Entry System and TPS for In-situ Exploration of Ice Giant Probe (IGP) Missions

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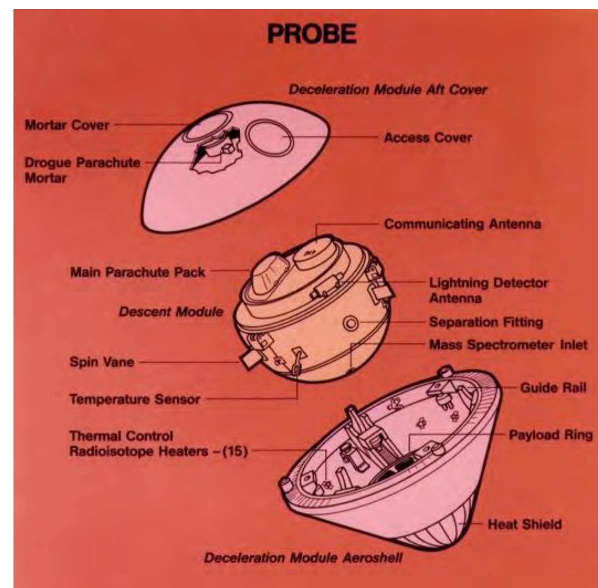
Objective and Background

- **Provide an overview of entry and TPS systems in 30 min.**
  - It is going to be fast paced and will do my best to address the most important aspects
- **Entry System to enable IGP missions**
  - Will need to withstand extreme entry environment
  - Key element is TPS
    - Need to be robust
    - Need to be mass efficient
- **Requires in-depth understanding of**
  - Design requirements
    - To protect and deliver the descent probe
  - Entry environment

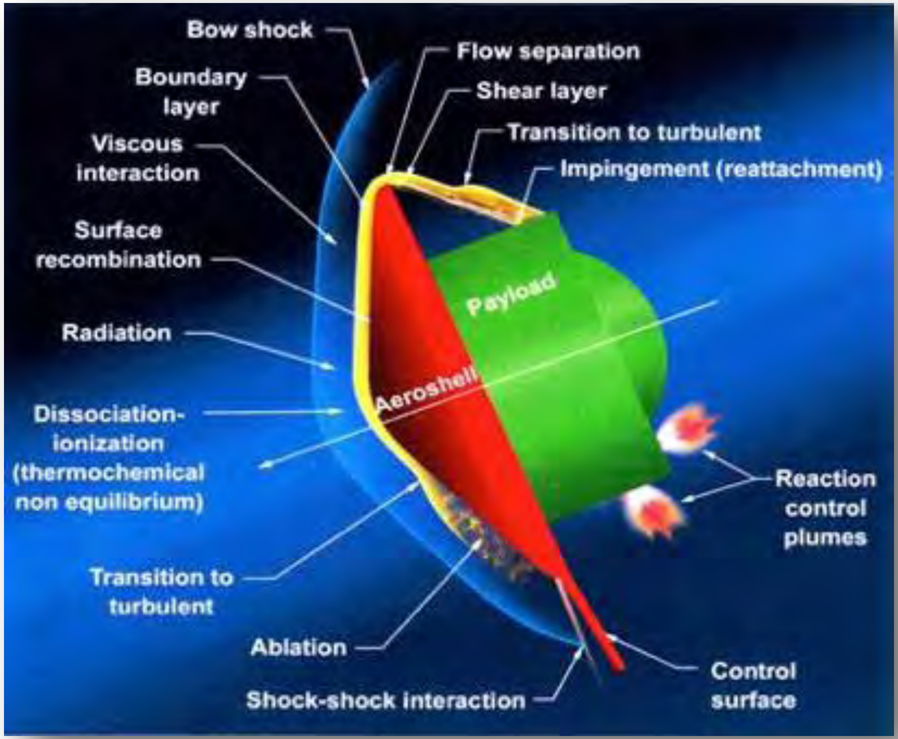
Galileo Entry System



Entry System 101

Deceleration during atmospheric entry causes substantial heating

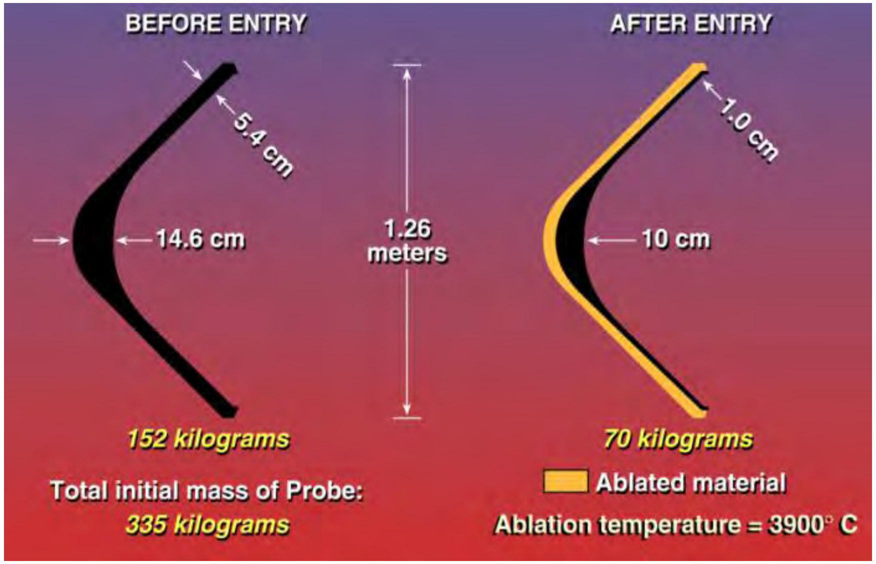
- Entry vehicle (aero-shell) shape, size and design
  - Payload accommodation
    - Packaging , C.G.
  - Aerodynamic stability
    - Predictable trajectory
  - Entry environment (thermal and pressure)
  - Parachute
    - At subsonic conditions to extract probe
- Other design parameters to consider
  - Entry velocity and entry flight path angle
- Fail safe and efficient TPS
  - TPS performance
    - Reject most of the energy through re-radiation to the atmosphere
  - TPS failure mode
  - TPS testing and verification



Credit: NASA

TPS for Extreme Entry: Historical Perspective and Lessons Learned

- **Galileo experience**
  - Very near failure
- **TPS needs to be ablative for IGP**
  - Seamless monolithic vs Tiled
- **TPS needs to be robust**
  - Limited ground test capabilities
- **TPS needs to be mass efficient for Ice Giant missions**
  - Carbon Phenolic (CP) is not !



Galileo Heat-shield Flight Performance

Monolithic Systems

Honeycomb System

Single Piece Molded

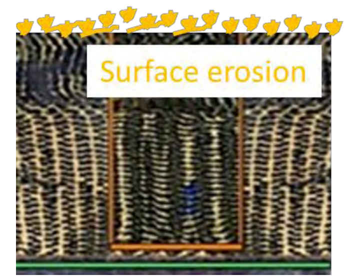
Tiled System (MSL)

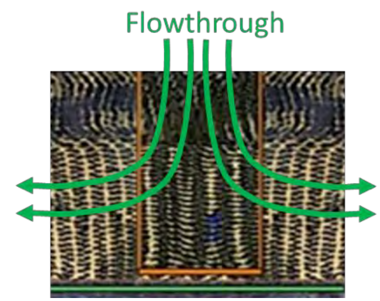
New Ablative TPS

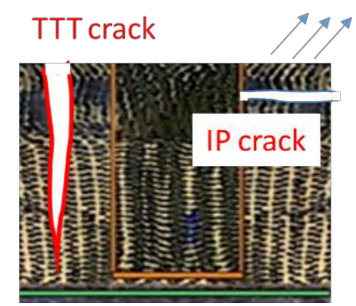
Selecting TPS – It is all about avoiding failure - ?

- 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







Entry System, Trajectory and Entry Conditions

Planet Relative Entry Velocity

- Prograde vs Retrograde
- Higher vs lower latitude

Gas Composition

- (H2/He)

Entry Flight Path Angle

- Steeper entry
  - higher heat flux and pressure,
  - time of flight is shorter => Lower heat-load
- Shallow entry => lower heat flux and pressure but larger heat-load

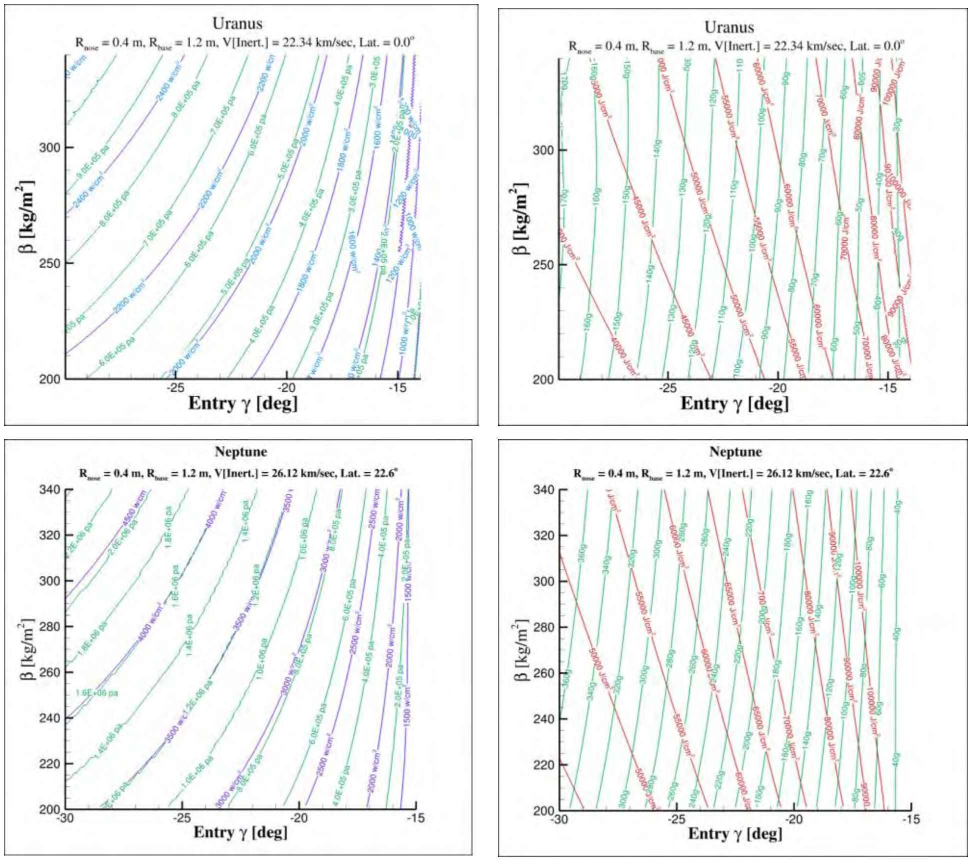
Ballistic Coefficient:

- Lower ballistic coefficient => lower heat-flux, lower pressure and lower heat-load
  - Lower mass or larger probe diameter

Shape (& Nose Radius) and size:

- Bluntness
  - Lowers convective heating but raises shock-layer radiative heating, if shock layer is radiating
- Turbulent augmentation

Stagnation Point Entry Conditions



Ballistic Coefficient = m/C_DA
m = Entry mass; C_D = Drag Coeff.
A = Reference Area

Summary of Aerothermal Environments for R_n = 0.4 m

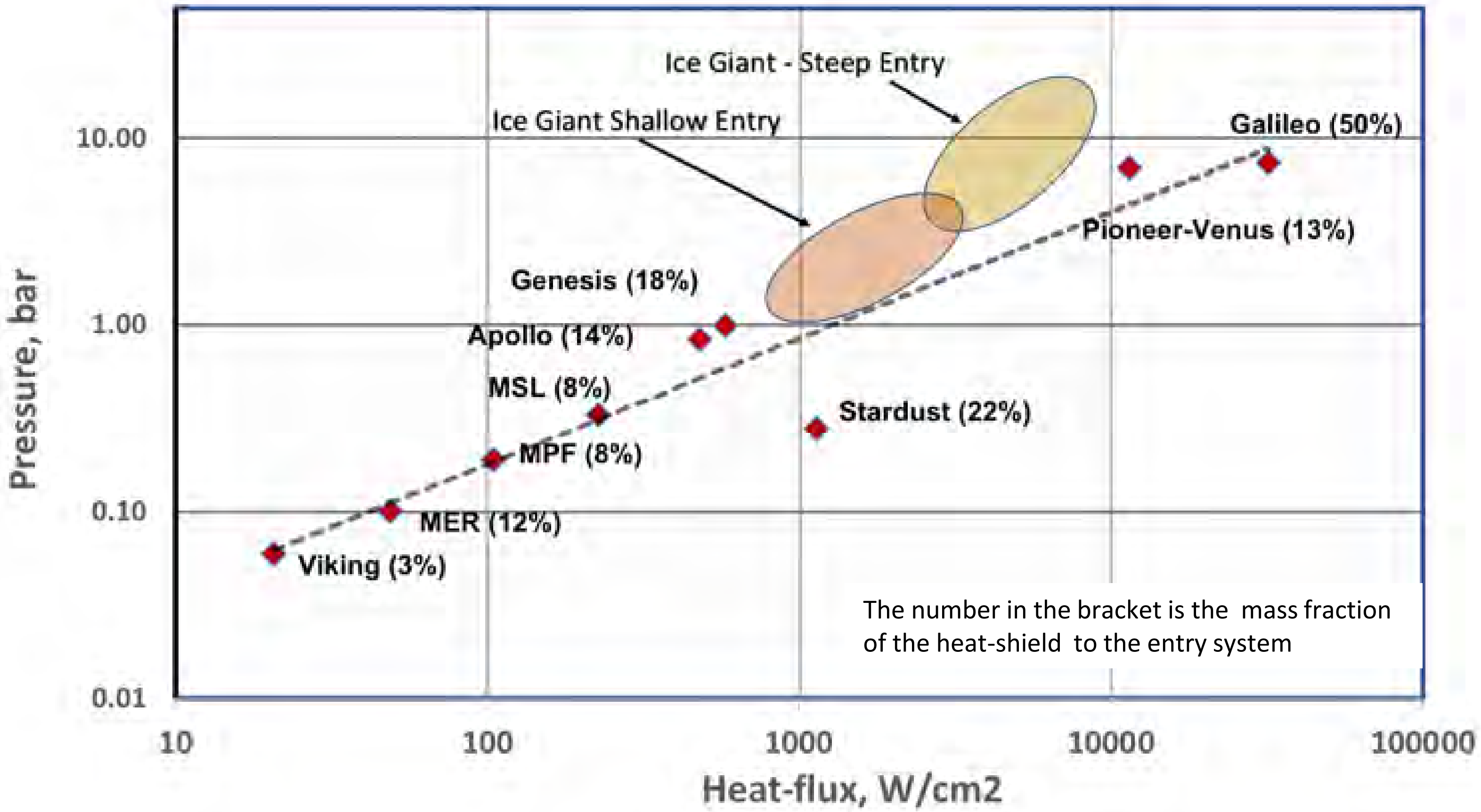
Stagnation point heat flux/W.cm^{-2}

Ballistic coeff./kg.m^{-2}	Shallowest			Steepest		
	Uranus (γ = -16.5°)	Neptune (γ = -16°)	Neptune (γ = -16°)	Uranus (γ = -36.5°)	Neptune (γ = -26°)	Neptune (γ = -26°)
200	1300	1050	1800	2304	1800	3300
250	1520	1200	2000	2500	2000	3700
300	1700	1300	2200	2700	2200	4100
350	1825	1400	2400	2900	2400	4200

Stagnation point pressure/bar

Ballistic coeff./kg.m^{-2}	Shallowest			Steepest		
	Uranus (γ = -16.5°)	Neptune (γ = -16°)	Neptune (γ = -16°)	Uranus (γ = -36.5°)	Neptune (γ = -26°)	Neptune (γ = -26°)
200	1.9	1.8	2.0	8.0	8.1	10.3
250	2.4	2.6	2.7	10.0	10.6	13.7
300	3.0	3.4	3.4	12.6	13.1	17.0
350	3.6	4.2	4.3	15.0	15.5	17.8

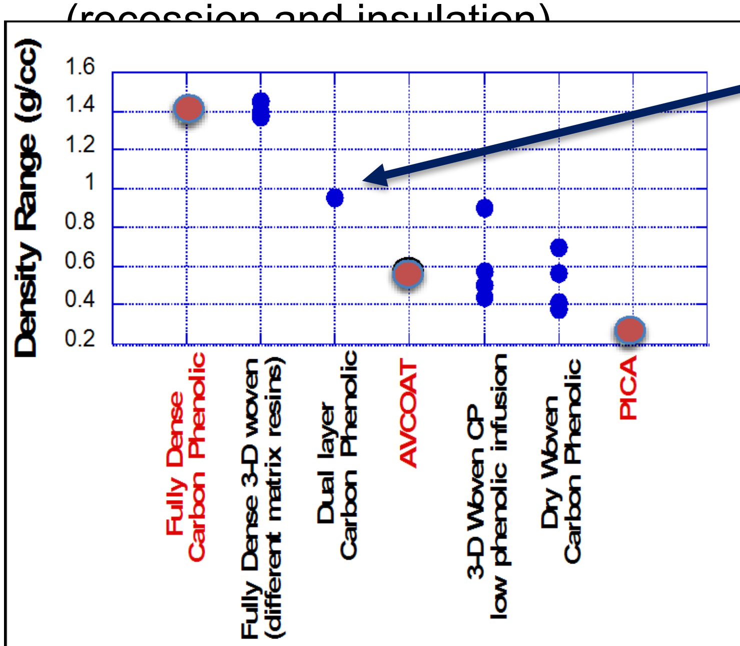
Ice Giant Probe Entry Environment Comparison with other Historical Missions



Ice Giant Probe Mission Entry Environment can be extreme depending on the interplanetary trajectory design and other mission architecture constraints

Heat-shield for Extreme Entry Environment (HEEET)

- Challenges of reviving heritage CP 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 but interwoven layers (recession and insulation)

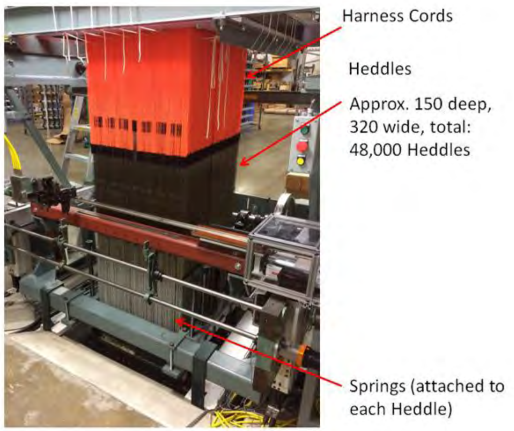


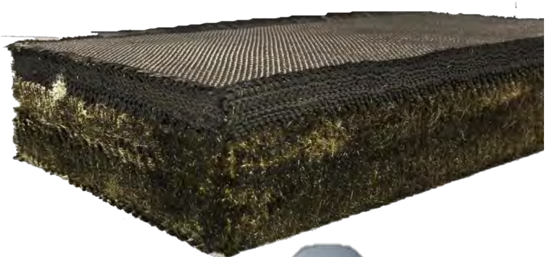
Infused High Density Carbon Weave

Infused Lower Density Blended Yarn

HEEET Status for Ice Giant Probe Missions

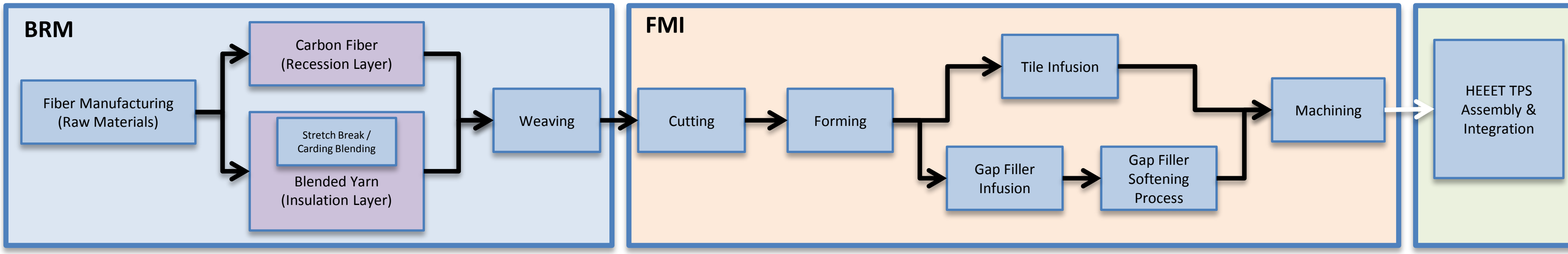
- A dual layer system - robust and mass efficient across a range of extreme entry environments
- Successful development to-date includes:
  - Requirements and developing concept
  - Testing – Aerothermal and Thermo-structural
  - Specifications from raw materials to weaving, tile fabrication (forming/resin infusion) and integration
  - Technology transfer to industry (BRM and FMI)
  - Heat-shield ETU design, build and successfully tested
  - Documentation.
- **HEEET at TRL 6 for Ice Giant probe missions**





Full Scale MDU/ETU

HEEET Manufacturing Readiness



- 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 and bonded in place
- Final machining operation on the outer and inner mold lines results in an integrated heatshield

Seam: A Critical Element of HEEET

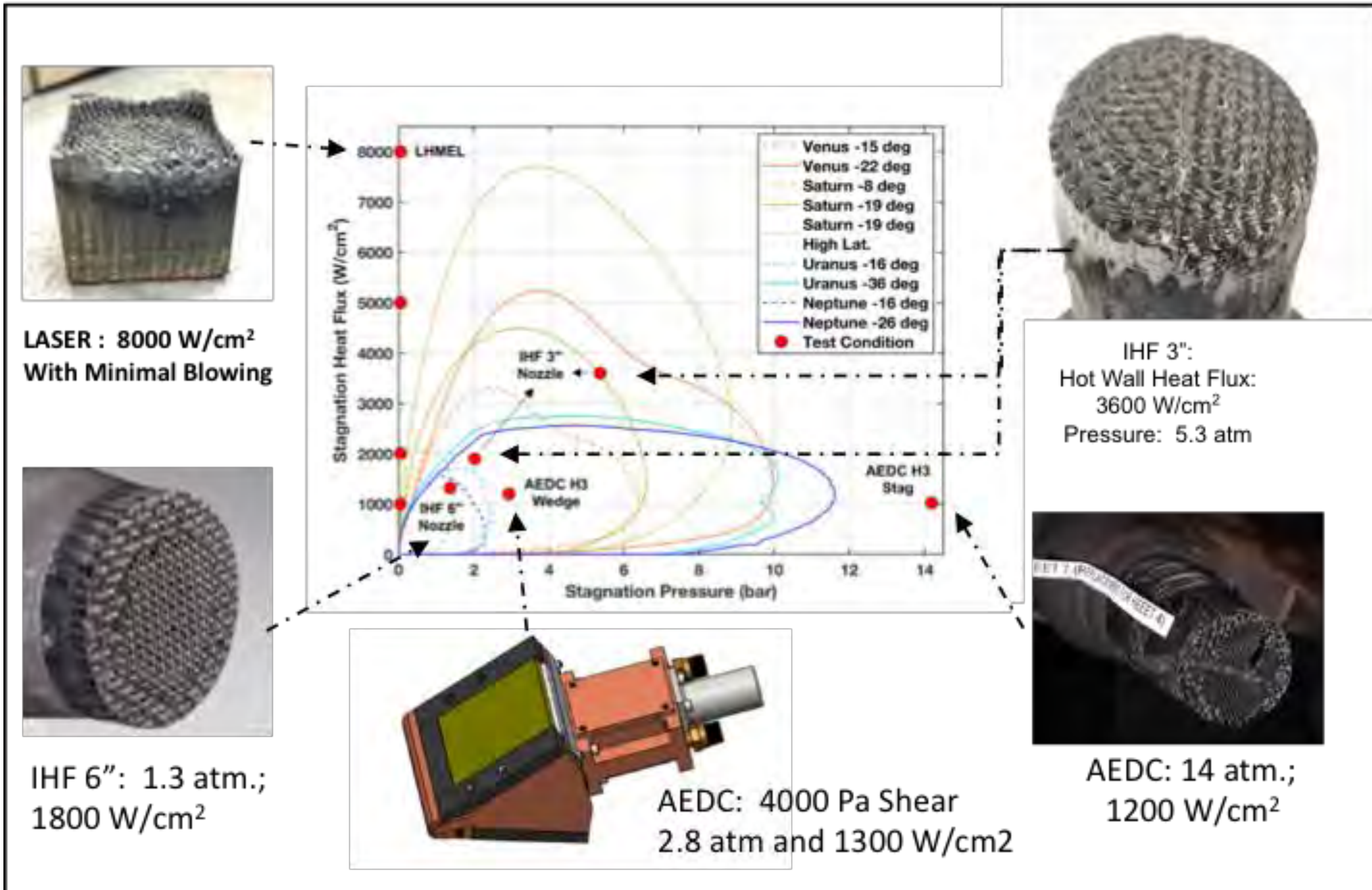
- Development, manufacturing and testing of ***compliant*** seam bonded to acreage, and integration at full scale on ETU were significant challenges; tackled successfully.
  - Strain relief through compliant seam
  - Seam has to behave similar to acreage.
  - Bonding between seam and acreage has to be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

IHF 3” Stag Model
3600 W/cm^{2}; 5.3 atm

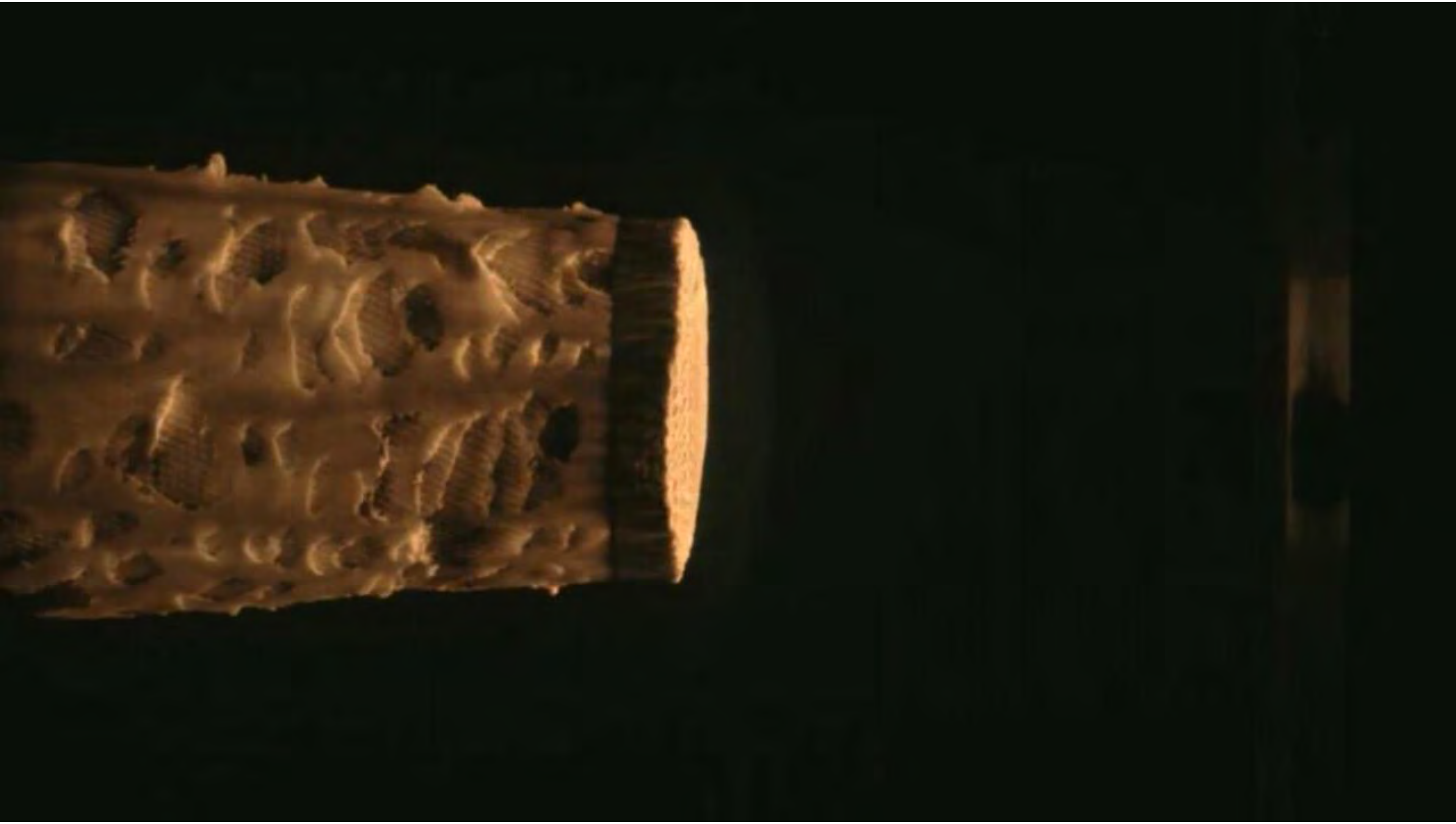
AEDC: 2” model
2000 W/cm2; 14 atm.

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

HEEET Aerothermal Test Campaign vs IGP Peak Conditions

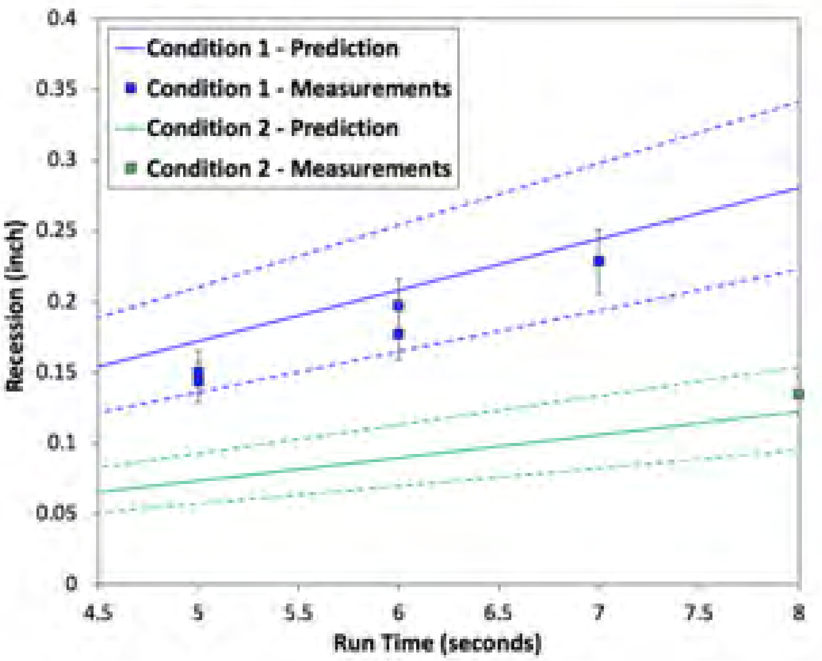


Highlights from the HEEET Arc Jet Test Campaigns

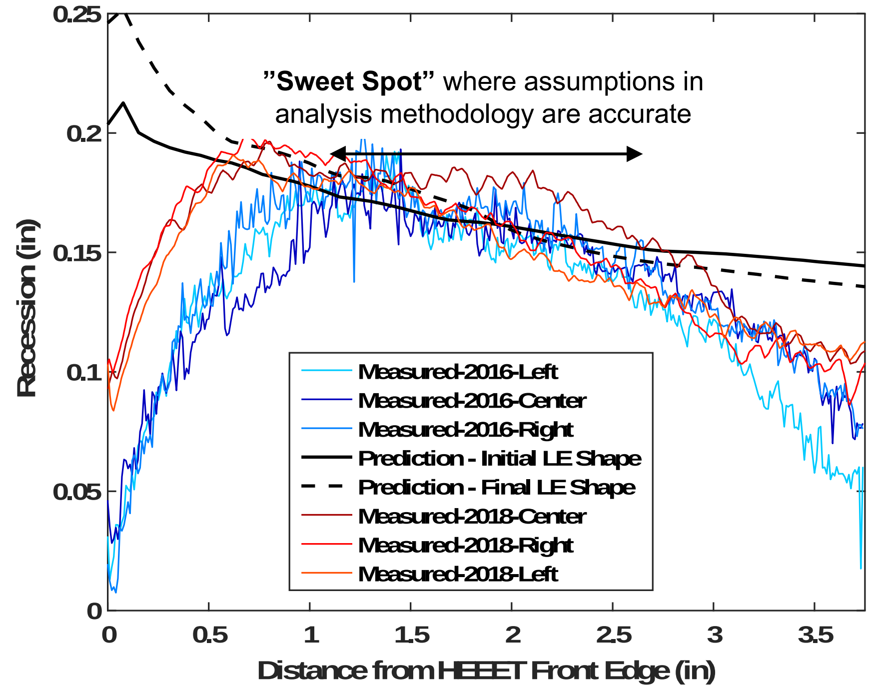


Predictable Acreage Recession

IHF 3" Nozzle Testing



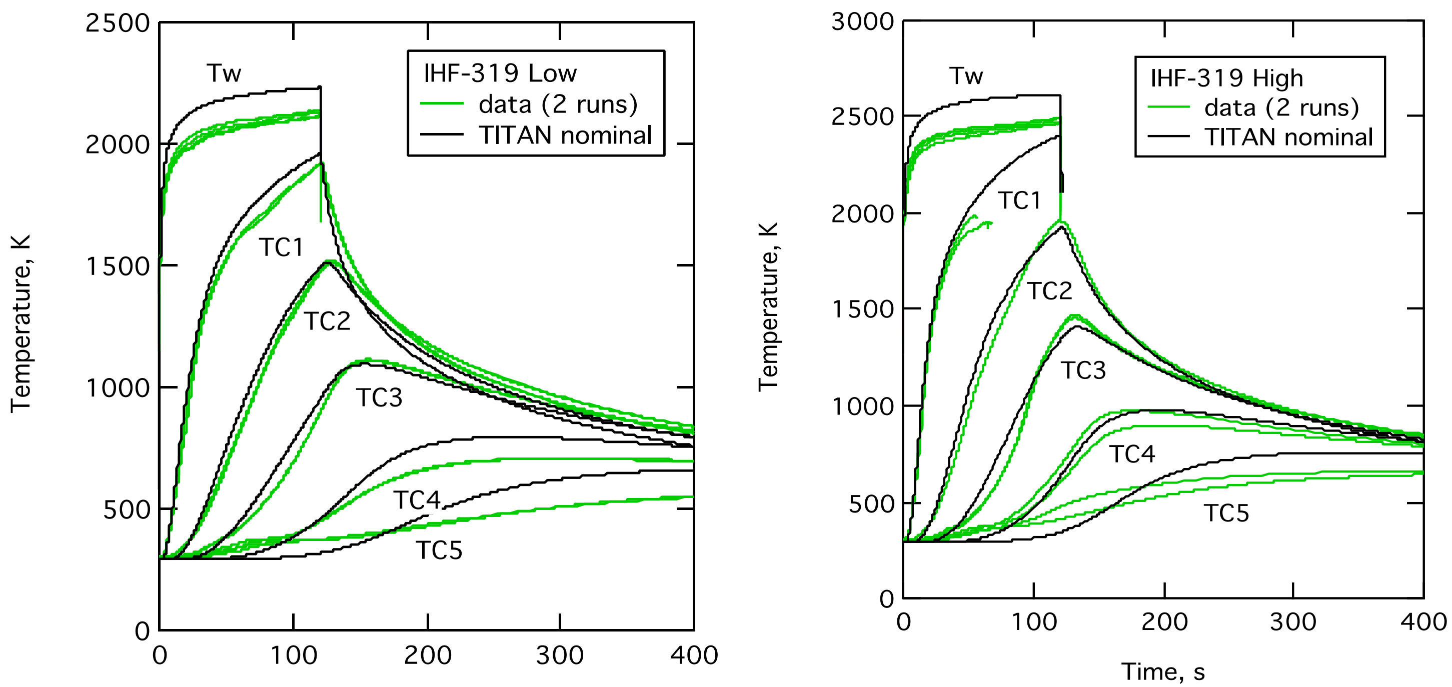
AEDC Wedge (Shear) Test



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

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

Predictable In-Depth Thermal Response



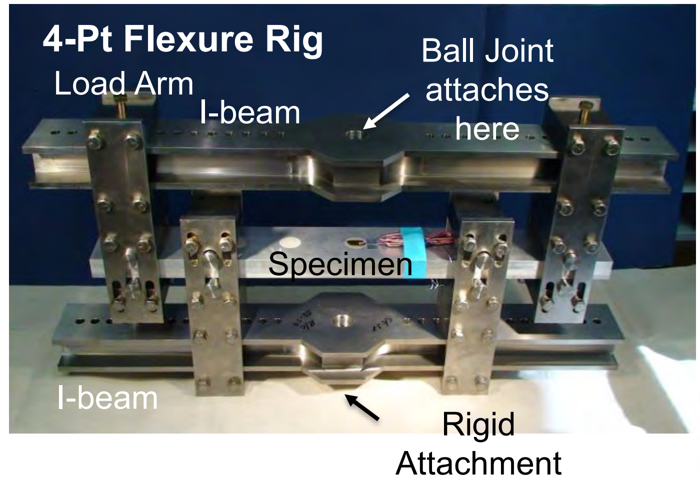
Good match between thermocouple data and model predictions at both the low and high heating conditions

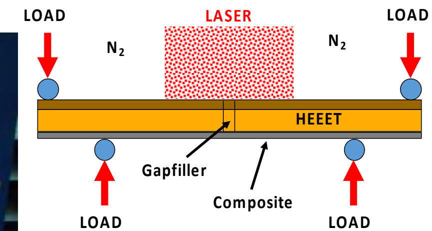
- Slight overprediction for insulating layer at low temperatures (mostly due to unmodeled water evaporation) – sizing model is conservative

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

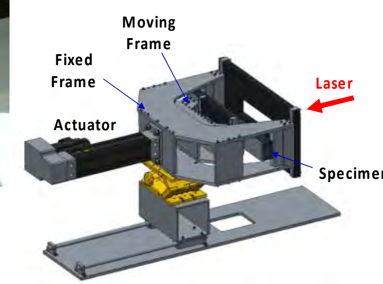
Structural Elements and Components Testing

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



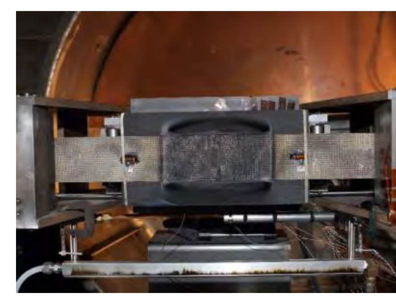


Schematic of LHMEL Structural Panel Test



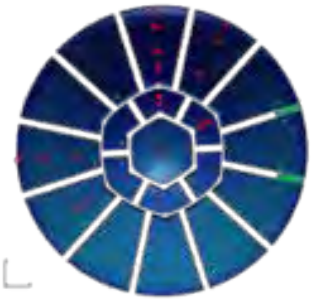
Load Application Apparatus

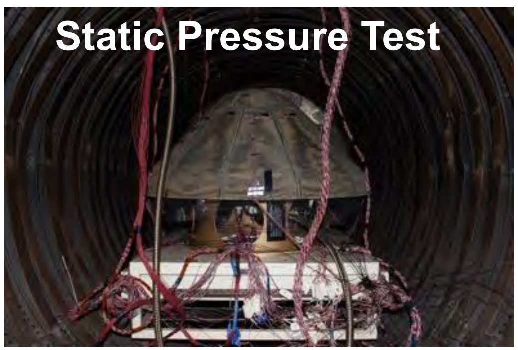
Shock Testing



Subsystem (ETU) Testing

79 Total Strain Gages For Test:





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

⇩

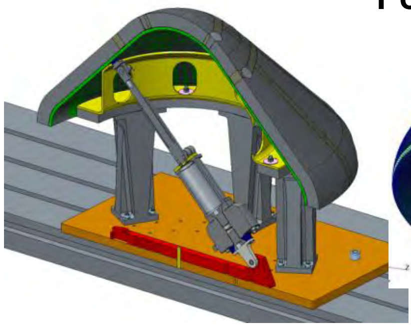
Thermal-Vacuum

NDE

⇩

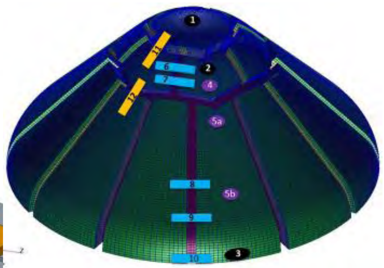
Static Point Load (Rd2)

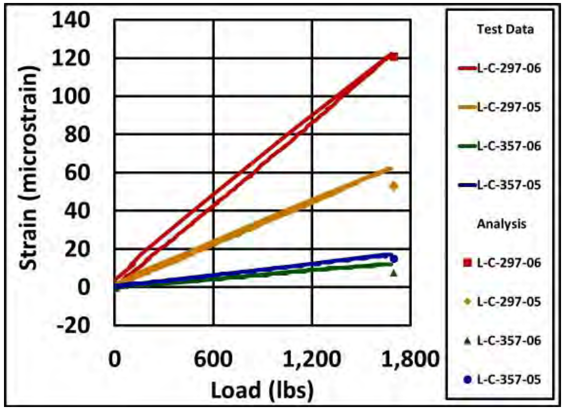
NDE (CT)



Static Point Load Configuration

Point Load Locations

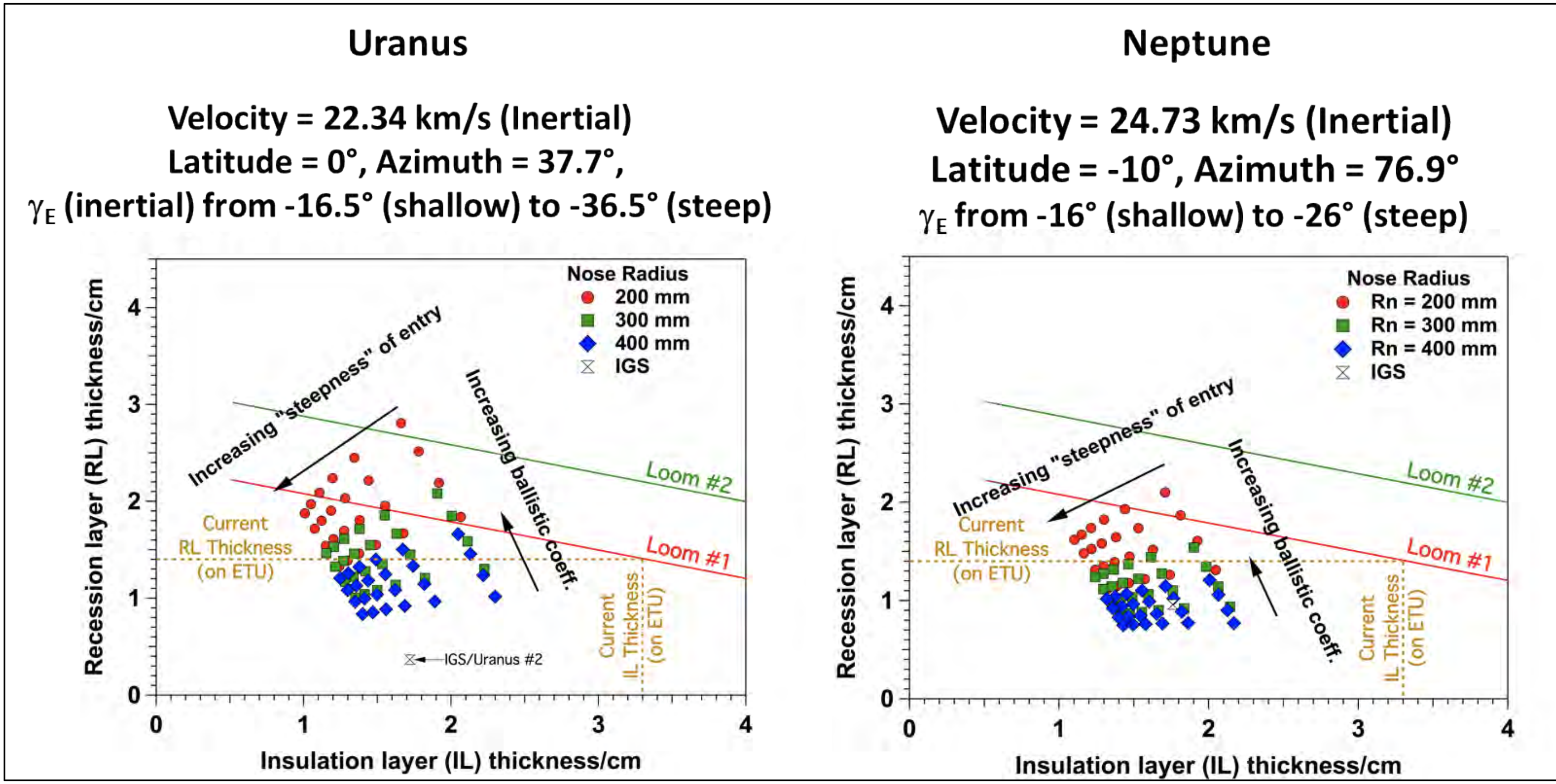




Pt 12: Under Closeout Plug

HEEET Capability Limitation and Mission Design Considerations

- Current 3-D weaving capability has been demonstrated upto 0.5” recession layer (RL) and 1.1” insulating layers (IL) at 24” width



- Current HEEET capability and ground test facility limitations can support majority of the Ice-Giant Missions but not all
- Mission formulation need to take into account TPS constraints early in the design cycle

Concluding Remarks

- Introduced Entry System and TPS for Ice Giant Probe Missions
  - Focus was on TPS and used HEEET development to highlight key areas

- Understanding test capabilities is crucial not only in TPS design development, also in TPS flight design certification

- Mission success requires understanding the capability, the constraints and balancing the entry system with rest of the mission design

Key References

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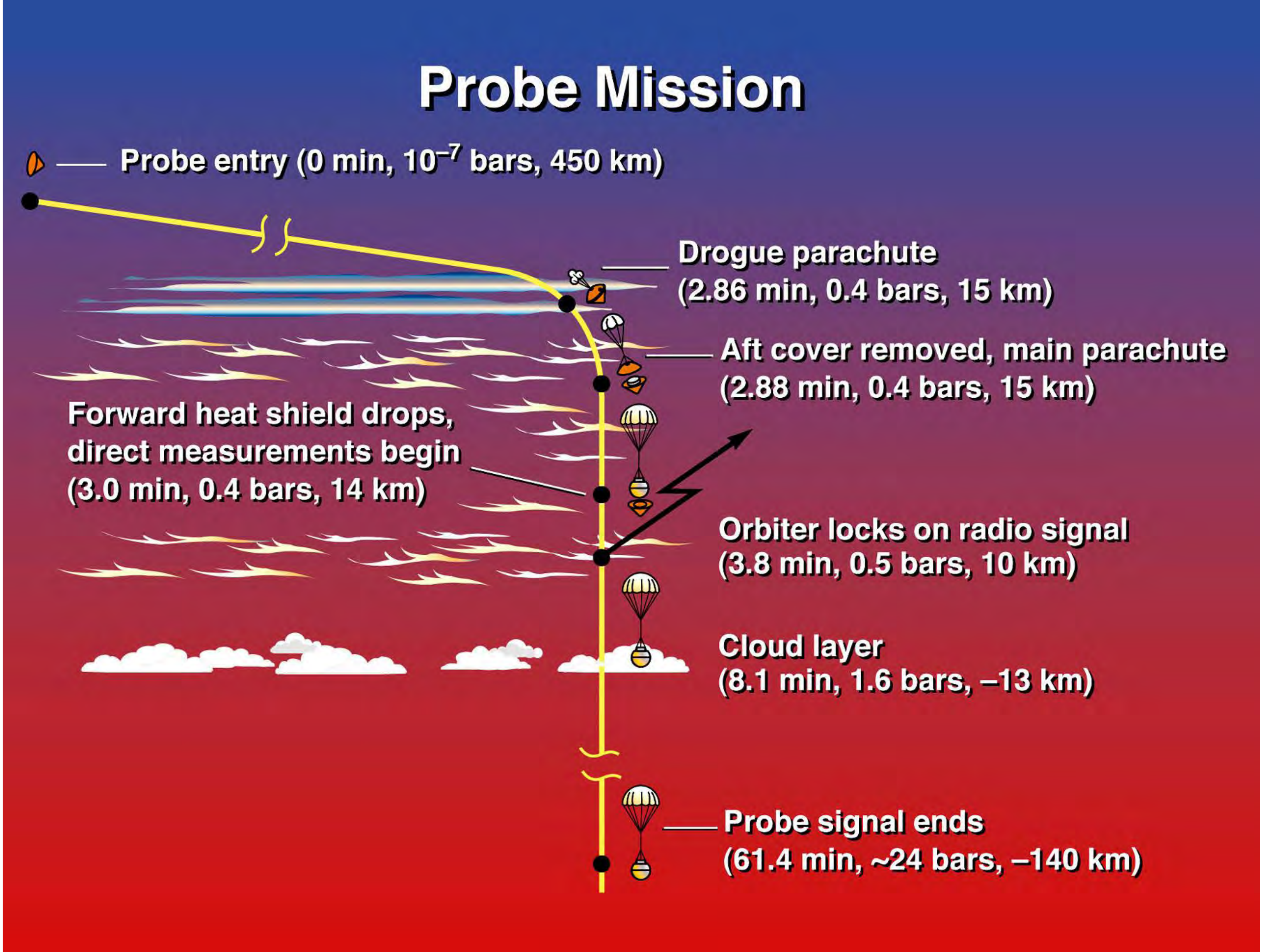
Entry Systems and Technology Division


Probe Mission
Probe entry (0 min, 10^{-7} bars, 450 km)
Drogue parachute
(2.86 min, 0.4 bars, 15 km)
Aft cover removed, main parachute
(2.88 min, 0.4 bars, 15 km)
Forward heat shield drops,
direct measurements begin
(3.0 min, 0.4 bars, 14 km)
Orbiter locks on radio signal
(3.8 min, 0.5 bars, 10 km)
Cloud layer
(8.1 min, 1.6 bars, –13 km)
Probe signal ends
(61.4 min, ~24 bars, –140 km)