Thermal Protection System Design of Aerocapture Systems for Uranus Orbiters

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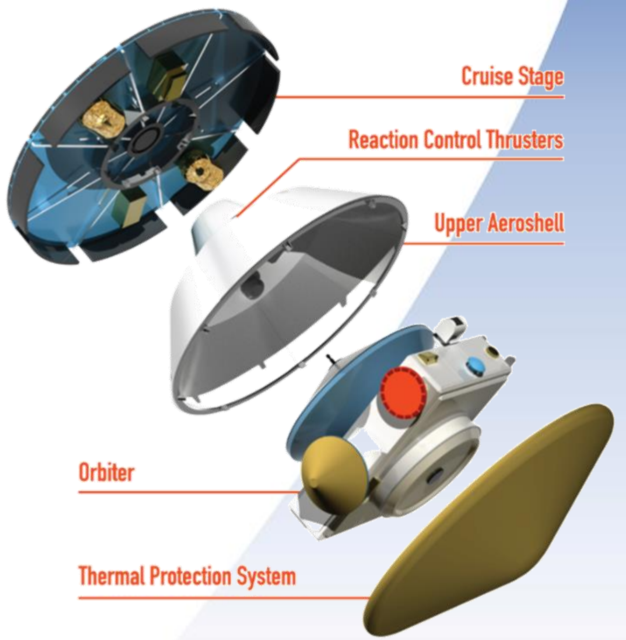
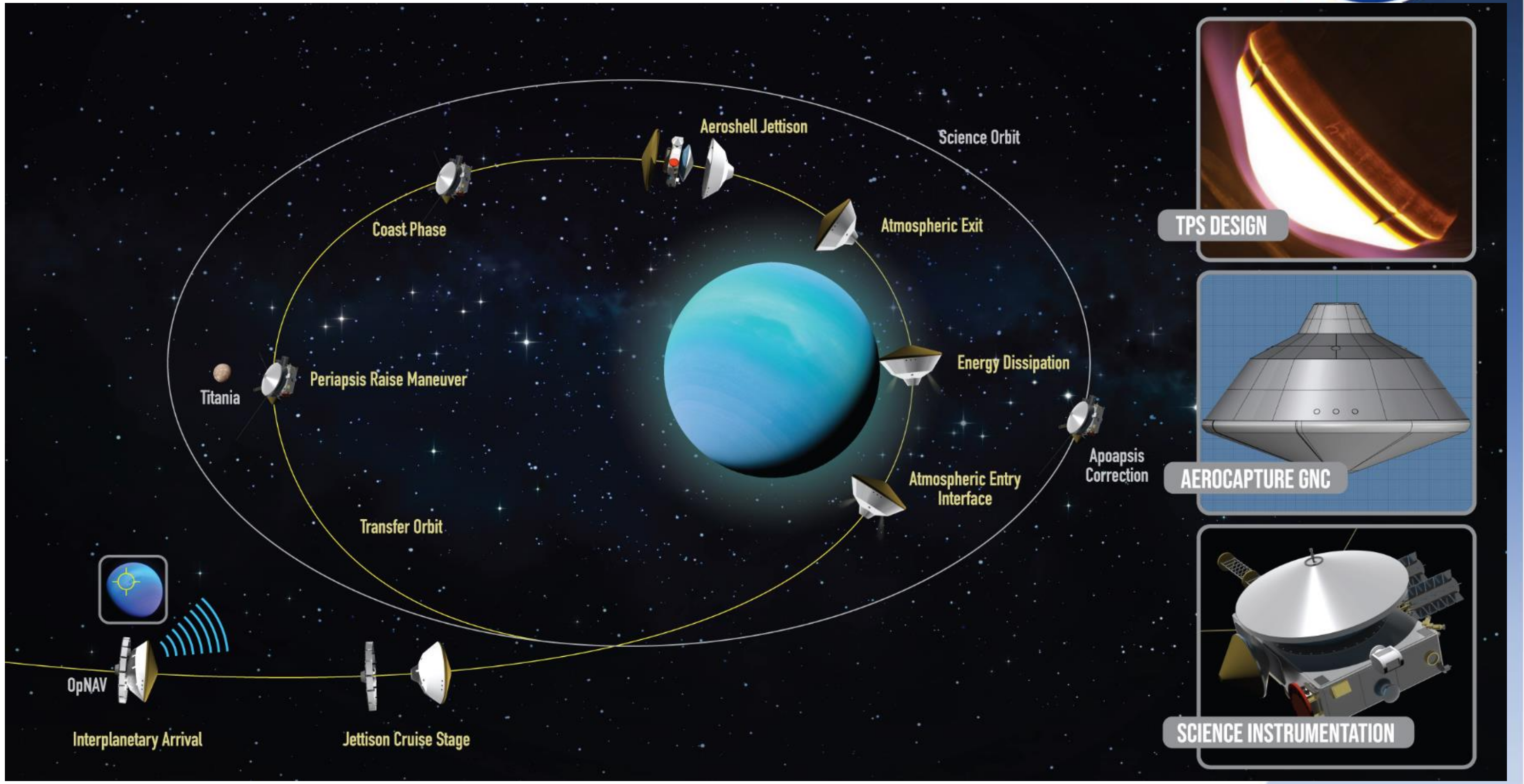


Outline & Background

- ➢ Motivation & Previous TPS Solutions
- ➢ Vehicle Design & Environments
- ➢ Forebody TPS Design Solutions
- ➢ Aftbody TPS Design Solutions
- ➢ Conclusions

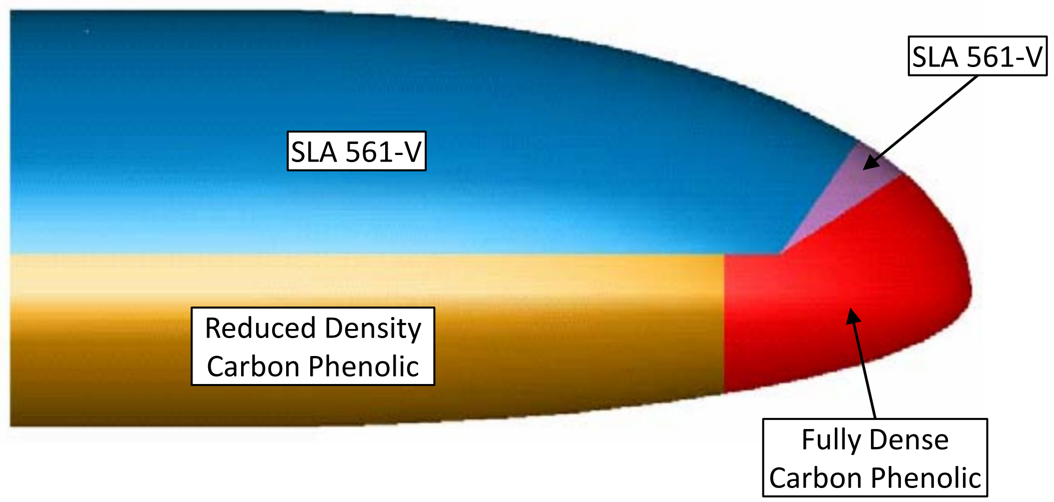


Science Priorities: The National Academies Planetary Science and Astrobiology Decadal Survey recently identified Uranus as the highest priority Flagship-class mission for science in the next decade.

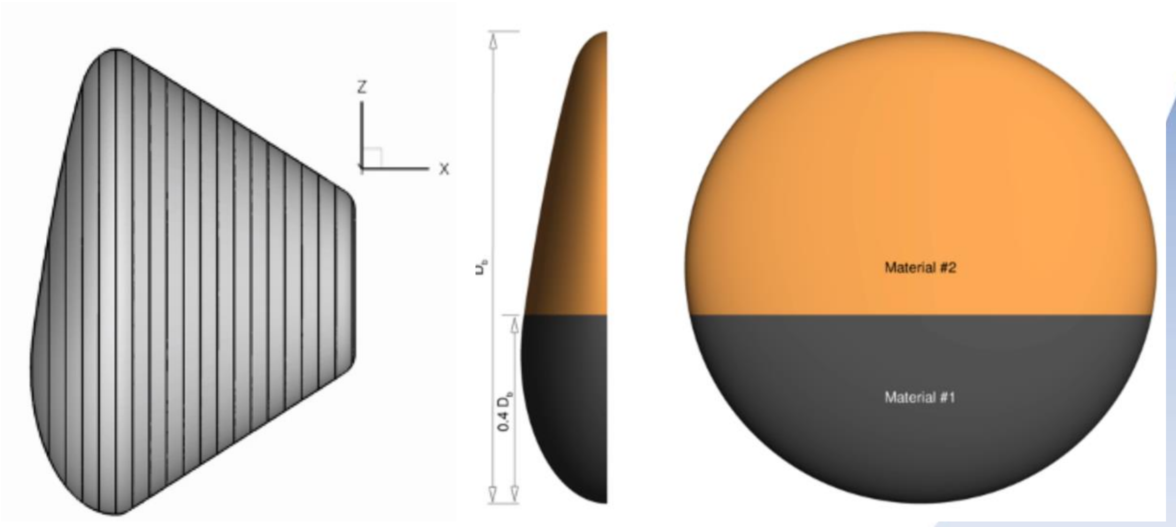
Aerocapture: the use of a planet's or moon's atmosphere to accomplish an orbit insertion maneuver with a spacecraft using minimal propellant.

Motivation & Previous TPS Solutions

- Aerocapture delivers larger payload masses, faster to Uranian orbits compared to traditional fully propulsive architectures like was shown for the Uranus Orbiter and Probe (UOP) mission concept.
- Past studies of Ice Giant aerocapture determined higher lift-to-drag (L/D > 0.4) vehicles necessary for adequate margin when considering atmospheric and overall system uncertainty.
- Higher L/D vehicle designs of this nature have unique aerodynamics, and in the case of the Ellipsled (2006), did not have TPS that could be manufactured to satisfy requirements.



Ellipsled[1], L/D $\approx$ 0.8

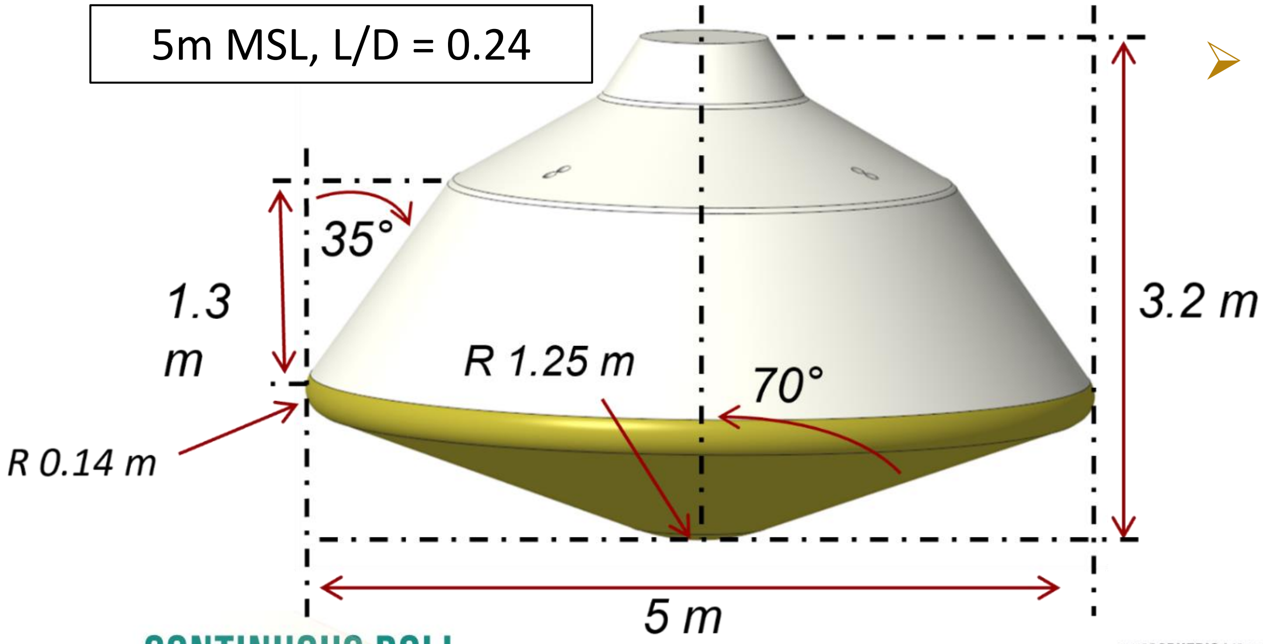


Asymmetric Capsule Vehicle[2], L/D $\approx$ 0.4

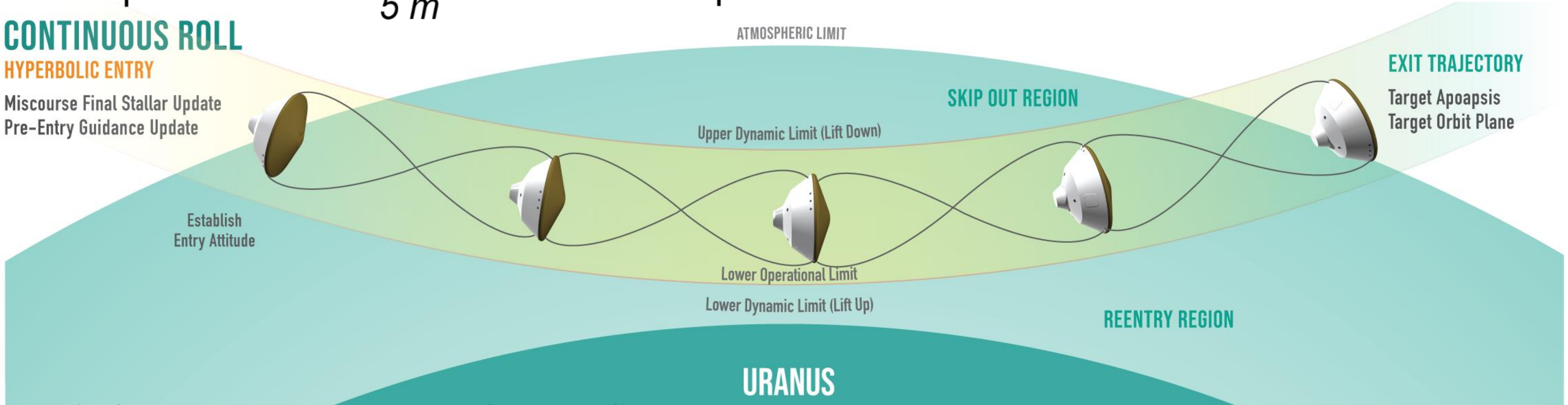
[1]Lockwood, M. K., Edquist, K. T., Starr, B. R., Hollis, B. R., Hrinda, G. A., Bailey, R. W., Hall, J. L., Spilker, T. R., Noca, M. A., and O'Kongo, N., "Aerocapture systems analysis for a Neptune Mission," Tech. rep., 2006

[2] Venkatapathy, E., Prabhu, D., Allen, G., and Gasch, M., "Thermal Protection System to Enable Ice Giant Aerocapture Mission for Delivering both an Orbiter and an In Situ Probe," 2020.

Vehicle Definition and Con-Ops



- **The concept vehicle is a scaled version of the Mars Science Laboratory (MSL) Vehicle for the following reasons:**
  - Better knowledge in aerodynamics.
  - Success in Bank Angle Modulation implementation.
  - Favorable packaging for items like the large antennae needed for deep-space communications.
  - Better knowledge of how to integrate TPS on forebody and afterbody.

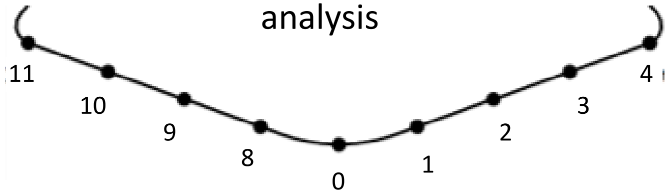


More details on Aerocapture at Uranus: S. Dutta et al., AIAA SciTech 2024 AIAA-2024-0714

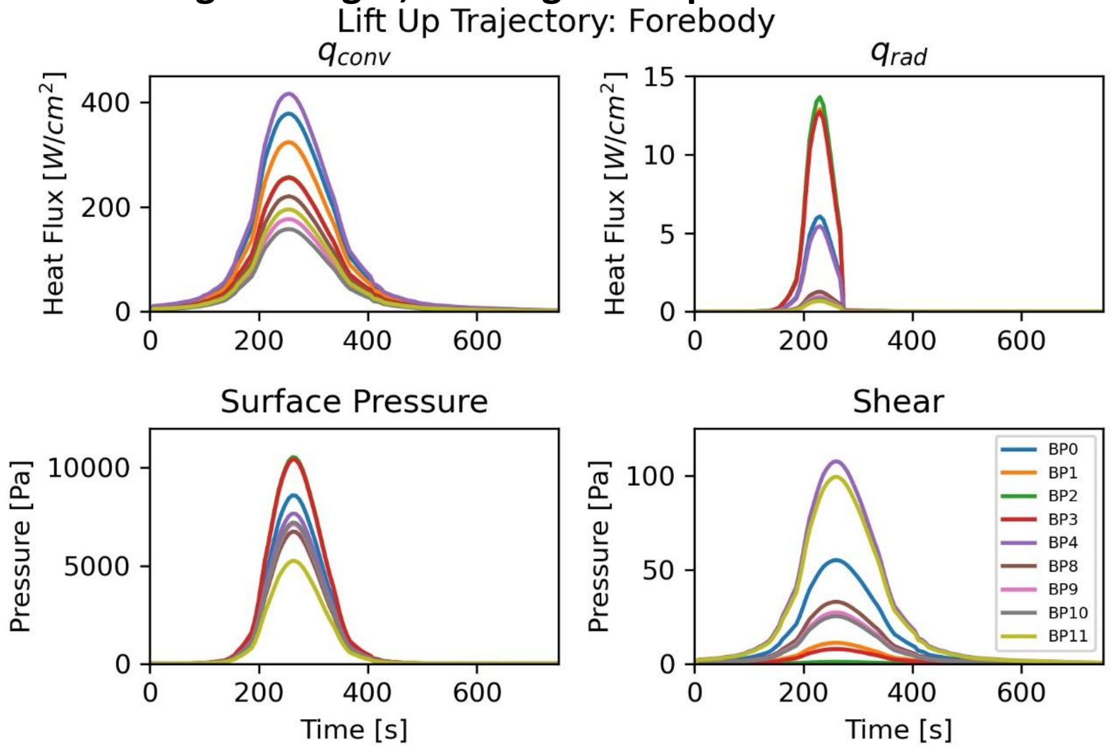
Forebody Environments

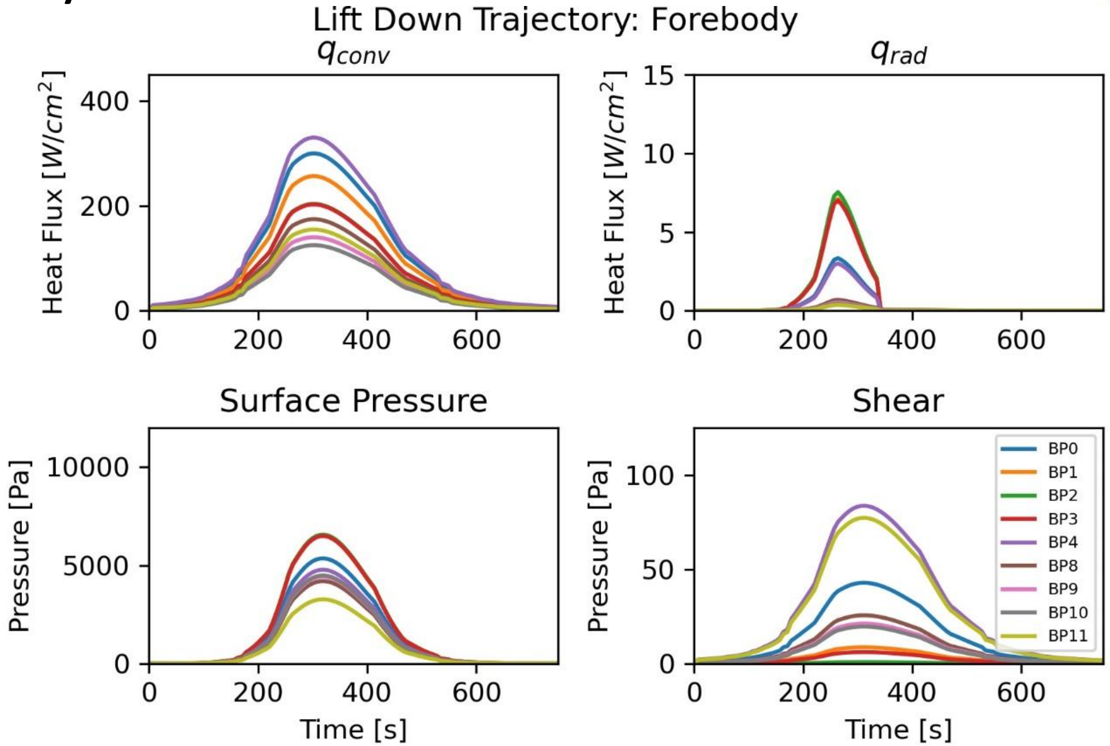
- **Two, constant bank-angle trajectories bound the entry corridor:**
  - The Lift-Up trajectory diving deep into the atmosphere, maximizes heat flux of approximately 400 W/cm^2 and 11 kPa.
  - The Lift-Down trajectory remains at high altitude, producing reduced environments yet increasing total heat load to 87 kJ/cm^2 – eclipsed only by Galileo.
- Radiative heating is low with limited CH4 present in the upper atmosphere. Radiation drops due to different fits used during the simulations, but radiative heating is small.
- **The challenge for TPS designers is to manage the enormous total heat load. Note that as bank angle changes, the stagnation point will move around the forebody!**

Body points (BP) used for TPS analysis



BP	0	1	2	3	4	8	9	10	11
Lift-Up Heat Load [kJ/cm^2]	66	56	44	44	72	38	30	27	34
Lift-Down Heat Load [kJ/cm^2]	79	68	54	53	87	46	37	33	42





Forebody TPS Design Solutions

- **NASA possess three ablative solutions that are appropriate for the heat flux and pressure environments:**
  - 3MDCP: a 3D woven medium density carbon phenolic derived from the HEEET-IL material.
  - PICA-D: low-density phenolic infused carbon ablator that replaces PICA, whose design has significant flight heritage and test history.
  - CPICA: a low-density carbon felt that can be infused PICA-D density with lower thermal conductivity and higher strain to failure.
- **A three-branch RSS process derived from M2020 is implemented to perform TPS sizing.**
- **The Lift-Down trajectory generates the thickest solutions due to the larger heat load.**
- **Currently, CPICA and PICA-D can be manufactured to the required thickness, but CPICA's mass-efficiency, as shown by the low areal mass, make it the TPS of choice for this mission concept. TPS mass fraction is 8% compared to Mars2020 6.4%.**

Constant Substructure		Margin Values	
Material	Thickness [cm]	Thermal Margin	70°C – 96°C
HT-424	0.025	Gap-filler Margin	1x
M55JA-composite	0.1	Aerothermal Margin	1.35x
Al-HC-21 2.5in	6.0	Radiative Margin	1.5x
M55JB-composite	0.1	Pressure Margin	1.05x

TPS	CPICA	PICA-D	3MDCP
Areal Mass* (kg/m^2)	14	24	48

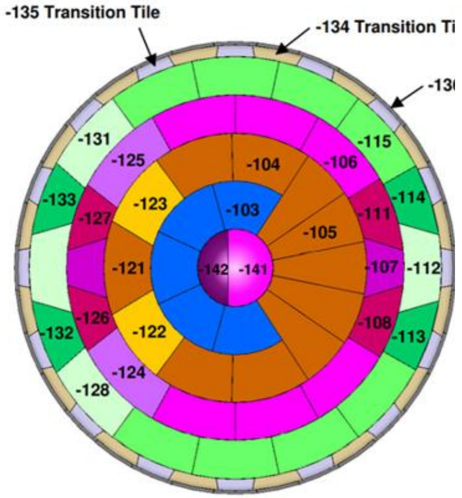
*estimated using largest thickness for forebody area.

[cm]	C-PICA		PICA D		3MDCP	
BP	Lift Down	Lift Up	Lift Down	Lift Up	Lift Down	Lift Up
0	5.22	4.61	8.70	7.81	6.47	5.80
1	4.97	4.36	8.32	7.42	6.16	5.51
2	4.71	4.12	7.99	7.10	5.81	5.19
3	4.71	4.11	7.99	7.09	5.80	5.18
4	5.17	4.57	8.59	7.72	6.50	5.84
8	4.48	3.90	7.72	6.81	5.54	4.94
9	4.24	3.69	7.37	6.45	5.21	4.63
10	4.12	3.58	7.18	6.25	5.04	4.47
11	4.32	3.76	7.51	6.60	5.35	4.77

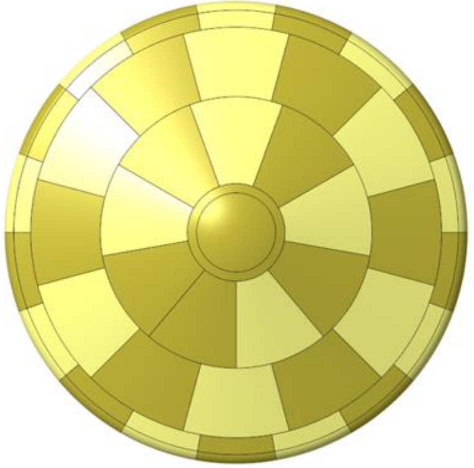
Forebody TPS sizing for each body point, showing approximately 20% variation across heatshield.

Forebody Manufacturing and Testing

- CPICA could be made to a size of 1.3m x 1.3m, reducing the number of gaps. Otherwise, a heritage gap-filler scheme like MSL could be implemented.



MSL tile array

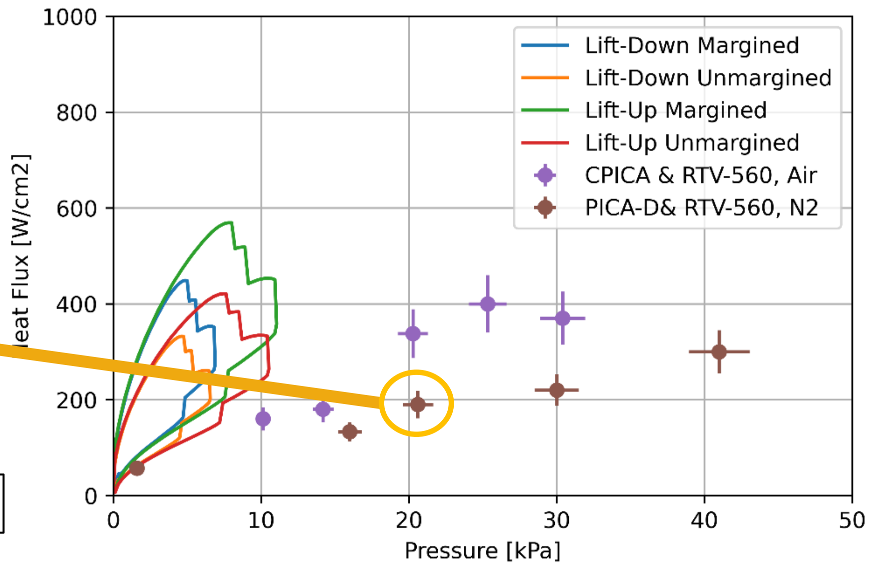


Concept vehicle array

Infused curved CPICA

- Demonstrated CPICA curved tile enables improved shoulder TPS response by reducing in-plane heating.

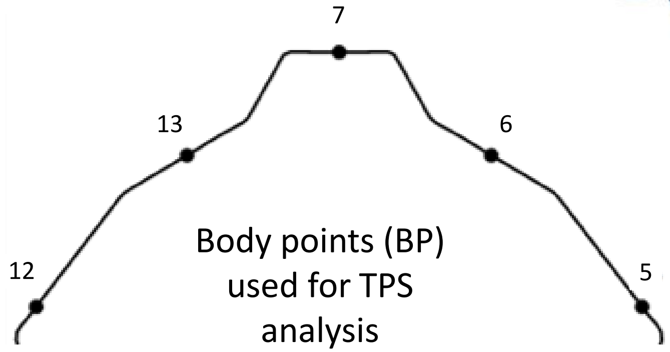
Post-test PICA-D & RTV-560

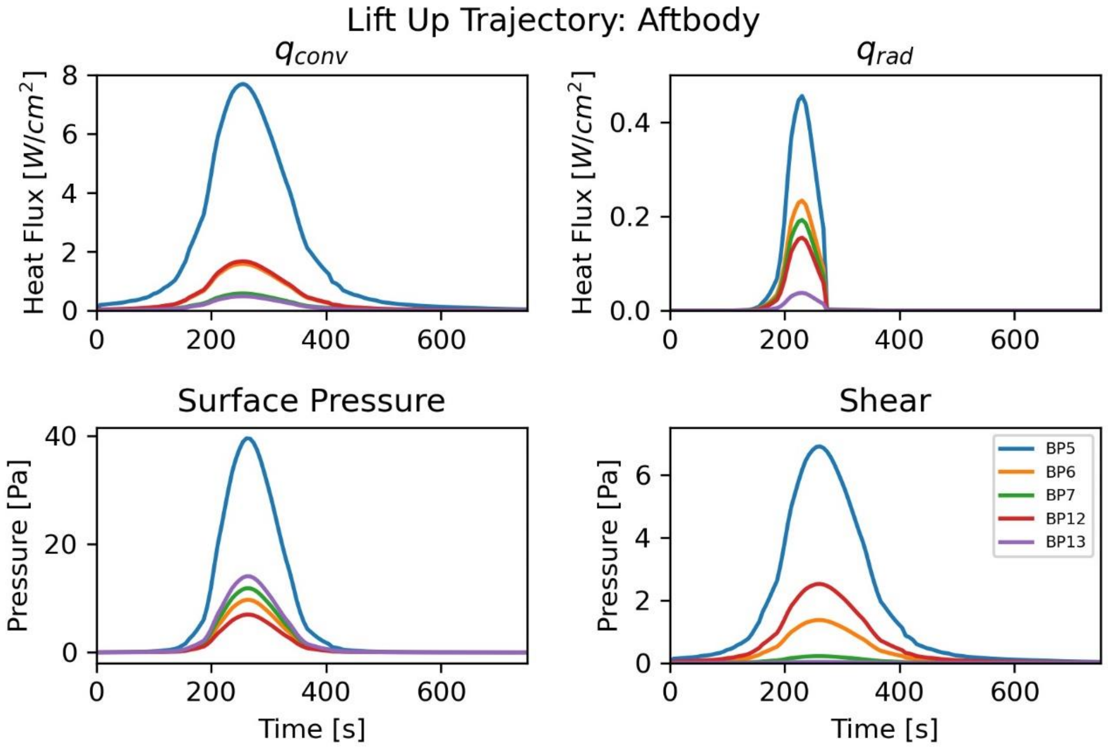


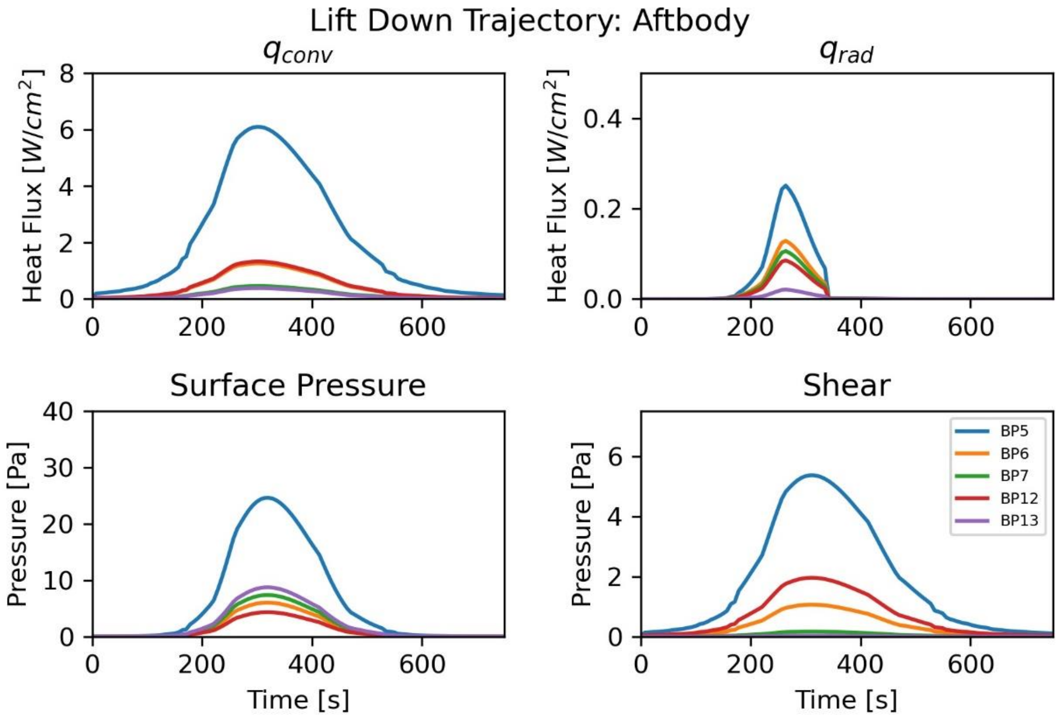
- CPICA & RTV-560 has been successfully tested to heat flux and pressures that are relevant, but in air only.
- PICA-D & RTV-560 testing to relevant heat fluxes in nitrogen shows greater porosity in the gap-filler but no augmentation to char thickness and minimal recession due to low oxidation.
- To fully vet CPICA & RTV-560, testing should be done to assess system response in relevant environments.

Aftbody Environments

- The Lift-Up and Lift-Down Trajectory are predicted to have benign aftbody environments which allow for a large TPS trade space to accommodate features and requirements governing navigation and communication.
- The environments predicted do not account for RCS augmented heating.
- Low backshell radiation is predicted as well with a similar cut-off due to simulation changes.







Aftbody TPS Design Solutions

- **Solutions exist that are qualified for the heat flux and pressure environments – but this is not exhaustive.**
  - Acusil: a silicone-glass foam with RF-transparency that is packed then machined to final shape used on MSL and Mars2020
  - SIRCA: Silicone Impregnated Reusable Ceramic Ablator is an infused ceramic tile that can ablate and was used on Pathfinder and MER.
  - SLA-561V: hand-packed composite into honeycomb that is machined to thickness with significant flight and test heritage as an ablator.
- **The three-branch RSS process has increased environmental margins, owing to complex flowfield on the backshell, but lower thermal margins due to lower environments and reduced material uncertainties.**
- **The Lift-Down trajectory again generates the thickest solutions due to the larger heat load – mass not estimated as detailed design will vary significantly from constant-thickness estimate for peak-environment body point.**

Constant Substructure		**Margin Values**	
Material	Thickness [cm]	Thermal Margin	26°C – 39°C
HT-424	0.025	Gap-filler Margin	1x
M55JA-composite	0.1	Aerothermal Margin	3x
Al-HC-21 2.5in	6.0	Radiative Margin	3x
M55JB-composite	0.1	Pressure Margin	1x

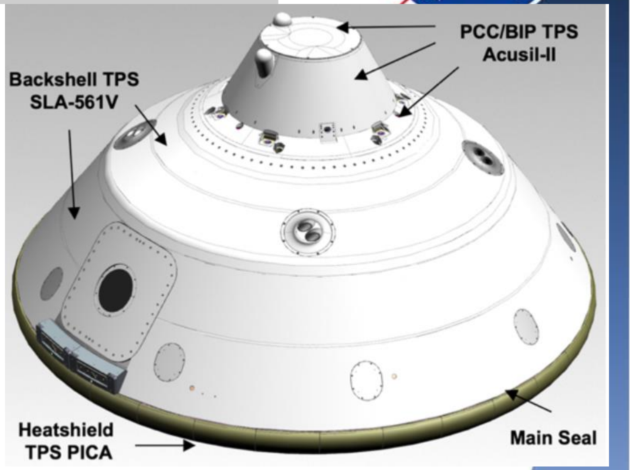
[cm]	Acusil		Sirca		SLA	
BP	Lift Down	Lift Up	Lift Down	Lift Up	Lift Down	Lift Up
5	1.20	0.98	0.99	0.80	0.75	0.60
6	0.26	0.22	0.43	0.33	0.20	0.17
7	BLT Not Reached		BLT Not Reached		BLT Not Reached	
12	0.28	0.24	0.45	0.35	0.22	0.18
13	BLT Not Reached		BLT Not Reached		BLT Not Reached	

Sizing without margin for each body point, where some bondline temperatures are not reached.

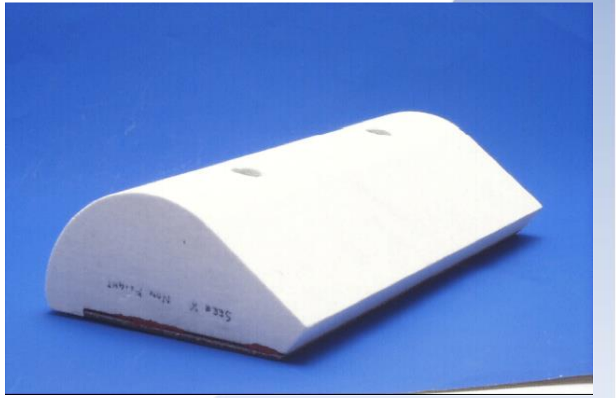
TPS	**Acusil**		**SLA-561V**		**SIRCA-15**	
Trajectory	Lift-Up	Lift-Down	Lift-Up	Lift-Down	Lift-Up	Lift-Down
BP 5 [cm]	1.97	2.43	1.64	1.97	1.14	1.39

Aftbody Manufacturing and Test

- **SLA-561V and Acusil have significant test and flight heritage from MSL and M2020 projects.**
  - Can be manufactured to required thickness with machining after hand-packing.
  - Systems have ablative capability that may not be used under these environment where optimized insulators may be better suited.
- **SIRCA has been tested and flown on MER and Pathfinder.**
  - Tiles can be made but require considerable production effort to implement across a large areas.
  - Ablative capability unlikely to be used in all areas.
- **Multiple TPS may be needed, and optimization for lower heat flux with material that can be spray-applied or pre-coated for the large backshell will yield greater mass efficiency.**
  - Lockheed Martin's SLA-561S is a sprayable TPS with flight heritage on Pathfinder, but NASA does not have a material response model.
  - FireX RX2390 is an intumescent sprayable compound that has been tested and shown good performance as an ablator.



Mars2020 backshell figure denoting SLA-561V and Acusil locations. Source: https://arc.aiaa.org/doi/epdf/10.2514/6.2022-3951



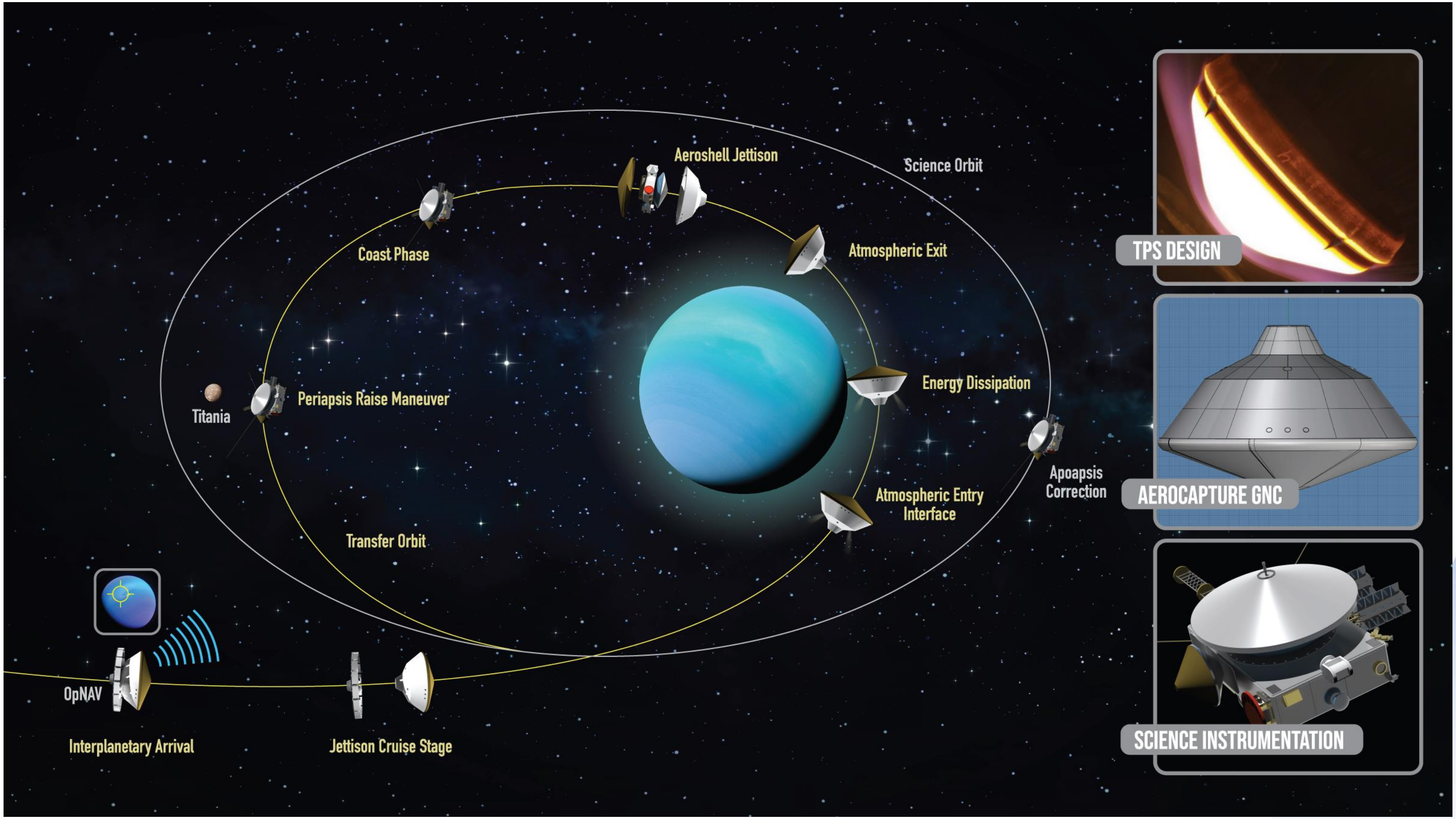
Machined SIRCA tile for the X-34 wing leading edge. Source: https://www.nasa.gov/general/thermal-protection-materials-branch-low-density-ablators/

Conclusions

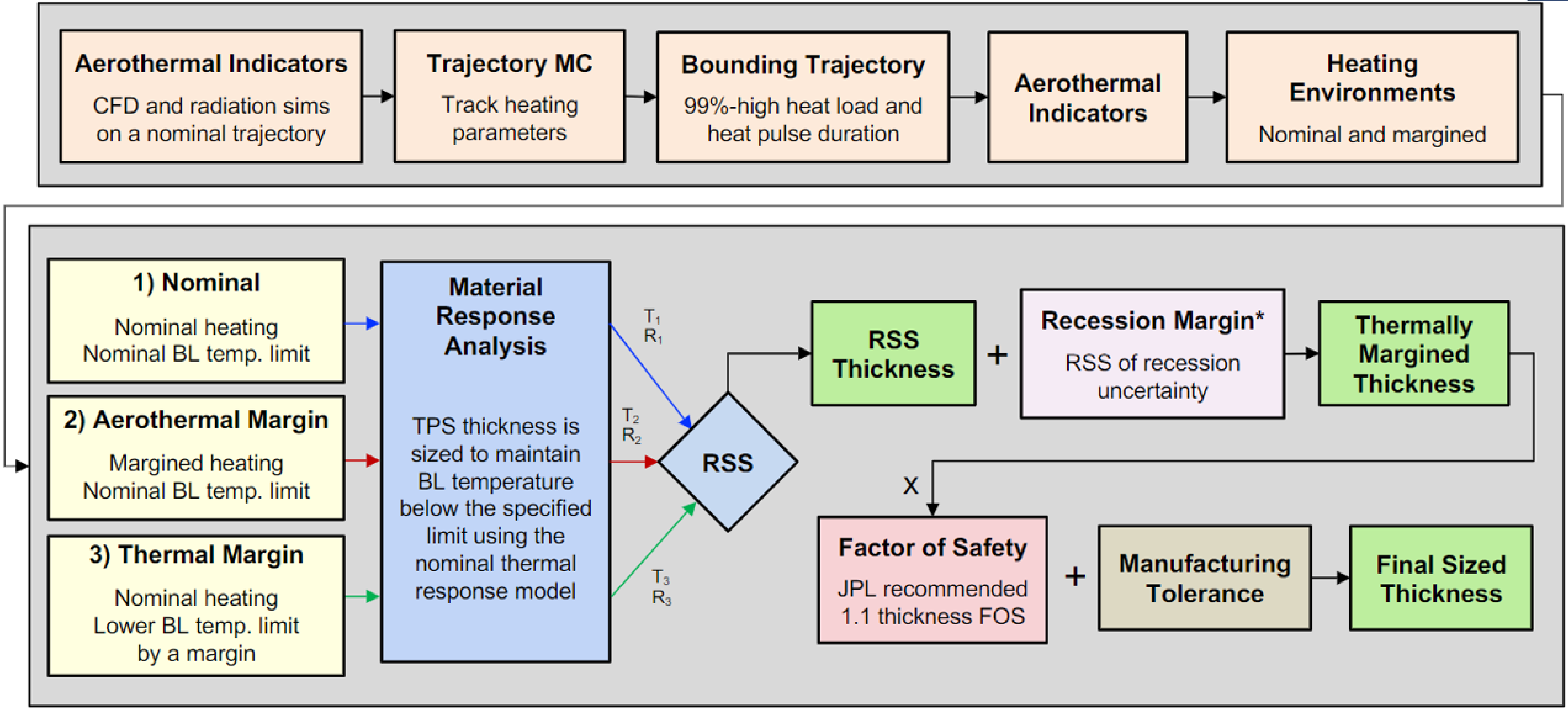
- **A traditional blunt body vehicle performing aerocapture at Uranus generates forebody environments that can be accommodated by *existing* NASA TPS technology.**
  - CPICA poses the most mass-efficient solution for the forebody and may yield improvements over previous tiled design with scaled manufacturing tailored to the aeroshell substructure.
  - CPICA & RTV-560, as a notional system, needs to be tested in relevant test gas to understand performance, but PICA-D & RTV-560 as a similar system has shown good performance under non-oxidative testing.
  - Beyond testing, performing a flight demonstration with TPS under relevant conditions and configurations will reduce risk for future missions as stated by ADRAT (2023) and supported by NASA's Planetary Exploration Science Technology Office[3].
- **The backshell can be protected by current technology that is adequate for the predicted environments, but we can do better by developing and maturing mass-efficient TPS for low environments that can be applied over large areas with ease.**
  - SLA-561V and Acusil can be machined to the necessary thickness but are not optimized for the environment, while SIRCA tiles would pose significant effort in installation while not being mass-efficient.
  - Further reducing TPS mass increases margin for other subsystems and will benefit CG location.

[3]Montbach, E. et al, Planetary Science Technology Development Plan Status, Outer Planetary Assessment Group (OPAG) Fall Meeting, Nov 2023, https://www.hou.usra.edu/meetings/opagnov2023/presentations/Tuesday/1400_Montbach.pdf

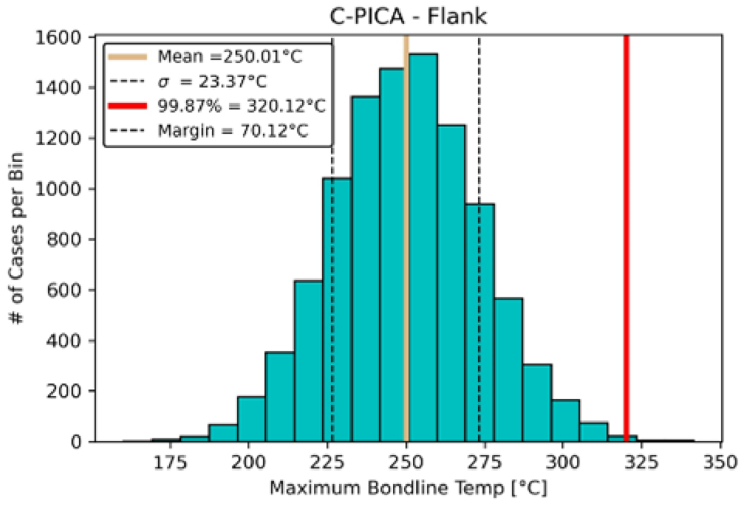
Questions

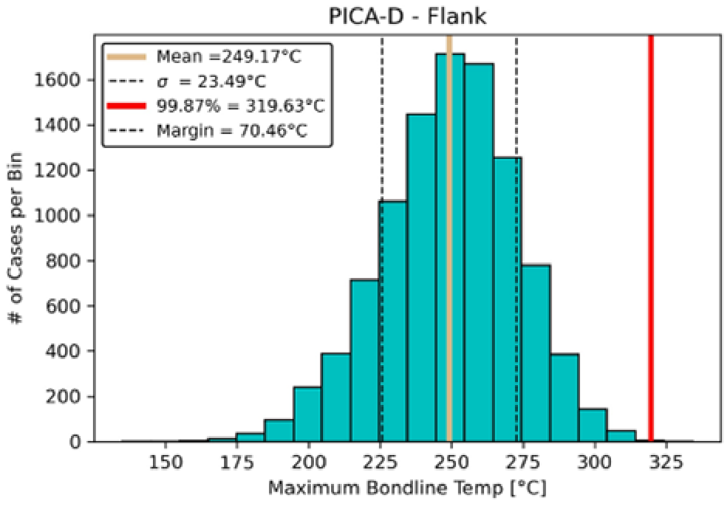

Aeroshell Jettison
Science Orbit
Coast Phase
Atmospheric Exit
Energy Dissipation
Titania
Periapsis Raise Maneuver
Apoapsis Correction
Atmospheric Entry Interface
Transfer Orbit
OpNAV
Interplanetary Arrival
Jettison Cruise Stage
TPS DESIGN
AEROCAPTURE GNC
SCIENCE INSTRUMENTATION

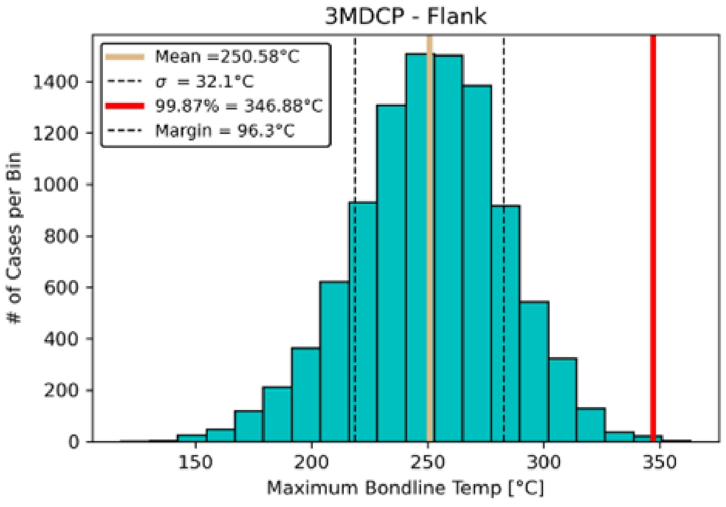
RSS

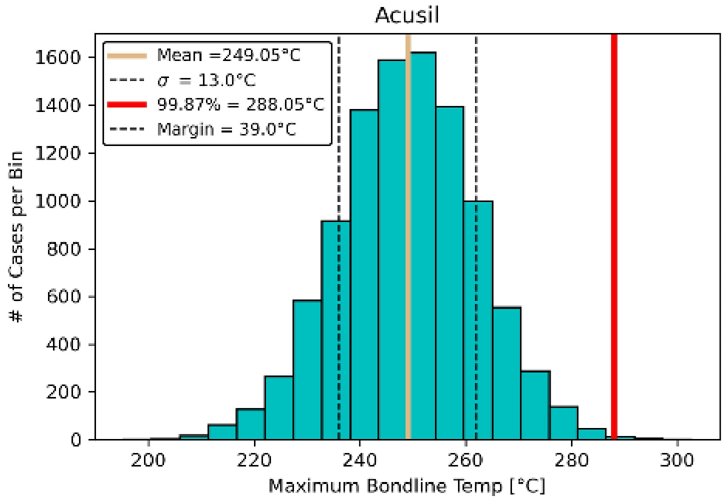

Aerothermal Indicators
CFD and radiation sims on a nominal trajectory
Trajectory MC
Track heating parameters
Bounding Trajectory
99%-high heat load and heat pulse duration
Aerothermal Indicators
Heating Environments
Nominal and margined
1) Nominal
Nominal heating
Nominal BL temp. limit
2) Aerothermal Margin
Margined heating
Nominal BL temp. limit
3) Thermal Margin
Nominal heating
Lower BL temp. limit by a margin
Material Response Analysis
TPS thickness is sized to maintain BL temperature below the specified limit using the nominal thermal response model
T1 R1
T2 R2
T3 R3
RSS
RSS Thickness
+
Recession Margin*
RSS of recession uncertainty
Thermally Margined Thickness
X
Factor of Safety
JPL recommended 1.1 thickness FOS
+
Manufacturing Tolerance
Final Sized Thickness

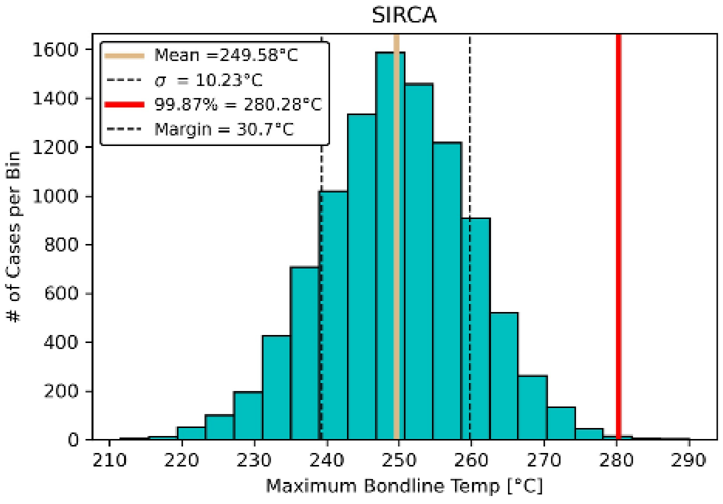
Backup

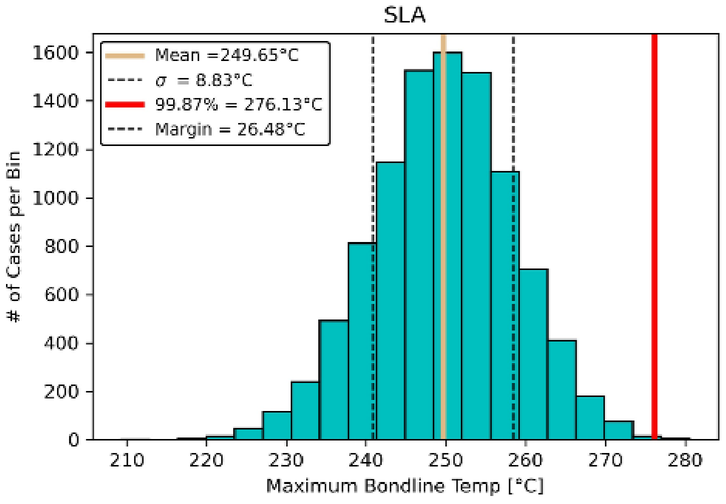

C-PICA - Flank
Mean =250.01°C
σ = 23.37°C
99.87% = 320.12°C
Margin = 70.12°C
# of Cases per Bin
Maximum Bondline Temp [°C]


PICA-D - Flank
Mean =249.17°C
σ = 23.49°C
99.87% = 319.63°C
Margin = 70.46°C
# of Cases per Bin
Maximum Bondline Temp [°C]


3MDCP - Flank
Mean =250.58°C
σ = 32.1°C
99.87% = 346.88°C
Margin = 96.3°C
# of Cases per Bin
Maximum Bondline Temp [°C]


Acusil
Mean =249.05°C
σ = 13.0°C
99.87% = 288.05°C
Margin = 39.0°C
# of Cases per Bin
Maximum Bondline Temp [°C]


SIRCA
Mean =249.58°C
σ = 10.23°C
99.87% = 280.28°C
Margin = 30.7°C
# of Cases per Bin
Maximum Bondline Temp [°C]


SLA
Mean =249.65°C
σ = 8.83°C
99.87% = 276.13°C
Margin = 26.48°C
# of Cases per Bin
Maximum Bondline Temp [°C]