Exploration of Atmospheric Entries at Uranus & Neptune with HEEET as Heatshield TPS

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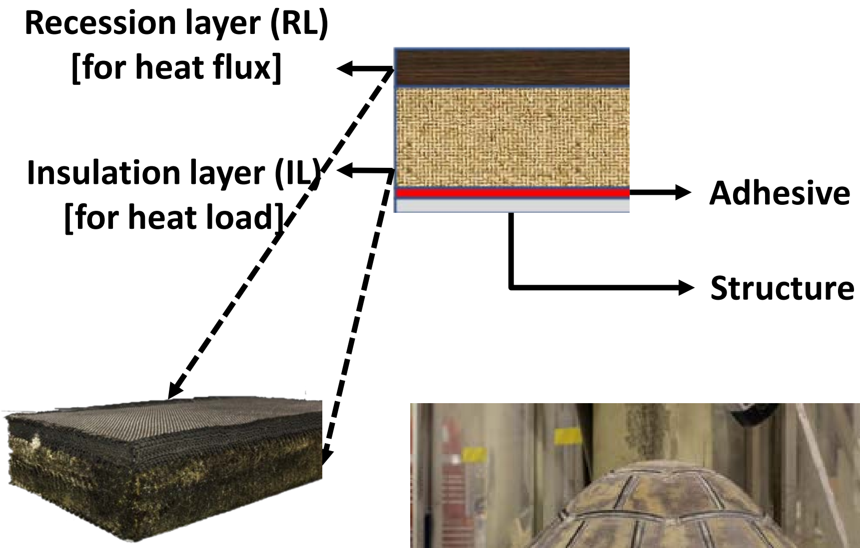
Background

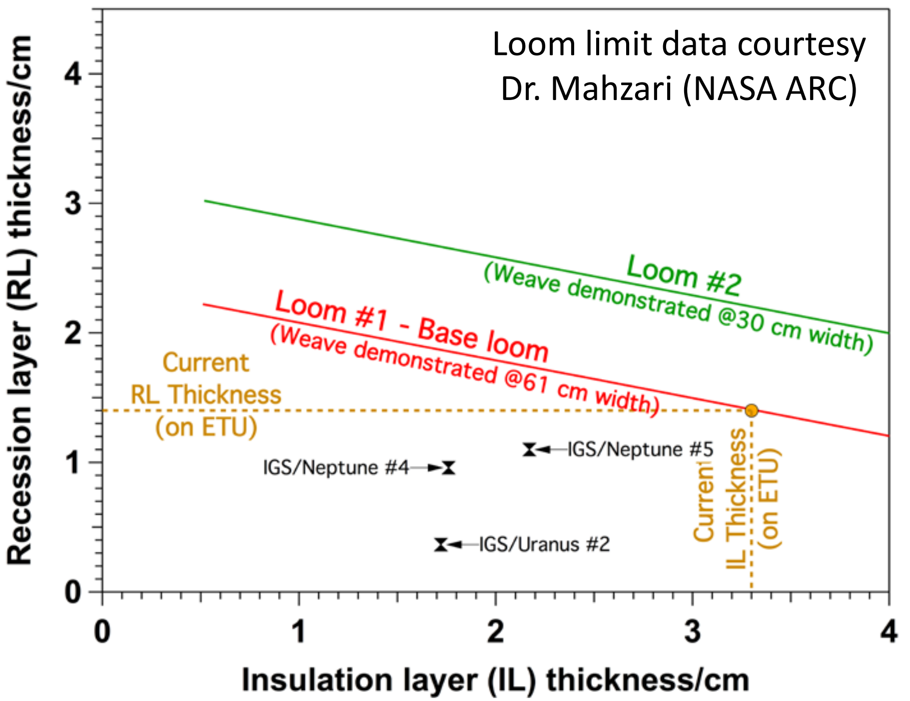
- In 2016 NASA commissioned a pre-Decadal Survey study on missions to the Ice Giants (Uranus and Neptune) [1]
  - Comprehensive study of Flagship mission architectures, incorporating several technology advancements
  - 3 of 4 mission concepts included an **instrumented probe (0.95-scale *Galileo*)** for *in situ* atmospheric science
  - 2 TPS materials considered for the forward heatshield:
    - Legacy material: FDCP (***F***ull-***D***ensity ***C***arbon-***P***henolic); or
    - **New material: HEEET (*H*eatshield for *E*xtreme *E*ntry *E*nvironment *T*echnology)**

Reference:

1. *Ice Giants – Pre-Decadal Survey Mission Study Report*, JPL D-100520, June 2017

HEEET in the Ice Giants Study





- **Thicknesses can be customized to mission**
- **The region below each loom limit line is the region of TPS weave feasibility**
- **5 point designs** considered in the IGS (Ice Giants Study): 2 Uranus & 3 Neptune
  - Thermal protection sizing performed only for 3 of the 5 point designs
  - Sizing based on stagnation point environments & preliminary margins policy

Objective and Approach

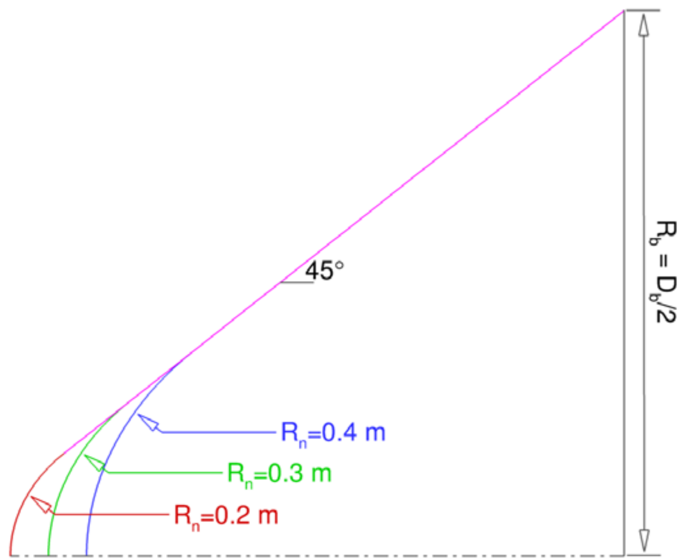
- **Would HEEET protect the Ice-Giant probes and what are the constraints?**
  - Look at atmospheric entry space for which HEEET does not require loom upgrade
  - Revisit the problem of Ice Giants entry with an expanded trajectory space;
    - From lessons learned in the Common Probe Study [1–3]; and
    - From detailed flow & material sizing computations performed for Saturn missions
      - Include estimated turbulent heating on conical flank
  - Include uncertainties (in both aerothermal environments & materials response); and
  - Use a more rigorous margins policy in the assessment [4]

References:

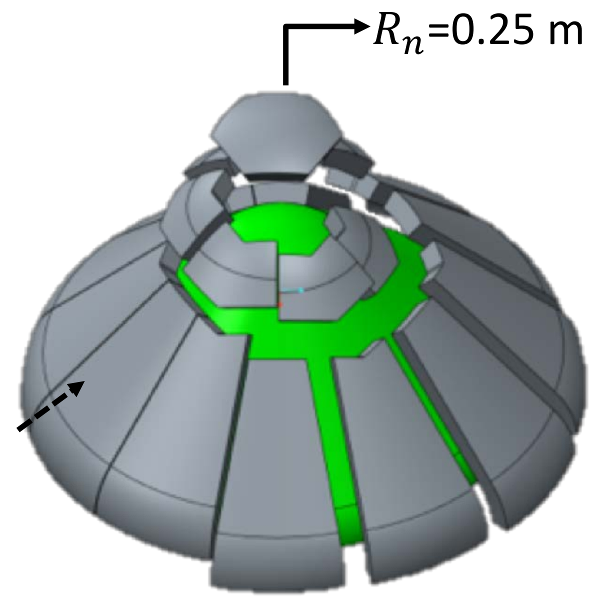
1. Hwang, H. (2018), *15th IPPW*, Boulder, CO, June 11–15.
2. Allen, G. A., Jr., Wright, M. J., and Gage, P. J. (2005) NASA/TM-2005-212847.
3. Milos, F. S. and Chen, Y.-K. (2013) *J. Spacecraft and Rockets*, 50(1), pp.137-149.
4. Mahzari, M. and Milos, F. (2018), *15th IPPW*, Boulder, CO, June 11–15.

Probe Forebody Geometry

- **45° Sphere-Cone** (Used in *Galileo*, Decadal Surveys, Ice Giants Study, …)



1 m (dia.) ETU (tiled configuration)



- **Nose radius is an important consideration**
  - Smaller nose radius ⇒ higher convective heating ($\propto 1/\sqrt{R_n}$), but lower radiative heating
  - Turbulent heating likely on the conical flank, esp. with increasing base diameter
    - Could be as high as stagnation point heating, if not higher
  - Nosecap spherical radius will be influenced by RL and IL thicknesses

Trajectory Space Exploration

- Parameter space (for direct ballistic entries & representative entry velocities)
  - **Entry velocity, latitude, and heading (azimuth) from the Ice Giants Study**
  - **Entry ballistic coefficient (proxy for *entry* mass): 200 kg/m^2 to 350 kg/m^2**
    - *Galileo* ballistic coefficient was 255 kg/m^2
    - For a given diameter, adding mass means increased ballistic coefficient
    - Larger ballistic coefficient ⇒ deceleration in deeper stratosphere ⇒ higher heat flux ⇒ thicker recession layer
  - **Entry flight path angle range to keep g loads between ≈50 and ≈300**
    - *Galileo* experienced peak deceleration of ≈226 g
    - g loads (and pressure loads) increase with increasing steepness
    - Increased g loads ⇒ increased expense of instrument qualification
    - Low g entries ⇒ longer atmospheric dwell time ⇒ higher heat load ⇒ thicker insulation layer
  - **Nose radius: 0.2, 0.3, or 0.4 m**
    - *Galileo* nose radius was 0.222 m
    - Nosecap of spherical radius 0.25 m demonstrated on HEEET ETU

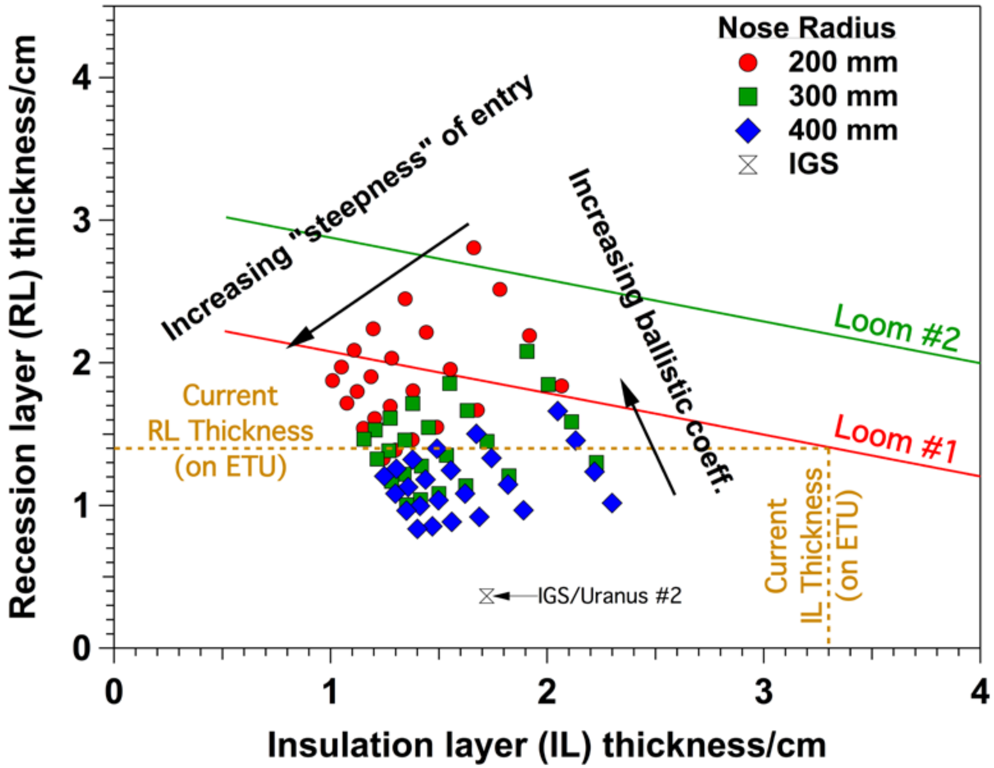
Other Considerations

- **Ground-test facilities (arc jets), used for qualification & certification of HEEET, place additional constraints**
  - **Pressure** – estimated limit is 5 bar in the smallest nozzle of the IHF arc jet at NASA ARC
    - Could consider high pressure arc heaters at AEDC, but heat fluxes expected to be lower than flight
  - **Heat flux** – estimated limit is 3 kW/cm^2 in the smallest nozzle of the IHF arc jet at NASA ARC
  - Regardless of choice of arc heater, replicating the composition of the atmosphere of Ice Giants in a ground-based facility remains a challenge

Uranus Entries (1/2)

Velocity = 22.34 km/s (Inertial)

Latitude = 0°, Azimuth = 37.7°, γ_E (inertial) from -16.5° (shallow) to -36.5° (steep)

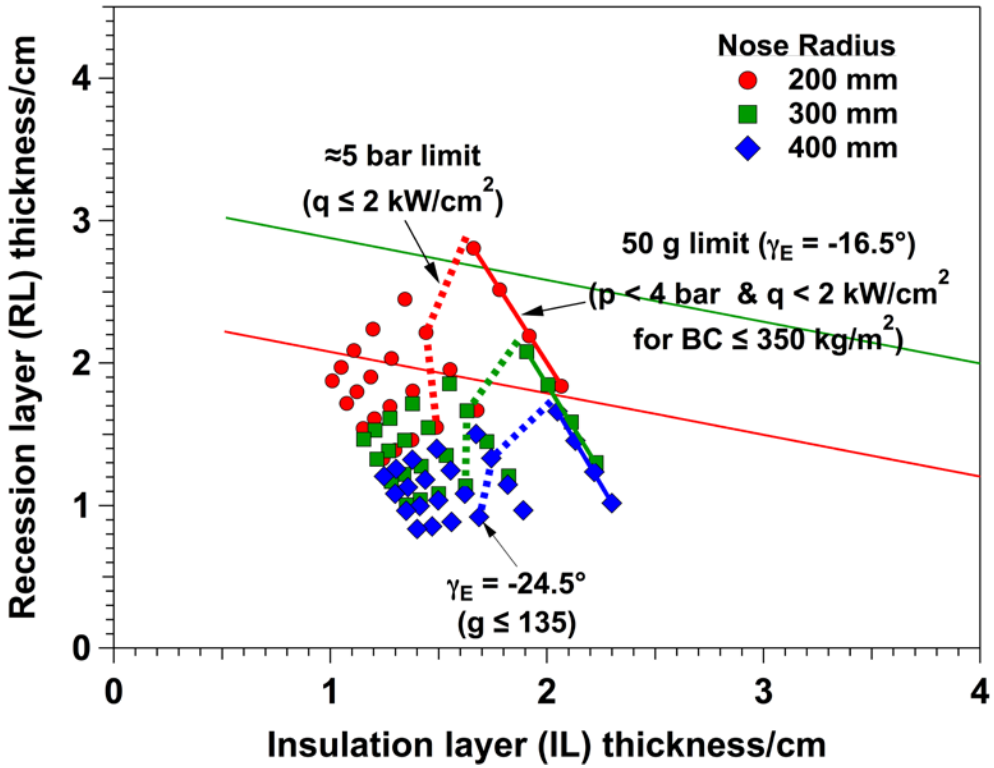


- Except for one point, *all* HEEET estimates fit within the limits of Loom #2, regardless of both ballistic coefficient *and* entry flight path angle
- Recession layer (RL) thickness estimates increase with decreasing nose radius
- For a nose radius of 0.4 m, HEEET estimates fit with the limit of Loom #1 (the base loom)

Uranus Entries (2/2)

Velocity = 22.34 km/s (Inertial)

Latitude = 0°, Azimuth = 37.7°, γ_E (inertial) from -16.5° (shallow) to -36.5° (steep)

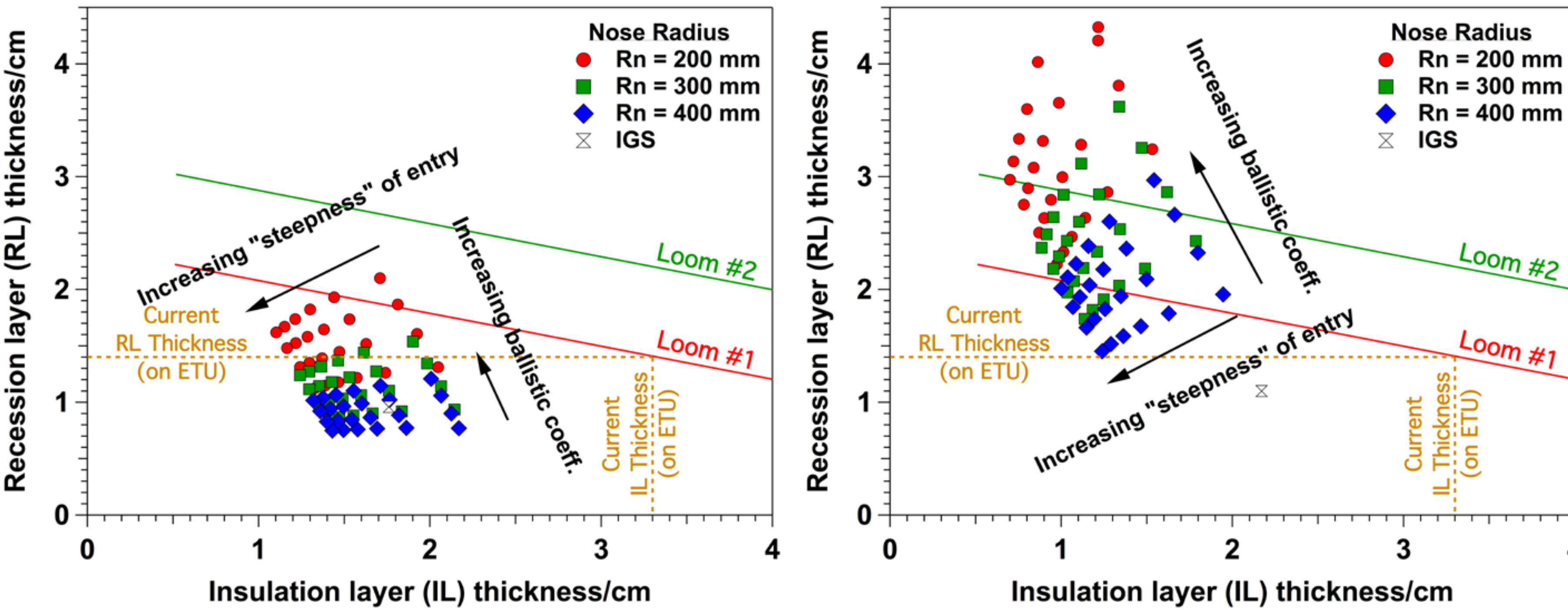


- For 50 g constraint, entry no steeper than -16.5° for all ballistic coefficients
- For 5 bar pressure constraint:
  - Allowable ballistic coefficient decreases: 350 kg/m^2 (γ_E= -16.5°) to 200 kg/m^2 (γ_E= -24.5°)
  - Stagnation point heat flux does not exceed 2.5 kW/cm^2 for entries shallower than -24.5°

Neptune Entries (1/2)

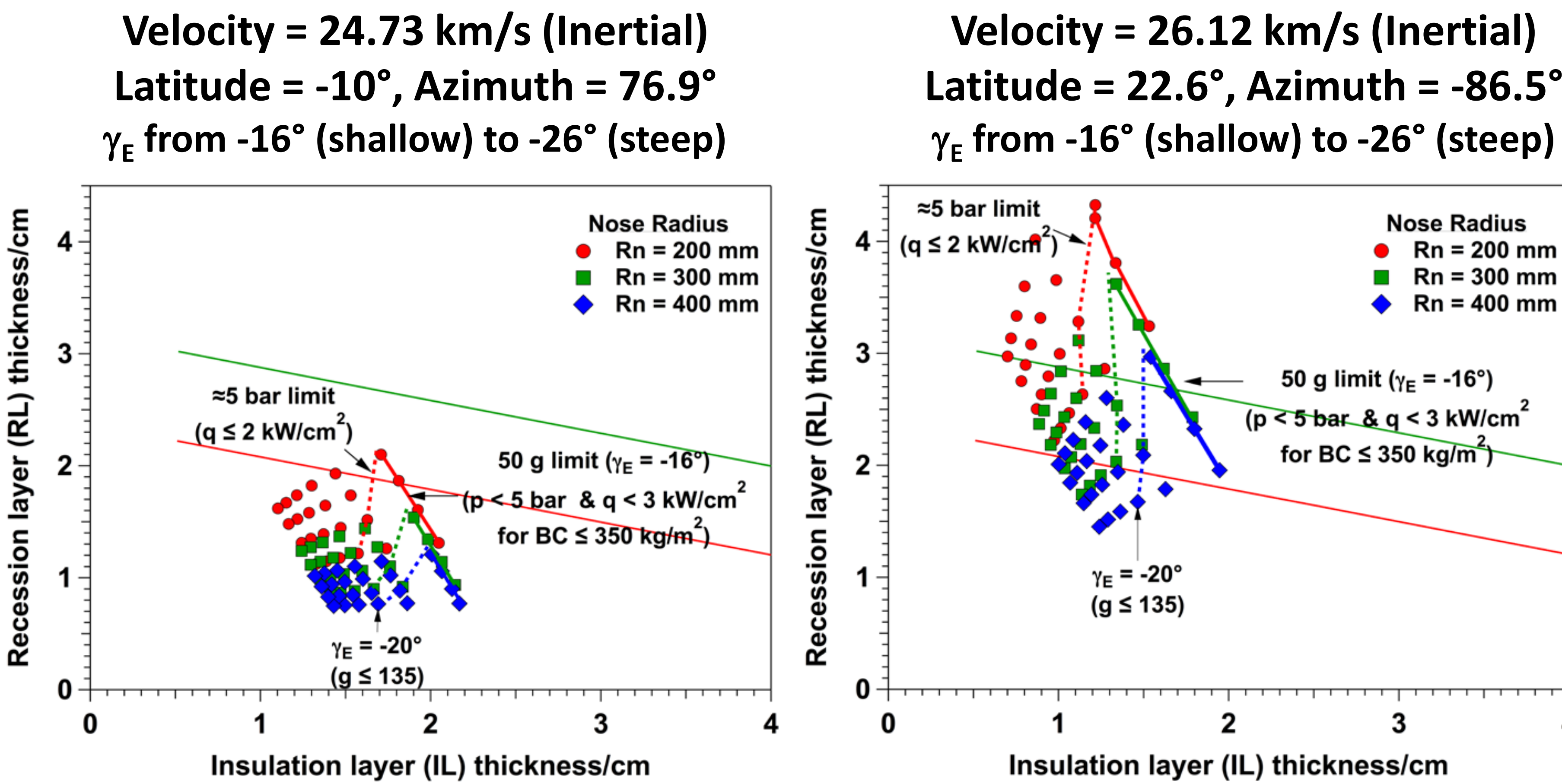
Velocity = 24.73 km/s (Inertial)
Latitude = -10°, Azimuth = 76.9°
γ_E from -16° (shallow) to -26° (steep)

Velocity = 26.12 km/s (Inertial)
Latitude = 22.6°, Azimuth = -86.5°
γ_E from -16° (shallow) to -26° (steep)



- *All* HEEET estimates fit within the limits of Loom #2, regardless of both ballistic coefficient *and* entry flight path angle, IF entry is prograde *and* low latitude
- For high latitude *and* retrograde entry, both nose radius *and* ballistic coefficient are constraints

Neptune Entries (2/2): Focus on High Latitude Entries



- For low latitude/prograde entry, steepness of entry limited by 5 bar pressure testing limit
- For high latitude/retrograde entry, 0.2 m nose radius will require a loom upgrade
  - Blunting nose *and* keeping ballistic coefficient to 250 kg/m^2 is beneficial – reduction in recession layer thickness (hence TPS mass)

Main Findings

- **Prefer to keep ballistic coefficient around 250 kg/m² (close to *Galileo*)**
  - Provides enough headroom to accommodate higher entry velocities: ≈23 km/s at Uranus and ≈25.5 km/s (prograde) at Neptune

Given mass (m) & ballistic coefficient (β)

$$D_b = \sqrt{(4m)/(\pi \beta C_D)}; \qquad C_D = 1.05$$

β kg/m⁻²	m 250 kg	m 350 kg	m 450 kg
	Diameter (D_b)/m		
250	1.10	1.30	1.48

Given base diameter (D_b) & ballistic coefficient (β)

$$m = \pi \beta C_D D_b^2 / 4; \qquad C_D = 1.05$$

β kg/m⁻²	D_b 1.0 m	D_b 1.25 m	D_b 1.5 m
	Mass (m)/kg		
250	206	322	464

- **Prefer to keep the nose radius around 0.3 m**
  - Meets HEEET forming radius constraint of 0.25 m *and* reduces heat flux (recession layer thickness, hence TPS mass)
  - Blunting shifts system CG aft – want x_{CG}/D_{base} ≈ 0.35-0.4 (*Galileo* and *Pioneer-Venus*)
- **50 g limit satisfied for approx. -16° entry flight path angle**
  - Heat flux does not exceed 3 kW/cm²
- **Heat flux does not exceed 3 kW/cm² for 5 bar pressure limit and entry angle < -20°**

HEEET can provide good thermal protection for Uranus and Neptune entry probes!

National Aeronautics and Space Administration

Ames Research Center
Entry Systems and Technology Division

Backup

Trajectory Space Exploration

- Parameter space (for direct ballistic entries & representative entry velocities)
  - **Entry velocity, latitude, and heading (azimuth) from the Ice Giants Study**
  - **Entry ballistic coefficient (proxy for *entry* mass): 200 kg/m² to 350 kg/m²**
    - Galileo had a ballistic coefficient of 255 kg/m²
    - For a given diameter, adding mass means increased ballistic coefficient
    - Larger ballistic coefficient ⇒ deceleration in deeper stratosphere ⇒ higher heat flux ⇒ thicker recession layer
  - **Entry flight path angle range to keep g loads between ≈50 and ≈300**
    - g loads (and pressure loads) increase with increasing steepness ⇒ increased expense of instrument qualification

Given mass (m) & ballistic coefficient (β)

$$D_b = \sqrt{(4m)/(\pi\beta C_D)}; \qquad C_D = 1.05$$

β kg/m⁻²	m 250 kg	m 350 kg	m 450 kg
	Diameter (D_b)/m		
250	1.101	1.303	1.477

Given base diameter (D_b) & ballistic coefficient (β)

$$m = \pi\beta C_D D_b^2/4; \qquad C_D = 1.05$$

β kg/m⁻²	D_b 1.0 m	D_b 1.25 m	D_b 1.5 m
	Mass (m)/kg		
250	206	322	464

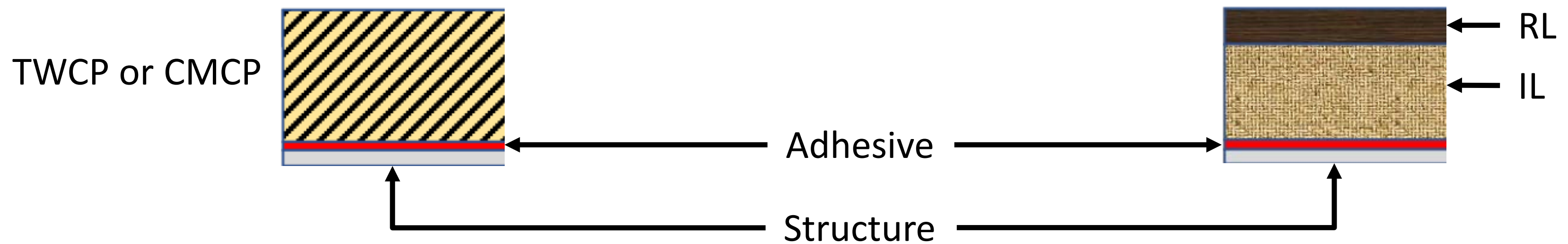
Candidate Thermal Protection Materials for Ice Giant Entries

FDCP

- **Legacy ablative material**
  - Used on Pioneer-Venus & Galileo Probes
  - Nose: chop-molded version (CMCP)
  - Flank: tape-wrapped version (TWCP)
- **Very high density ablator**
  - Not mass efficient (esp. for Jupiter)
- **Technology, esp. CMCP, for NASA use has atrophied**

HEEET

- **New ablative material**
  - Not flight proven, but at TRL 6
- **Dual-layer 3D woven material**
  - Dense outer layer of woven C fiber
    - **Recession layer (RL) – meant to handle heat flux of atmospheric entry**
  - Mid-density blended weave of carbon and phenolic fibers
    - **Insulation layer (IL) – meant to handle heat load during atmospheric entry**
  - **More mass efficient than FDCP**



Ice Giants Study Summary

- **IGS Probe Geometry: 45° s/c, 1.2 m dia., 0.21 m nose radius, 325 kg entry mass**
  - Galileo: 45° s/c, 1.26 m dia., 0.222 m nose radius, 335 kg entry mass
  - IGS probe has a ballistic coefficient of 273 kg/m^2 (*cf.* 255 kg/m^2 of Galileo)
    - This ballistic coefficient is outside of any flight experience, but probably okay

- **HEEET shown to have clear mass advantage over FDCP**

- **IGS point designs have deceleration loads >100 g & stag. point pressures > 6 bar**
  - Replicating high pressures (at high heat fluxes) is an issue for material qualification and flight certification in a ground-test facility

- **Nose radius of the IGS probe is unnecessarily small**
  - Small nose radius is a hedge against radiative heating, but rad. heating is very small for Ice Giant entries
    - Significantly lower kinetic energies compared to Galileo
  - Small nose radius => high convective heating => denser ablative TPS

3DOF Trajectory Space Exploration

- Parameter space (for direct ballistic entries & representative entry velocities)
  - **Entry velocity, latitude, and heading (azimuth) from the Ice Giants Study**
  - **Entry ballistic coefficient: 200 kg/m² to 350 kg/m²**
    - Ballistic coefficient can be converted to diameter (given mass), or mass (given diameter)
  - **Entry flight path angle range to keep g loads between ≈50 and ≈300**
  - **Nose radii: 0.2, 0.3, and 0.4 m (Galileo: 0.22 m)**

Given mass (m) & ballistic coefficient (β)

$$D_b = \sqrt{(4m)/(\pi\beta C_D)}; \qquad C_D = 1.05$$

β kg/m⁻²	m 200 kg	m 250 kg	m 300 kg
	Diameter (D_b)/m		
200	1.101	1.231	1.349
250	0.985	1.101	1.206
300	0.899	1.005	1.101
350	0.832	0.931	1.019

Given base diameter (D_b) & ballistic coefficient (β)

$$m = \pi\beta C_D D_b^2/4; \qquad C_D = 1.05$$

β kg/m⁻²	D_b 1.0 m	D_b 1.2 m	D_b 1.4 m
	Mass (m)/kg		
200	165	238	323
250	206	297	404
300	247	356	485
350	289	416	566

HEEET Sizing Methodology

- 3DOF trajectories using *TRAJ* [1] – only atmospheric density profile matters!;
- Material thermal response using *FIAT* [2]; and
- A margins policy which accounts for uncertainty in environments & material properties [3]
- Thicknesses determined with: (a) initial temperature of -10 °C, and (b) a maximum allowable back face (bondline) temperature of 250 °C
- Stagnation point sizing adjusted to margin against turbulent heating on the conical flank
  - Flank heating can be as high as stagnation point heating, but at a lower (≈50%) pressure level – increased material recession
  - Current solution to estimate flank thickness: Scale up stagnation point recession layer thickness by 1.2, and scale down insulation layer thickness by 1.2
- Manufacturing margins added to estimates of flank thicknesses (RL & IL)

References:

1. Allen, G. A., Jr., Wright, M. J., and Gage, P. J. (2005) NASA/TM-2005-212847.
2. Milos, F. S. and Chen, Y.-K. (2013) *J. Spacecraft and Rockets*, 50(1), pp.137-149.
3. Mahzari, M. and Milos, F. (2018), *15th IPPW*, Boulder, CO, June 11–15.

Pre-Decadal Ice Giants Study (IGS): Summary

- **IGS Probe Geometry: 45° s/c, 1.2 m dia., 0.21 m nose radius, 325 kg entry mass**
  - Payload mass of 200 kg included in the 325 kg entry mass
  - Galileo: 45° s/c, 1.26 m dia., 0.222 m nose radius, 335 kg entry mass
- **HEEET clearly demonstrated to be more mass efficient than FDCP**
- **Stagnation pressures in excess of 6 bar – implications to arcjet testing of material**

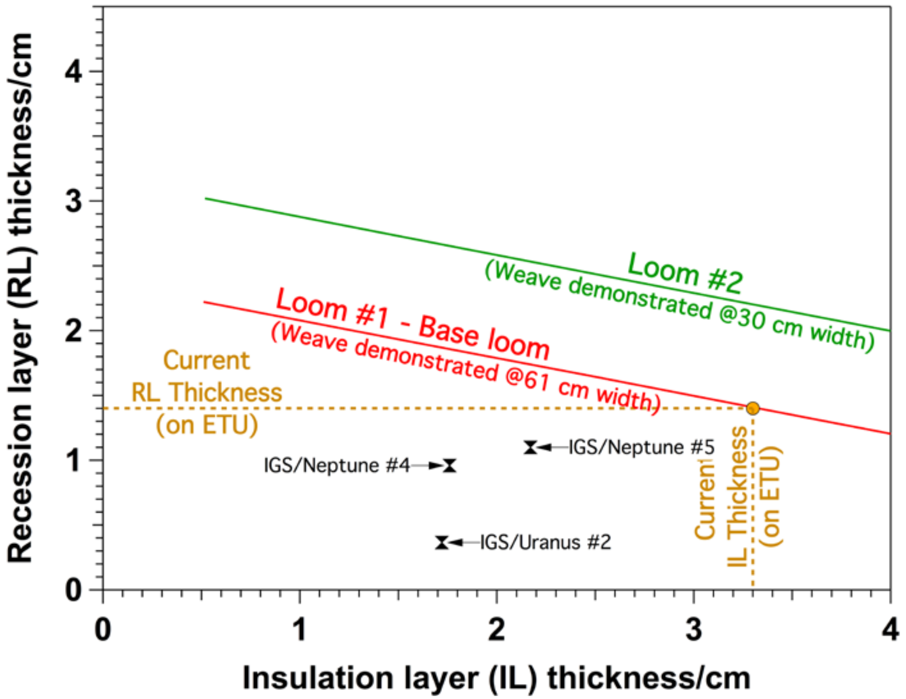
Entry Parameters	URANUS		NEPTUNE		
	Design #1	**Design #2**	Design #3	**Design #4**	**Design #5**
Entry velocity/km.s^{-1}	23.1	**22.52**	26.12	**25.73**	**25.72**
EFPA/deg	-35	**-30**	-34	**-20**	**-16**
Heading/deg	-5.82	**-20.02**	-99.1	**-84.26**	**-86.45**
Latitude/deg	-9.22	**-5.63**	-1.42	**24.8**	**22.64**
Max. deceleration/g	217	**165**	455	**209**	**125**
Max. pressure/bar	12	**9**	25	**11.5**	**6.84**
FDCP thickness/cm (mass/kg)		**2.6 (60)**		**3.2 (73)**	**3.9 (88)**
HEEET thickness/cm (mass/kg)		**2.1 (29)**		**2.7 (39)**	**3.3 (47)**
PICA thickness/cm (mass/kg)		**1.0 (4)**		**1.5 (5)**	**2.0 (7)**

Some Details about HEEET

- Core to HEEET technology is 3D-weaving of preforms – TPS thickness is limited by existing loom infrastructure
- A key to HEEET mass efficiency is dual layer nature of the weave
  - Dense outer Recession Layer (RL) to manage heat flux – thickness limited to amount of recession
  - Lower density Insulating Layer (IL) to mange heat load – thickness sized to temperature limit at bond line to underlying structure
- HEEET weaving has been demonstrated **on two loom configurations** with different width and thickness capabilities
  - Full range of thickness (RL & IL)/width combinations has not been demonstrated to date
- A tiled ETU has been built and structurally tested at a scale of 1.0 m diameter
- Small coupons have been arcjet tested up to a pressure of 5 bar & a heat flux of 3.5 kW/cm^2
- *Definition: The region below each loom limit line is the region of TPS weave feasibility*

Tiled HEEET Configuration (ETU)
(1 m diameter)

HEEET Looms Currently Available



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

Summary of Aerothermal Environments for R_n = 0.4 m

Deceleration load/g

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	50	50	53	213	217	275
250	52	56	57	212	226	292
300	53	61	61	225	233	300
350	55	65	66	233	238	270

Stagnation point heat load/J.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	29000	23000	38500	14250	13500	19400
250	32000	26000	42000	15500	14500	21000
300	34500	28000	45200	16500	15500	22000
350	37000	30000	50000	17350	16200	25000

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 heat load/J.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	29000	23000	38500	14250	13500	19400
250	32000	26000	42000	15500	14500	21000
300	34500	28000	45200	16500	15500	22000
350	37000	30000	50000	17350	16200	25000