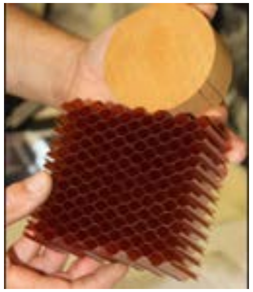

Mission Environments

Galileo Heat-shield Performance

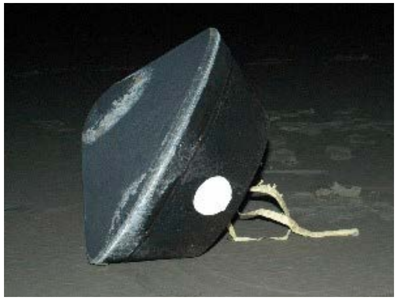


Monolithic Systems

Honeycomb System

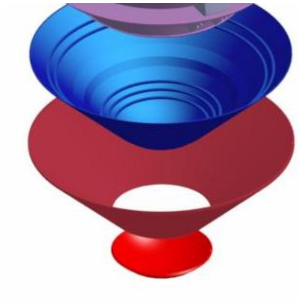


Single Piece Molded



Tiled System (MSL)

Carbon Phenolic(s) (P-V and Galileo)



Heatshield Structure

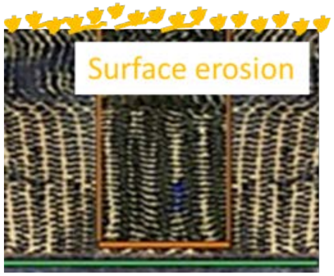
Tape wrapped carbon Phenolic

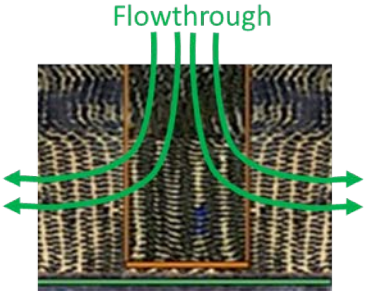
Chop molded carbon Phenolic

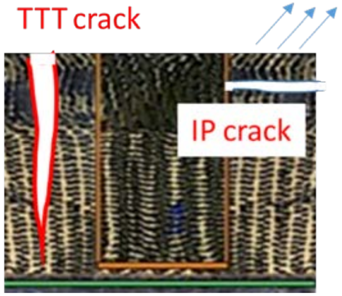
Selecting the TPS is all about Avoiding Failure !

- Excessive recession and/or conduction
  - Under-design - fidelity/validity of sizing tools
  - Unknown or unanticipated phenomenon / environment
    - Spallation or flow through
  - Tile or Gap failure
    - In-plane or through the thickness cracks
- Crack formation or opening of Seams
  - Adhesive mechanical failure ; Adhesive Char erosion
  - Tile failure adjacent to adhesive
- Loss of attachment of tiles/gap filler causing complete loss of material over the full tile area
  - Adhesive mechanical failure
    - Substrate (carrier structure) failure

Structural/Aero/Material





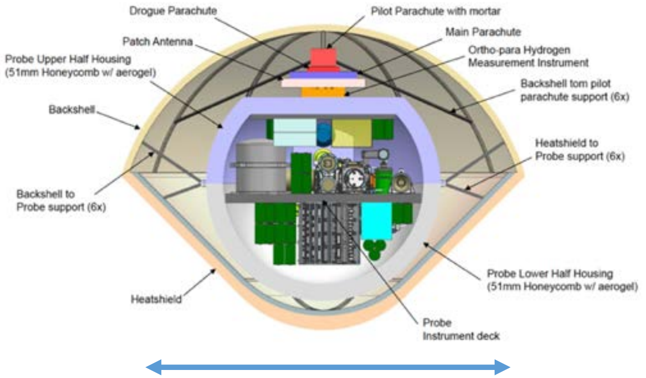


Ice Giant Entry Environment

ICE GIANTS Probe Mission Design Considerations:
(Ref: Ice Giants Pre-Decadal Study Final Report[1])

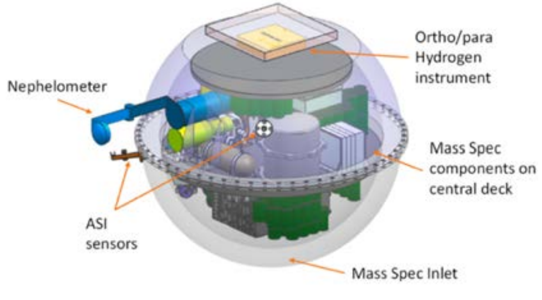
- Entry environment into Uranus and Neptune depends on
  - Entry System mass and size (ballistic coefficient), and Shape
    - Starts with science instrument package
  - Mission design
    - Relative entry velocity
    - Entry flight path angle
  - Atmospheric profile
    - Density, pressure, temperature and composition, and associated uncertainties
- Entry/TPS technology needs to be robust against entry environment and be mass efficient

From Ice-Giant Pre-Decadal Study



1.2 m diameter; 321.5 kg entry mass
(45 sphere cone with a spherical afterbody)

Descent Probe



~ 70 cm sphere ; ~ 32.5 kg

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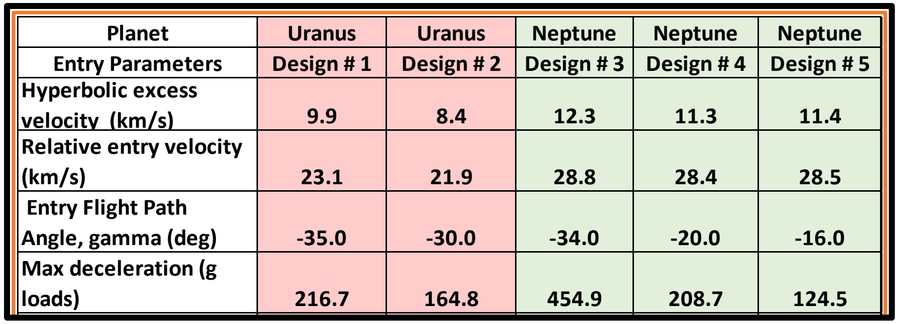
[1] Hofstadter, M., Simon, A., et. al. "ICE GIANTS PRE-DECADAL STUDY FINAL REPORT," JPL D-100520, June 2017.

Entry Environment
Contrasting Ice-Giants with Other Missions

- Ice-Giant entry parameters for the 321.5 kg, 1.2m dia. system, result in range of peak stagnation heat-flux and pressure that is comparable to Saturn probe entry[1].
- Heritage Carbon Phenolic used on Galileo at more severe conditions
  - Questionable design/performance.
    - Near failure at shoulder
  - No longer available
- Is HEEET capable for these entry conditions?
  - Robustness
  - Mass efficiency
  - Availability



Planet Entry Parameters	Uranus Design # 1	Uranus Design # 2	Neptune Design # 3	Neptune Design # 4	Neptune Design # 5
Hyperbolic excess velocity (km/s)	9.9	8.4	12.3	11.3	11.4
Relative entry velocity (km/s)	23.1	21.9	28.8	28.4	28.5
Entry Flight Path Angle, gamma (deg)	-35.0	-30.0	-34.0	-20.0	-16.0
Max deceleration (g loads)	216.7	164.8	454.9	208.7	124.5

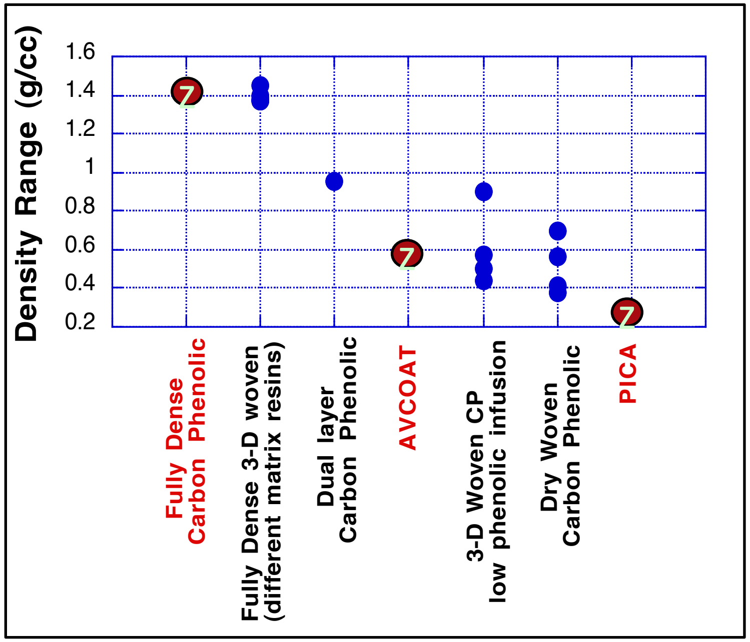
		Pressure	Heat Flux	Heat Load
		atm	W/cm2	J/cm2
Jupiter	Galileo	7.31	31954.5	200000
Saturn	Saturn 1	2	2000	250000
	Saturn 2	8	8000	75000
Uranus	Uranus 1	12	3500	44000
	Uranus 2	9	2500	41000
Neptune	Neptune 1	25	9600	82000
	Neptune 2	11.5	5500	109000
	Neptune 3	6.8	4400	134000
Titan	Titan 1	0.17	150	9500
	Huygens	0.1	62	3500
	MSL	0.33	225	6400

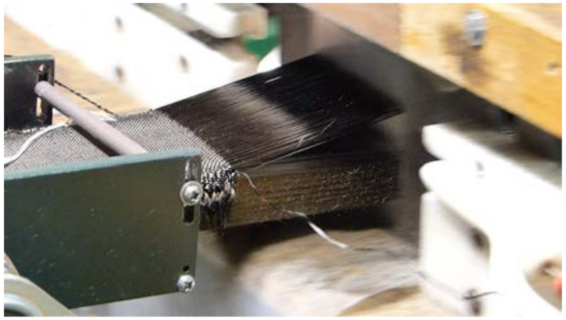
1. Hofstadter, M., Simon, A., et. al. "ICE GIANTS PRE-DECADAL STUDY FINAL REPORT," JPL D-100520, June 2017.

3-D Woven TPS - HEEET

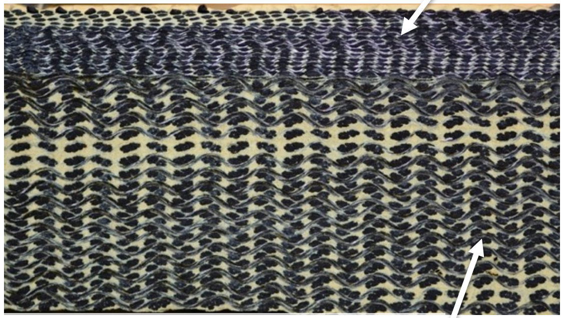
Heat-shield for Extreme Entry Environment (HEEET)

- Challenges of reviving heritage C-P led to NASA investigating 3-D Woven TPS
  - Interlocking layers deliver high through-thickness strength
- Scalable and tailorable design approach
  - Fiber material and volume fraction can be varied
  - Infusion level can be tailored for mission need
  - HEEET uses 2 distinct layers (recession and insulation)

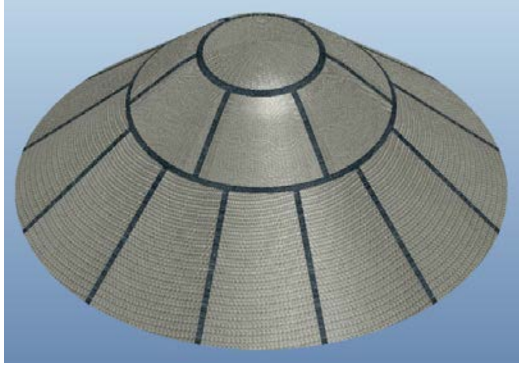




Infused High Density Carbon Weave

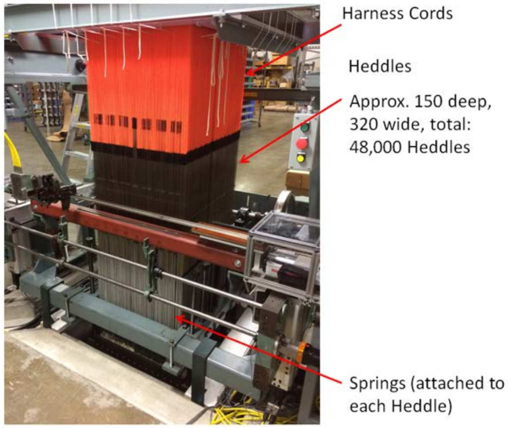


Infused Lower Density Blended Yarn



HEEET Status

- Leverages advanced 3-D weaving and resin infusion.
- A dual layer system - robust and mass efficient across a range of extreme entry environments
- TRL 6 by May of 2019
- The development to-date includes:
  - Establishing requirements and developing concept
  - Testing – Aerothermal and Thermo-structural
  - Specifications from raw materials to weaving, tile fabrication (forming/resin infusion) and integration
  - Technology transfer to industry (BRM and FMI)
  - Heat-shield (1m dia.) design, build and successfully tested
  - Documentation.



Full Scale MDU/ETU

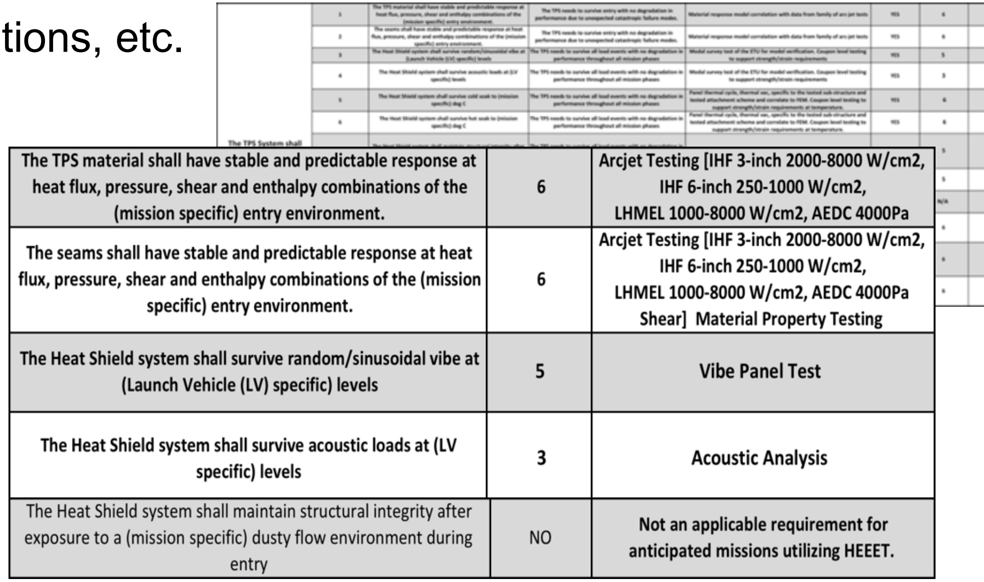
HEEET Development: Functional Requirements and Verification/TRL at Maturity

5 TPS Level I requirements identified:

- **The TPS System shall function throughout all mission phases.**
  - Ground, launch, transit and entry
- **The TPS System shall be operable.**
  - Dust generation, outgassing, shelf life, etc.
- **The TPS system shall be manufacturable.**
  - Thickness, conform to carrier structure, etc.
- **The TPS System shall interface with the entry vehicle.**
  - Back-shell, penetrations, instrumentations, etc.
- **The TPS System shall be certifiable.**
  - Inspectable

31 TPS Level II requirements identified

- 18 of these are prioritized focus within HEEET project

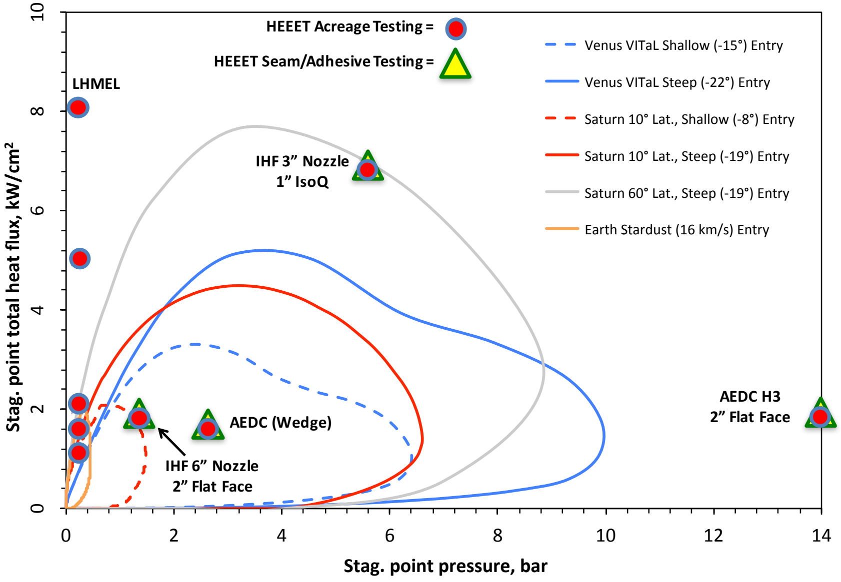


The TPS material shall have stable and predictable response at heat flux, pressure, shear and enthalpy combinations of the (mission specific) entry environment.	6	Arcjet Testing [IHF 3-inch 2000-8000 W/cm2, IHF 6-inch 250-1000 W/cm2, LHMEL 1000-8000 W/cm2, AEDC 4000Pa
The seams shall have stable and predictable response at heat flux, pressure, shear and enthalpy combinations of the (mission specific) entry environment.	6	Arcjet Testing [IHF 3-inch 2000-8000 W/cm2, IHF 6-inch 250-1000 W/cm2, LHMEL 1000-8000 W/cm2, AEDC 4000Pa Shear] Material Property Testing
The Heat Shield system shall survive random/sinusoidal vibe at (Launch Vehicle (LV) specific) levels	5	Vibe Panel Test
The Heat Shield system shall survive acoustic loads at (LV specific) levels	3	Acoustic Analysis
The Heat Shield system shall maintain structural integrity after exposure to a (mission specific) dusty flow environment during entry	NO	Not an applicable requirement for anticipated missions utilizing HEEET.

Technology Readiness for Ice-Giant Missions

HEEET Aerothermal Test Campaign

Test Date	Facility	Heat Flux (W/cm2)	Pressure (atm)	Shear (Pa)	Enthalpy (MJ/kg)	Sample Size	Sample Shape	Test Gas	TC Instrum.	Acreage Coupons	Seam Coupons
2014-Apr	LHEML	8000	0	0	N/A	1" x 1"	Flat Face	N2	BackFace	2	0
		5000	0	0	N/A	1" x 1"				2	0
		2000	0	0	N/A	2" x 2"				2	0
		1000	0	0	N/A	2" x 2"				2	0
2014-Oct	AEDC Wedge	1200	2.9	4000	11.6	4" x 5"	Wedge	Air	BackFace	2	12
2015-Feb	AHF 12" Nozzle	80	0.03	0	12.2	4"	IsoQ	N2	TC Stack	2	0
		62					Flat Face			2	0
		220	0.12		16.7		IsoQ			2	0
		170					Flat Face			2	0
2015-May	IHF 6" Nozzle	1025	1.35	0	24.8	2"	Flat Face	Air	None	0	10
2015-Nov	IHF 3" Nozzle	3600	5.3	0	23.4	1"	Flat Face	Air	None	8	12
2016-Aug	AEDC Stag	1025	14.5	0	11.6	2"	Flat Face	Air	None	1	2
2016-Aug	AEDC Wedge	1200	2.9	4000	11.6	4" x 5"	Wedge	Air	BackFace	2	6
2016-Aug	IHF 13" Nozzle	280	0.31	0	21.2	6"	Flat Face	Air	TC Stack	2	2
		150	0.13	0	17.3					2	2
2018-Mar	IHF 6" Nozzle	1320	1.35	0	21.3	2"	IsoQ	Air	None	1	0
2018-May	AEDC Wedge	1200	2.9	4000	11.6	4" x 5"	Wedge	Air	BackFace	2	16
2018-Jun	IHF 3" Nozzle	3600	5.3	0	23.4	1"	Flat Face	Air	None	6	20
2019-Jul	AEDC Wedge	1200	2.9	4000	11.6	4" x 5"	Wedge	Air	BackFace	2	16
									Total	44	98



AEDC wedge allows testing at mission relevant Hot Wall turbulent shears of 4000-6000Pa

- Demonstrate acreage material survival under mission-relevant conditions.
- Developed and validated acreage material’s thermal response model (surface response (recession) and in-depth response)
- Demonstrated the survival of seam concept under mission relevant conditions and validated the seam concept under differential recession

Seam: A Critical Element of HEEET

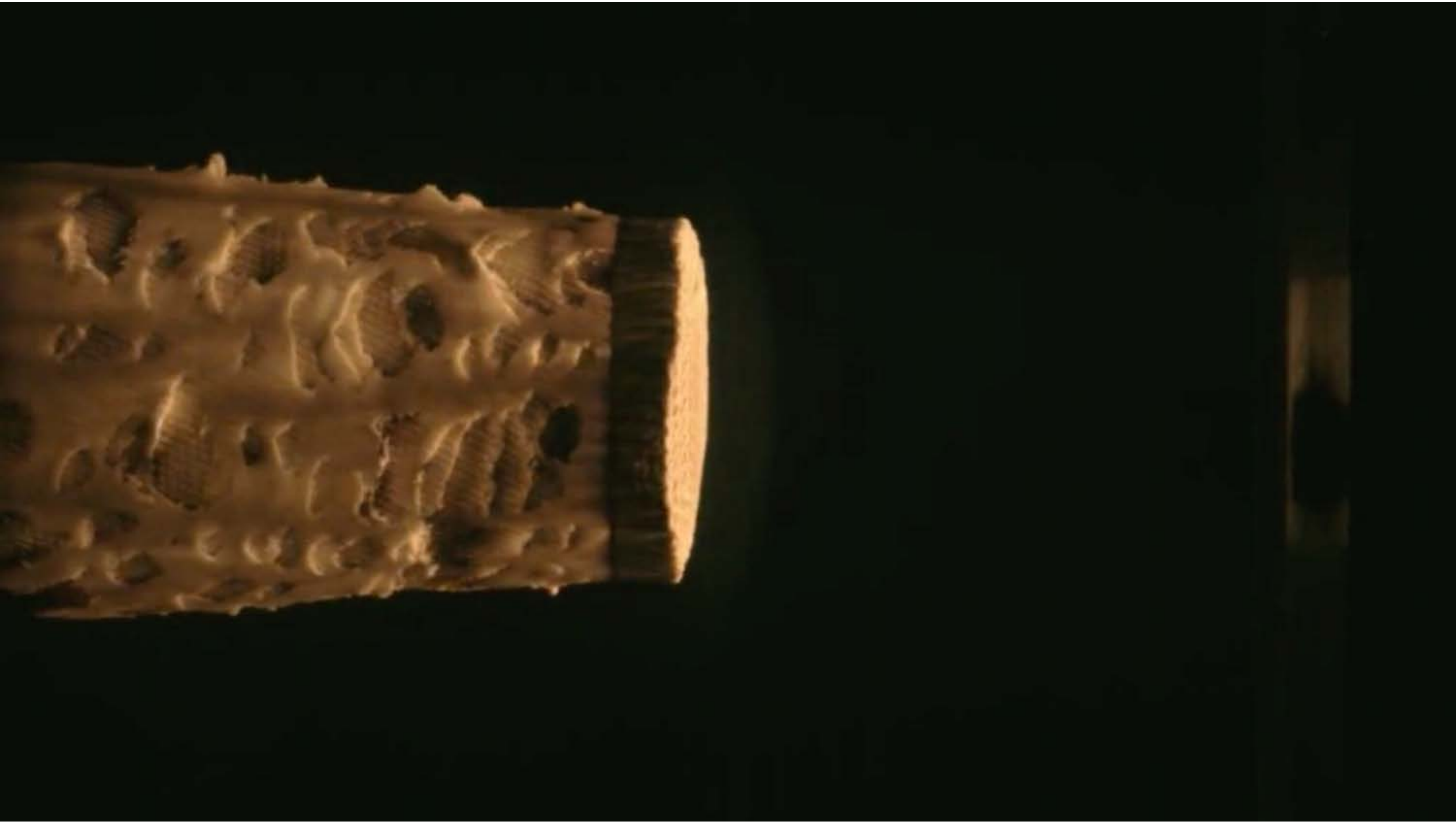
- Development, manufacturing and testing of ***compliant*** seam bonded to acreage, and integration at full scale on ETU were significant challenges; tackled successfully.
  - Strain relief through compliant seam
  - Seam has to behave similar to acreage.
  - Bonding between seam and acreage has to be robust against aerothermal and thermo-structural loads.
  - Down selection of seam required both thermal and thermo-structural component and sub-system tests
- Integrated seam with acreage has been successfully tested at system level (ETU).

IHF 3" Stag Model
3600 W/cm^2; 5.3 atm

AEDC: 2" model
2000 W/cm2; 14 atm.

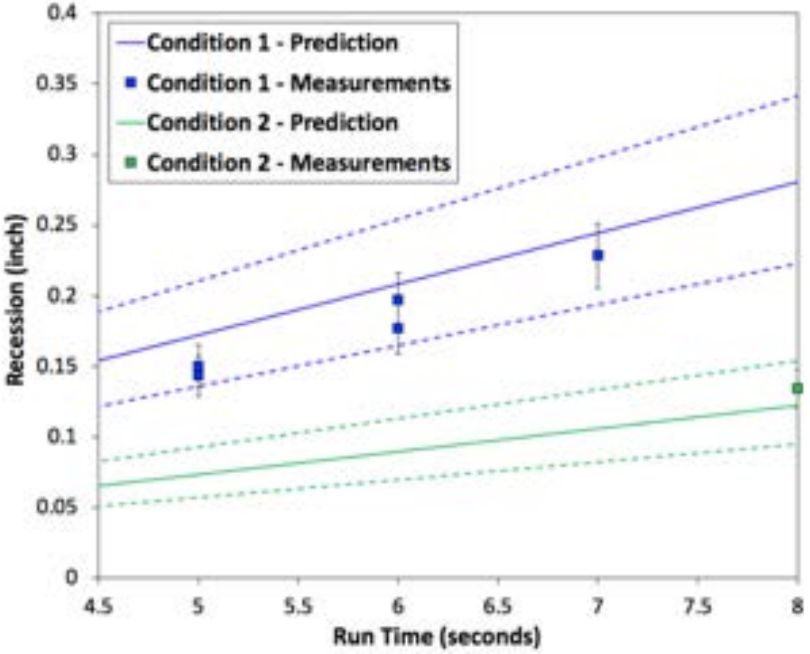
AEDC Wedge : 1200 W/cm^2; 2.9 atm.
with shear estimated at ~4000Pa

Highlights from the HEEET Arc Jet Test Campaigns



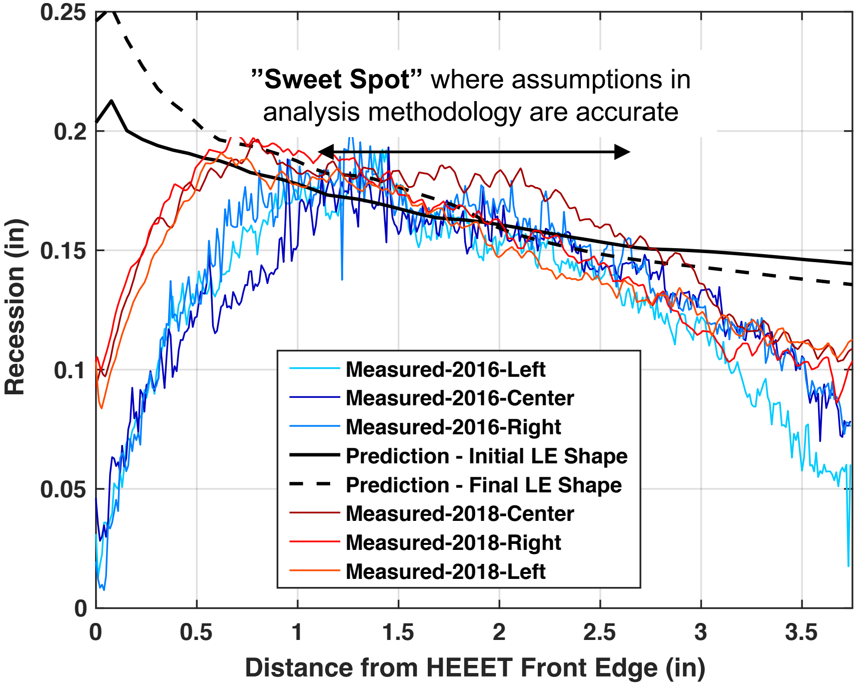
Verification of Predictable Acreage Recession

IHF 3" Nozzle Testing



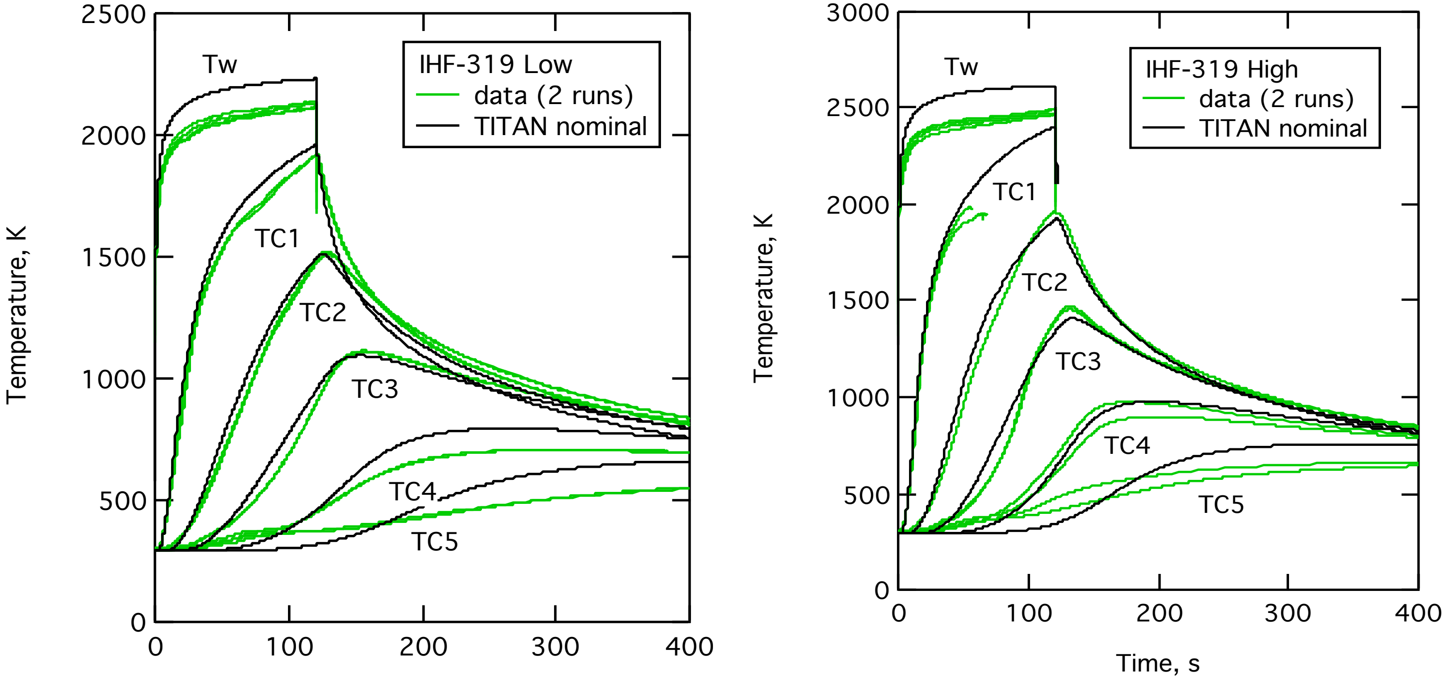
2018 Estimated Conditions:
Cond. 1: ~3600 W/cm², 5.3 atm
Cond. 2: ~1900 W/cm², 2.0 atm

AEDC Wedge (Shear) Test



Predicted recession at high heat-flux and pressure conditions, both at stagnation and shear, compares well with measurements.

Verification of Predictable In-Depth Thermal Response



Good match between thermocouple data and model predictions at both the low and high heating conditions

- Slight overprediction for insulating layer at low temperatures (mostly due to unmodeled water evaporation) – sizing model is conservative

Thermal Response model verified to be conservative based on recession and in-depth temperature prediction comparisons. High confidence in flight TPS sizing

Successful Testing at Component and System Level

Full Scale Integrated System Testing (1m Engineering Test Unit (ETU)– Saturn Design)

Carrier Structure

LaRC Autoclave

ETU Carrier Structure Proof Test Pre-Integration

↓

Integrate TPS on Carrier Structure

NDE (CT)

Static Mechanical Test

↓

Point Load Test 1

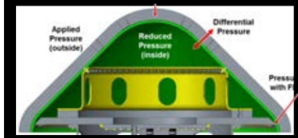
↓

Thermal-Vacuum

↓

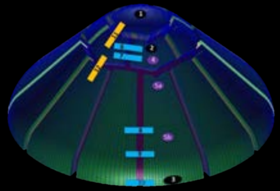
Point Load Test 2

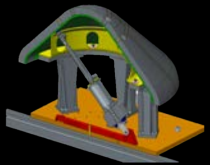
NDE (CT)



Static Pressure Load Diagram

OML Instrumentation (Strain Gages + TCs)





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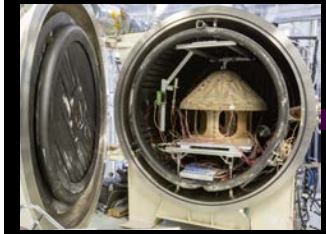
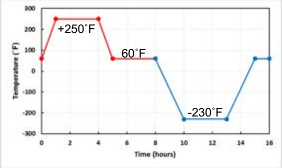
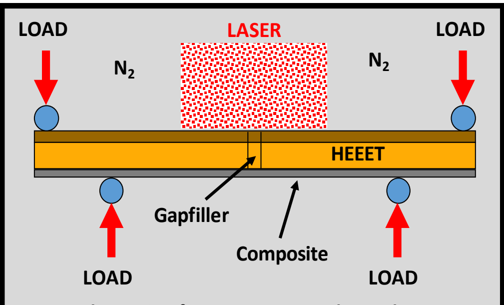


6x6-Foot Thermal Vacuum Chamber @ LaRC

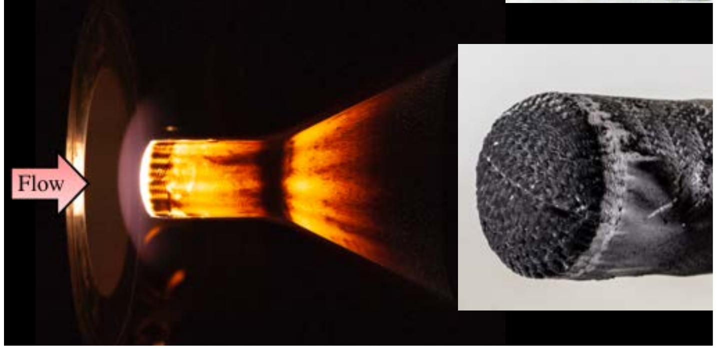


Thermal Cycle Nominal Profile

Component Level Testing Thermo-structural and Arc Jet



Schematic of LHMEL Structural Panel Test



Verification of Predictable Structural Response

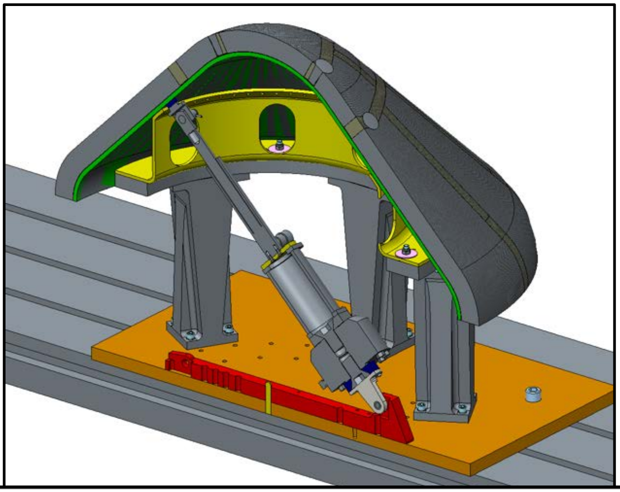
Typical Correlation for Local Static Loading

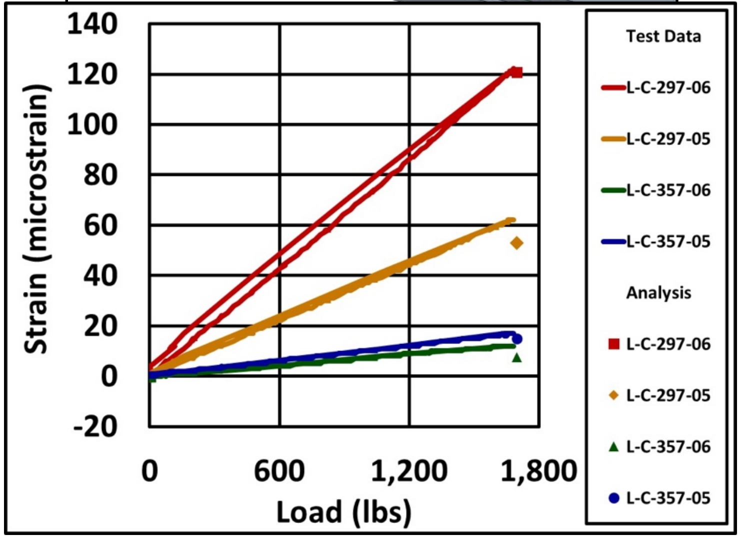
Test Objectives:

- Verify performance of the ETU under flight representative deflections
- Build confidence in finite element models used for design
- Expose manufacturing defects
- Validate acreage tile material property estimates
- Validate the expansion capabilities of:
    - Seam, Closeout Plug and T-Joint

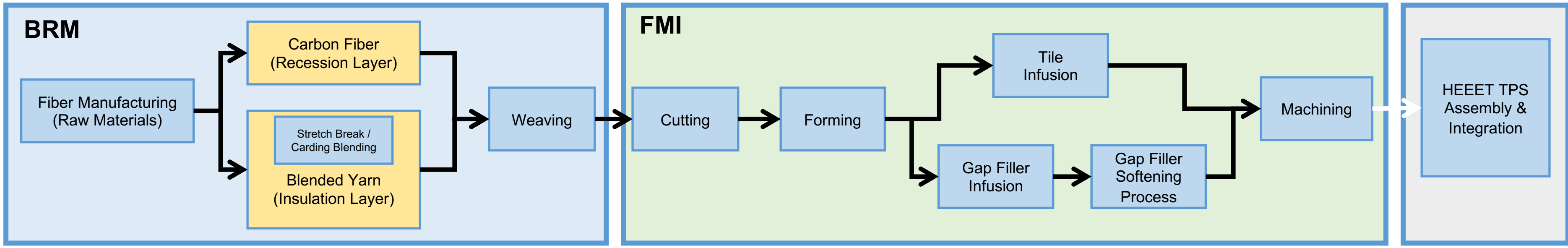
Summary – Successful testing

- No evidence of any failures
- Reasonably good agreement with pre-test predictions





HEEET Manufacturing



BRM

Fiber Manufacturing (Raw Materials)

Carbon Fiber (Recession Layer)

Stretch Break / Carding Blending

Blended Yarn (Insulation Layer)

Weaving

FMI

Cutting

Forming

Tile Infusion

Gap Filler Infusion

Gap Filler Softening Process

Machining

HEEET TPS Assembly & Integration

- Woven preforms are molded, resin infused, cured and machined.
- Individual tiles are bonded on to structure
- Channels along tile to tile joints are routed
- Oversized seam is inserted into the gap between tiles
- During autoclave operation, seam material is expanded and bonded
- Final machining operation on the outer and inner mold lines results in an integrated heatshield

HEEET Capability Limitation and Mission Design Considerations

- Current 3-D weaving capability is limited as to the thickness (recession and insulation).
  - Current HEEET loom is capable of weaving up to 24” width (Baseline or Loom 1) with installed thickness of 1.6” (0.5” recession and 1.1” insulating layer).
  - Thicker weaving possible on current loom at 12” width.
  - Weaving, molding, seam and integration have been demonstrated on the ETU at thickness (0.5” recession and 1.1” insulating layer)
- Mission design for optimizing science with proven HEEET capability may limit payload (mass, volume, c.g., etc.).
  - Mission/design parameters (relative entry velocity, flight path angle, atmospheric uncertainty, etc.) have to be selected along with the probe mass, volume, etc.
- Loom upgrade, under consideration, to weave ~(70” – 80”)width will eliminate seams.
  - A seamless, single piece heat-shield further improves the robustness, reduces mass and mission design constraints.
  - Mars Sample Return, Ice-Giant, Saturn and Venus Probes (size < 1.3m) will benefit from this

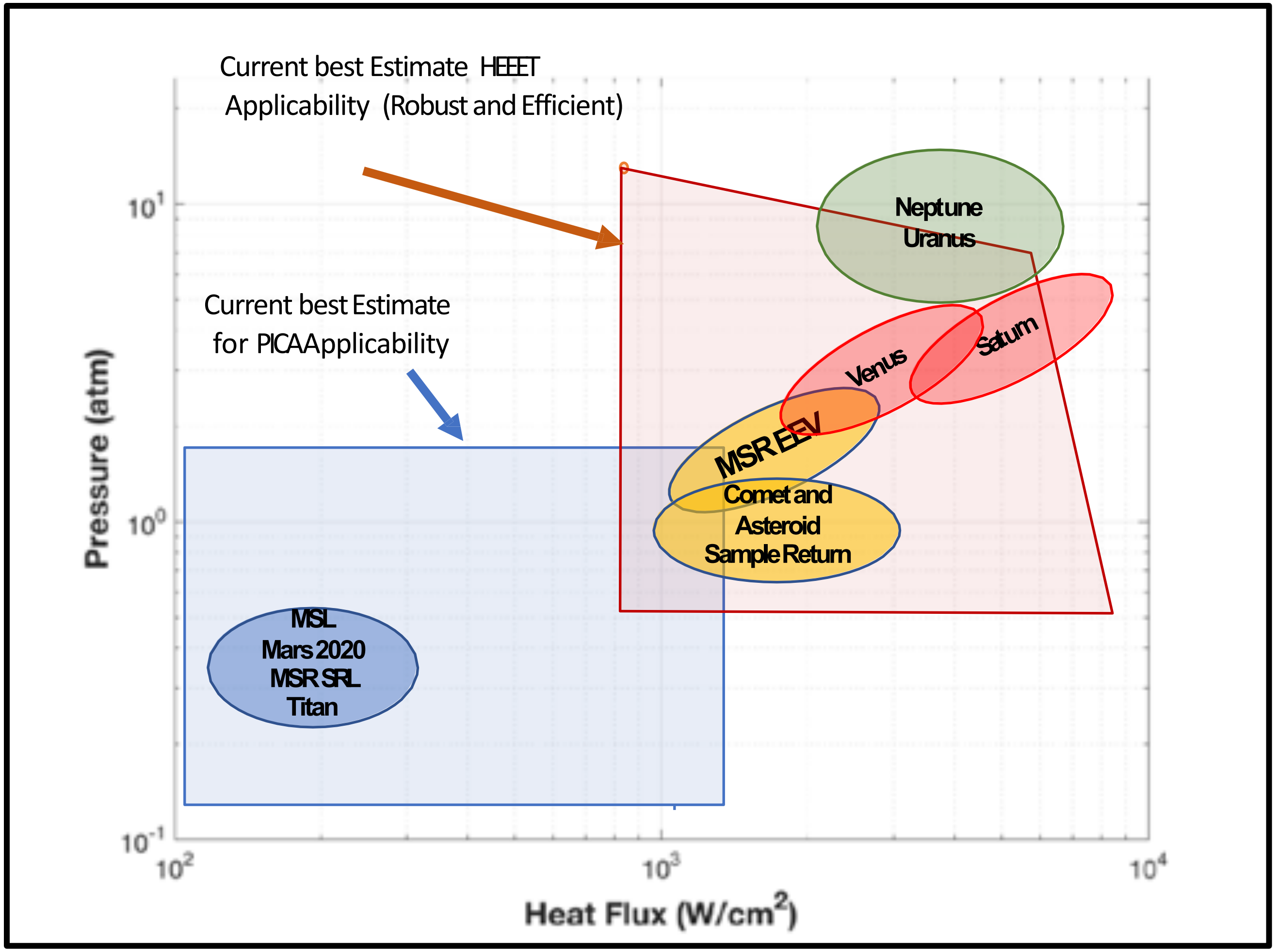
		atm.	W/cm²	J/cm²
Uranus	Uranus 1	12	3500	44000
	Uranus 2	9	2500	41000
Neptune	Neptune 1	25	9600	82000
	Neptune 2	11.5	5500	109000
	Neptune 3	6.8	4400	134000

~ 40,000 Heddles on the HEEET Loom

Concluding Remarks

- **HEEET is ready now for Ice Giant Probe missions**
  - **Ready to design** :
    - Successful thermal and thermo-structural testing and design tools verification
      - Using a variety of facilities and at the highest, relevant conditions.
      - Component, sub-system and system level testing provided data to verify models for flight design as well as established the robustness of HEEET.
  - **Ready to build** :
    - Successful manufacturing using certified industrial partners and ETU at 1m, scalable to large diameter successfully demonsrated.
  - **Ready to fly**:
    - Full scale ETU testing and design capability verification successfully completed.
    - HEEET, tailorable two layer architecture, is mass efficient and an enabler.
- **Mission design needs to take into account demonstrated HEEET capability especially for steeper entry.**
- **On capability sustainability.**
  - NASA is committed to ensuring HEEET is available in the future for extreme entry missions including Ice Giants.
    - Could a single entry system for multiple destination be designed and multiple copies built to address sustainability concerns and also reduce the entry system cost on a per mission basis?

Sustaining PICA and HEEET Capability Essential for future NASA missions


Current best Estimate HEEET Applicability (Robust and Efficient)

Current best Estimate for PICA Applicability

PICA and HEEET, NASA developed ablative TPS, can sustain future science missions (that require entry) across all destinations except for Jupiter.