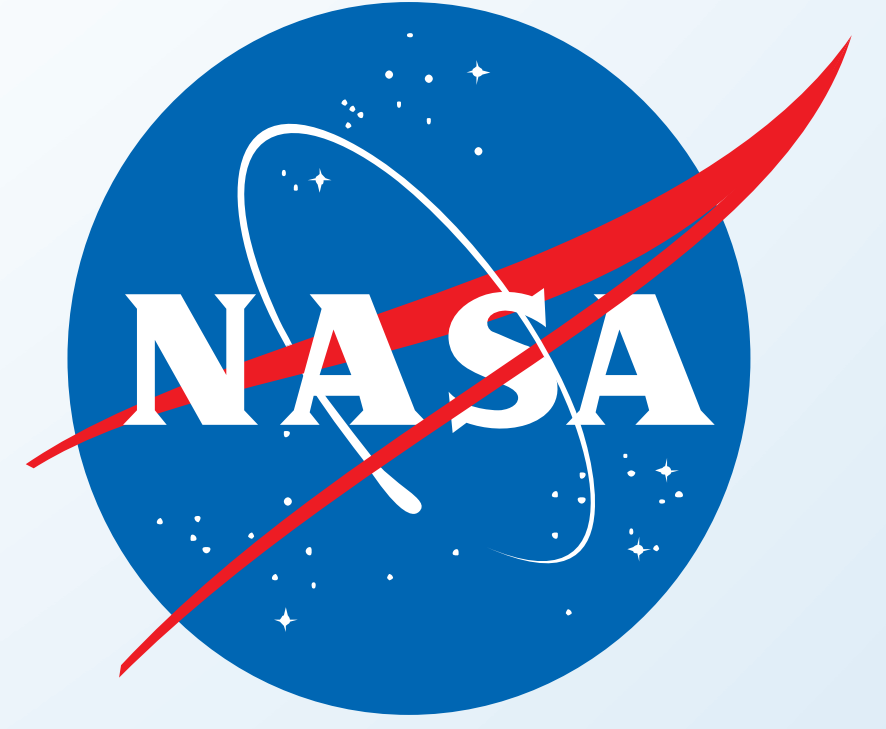
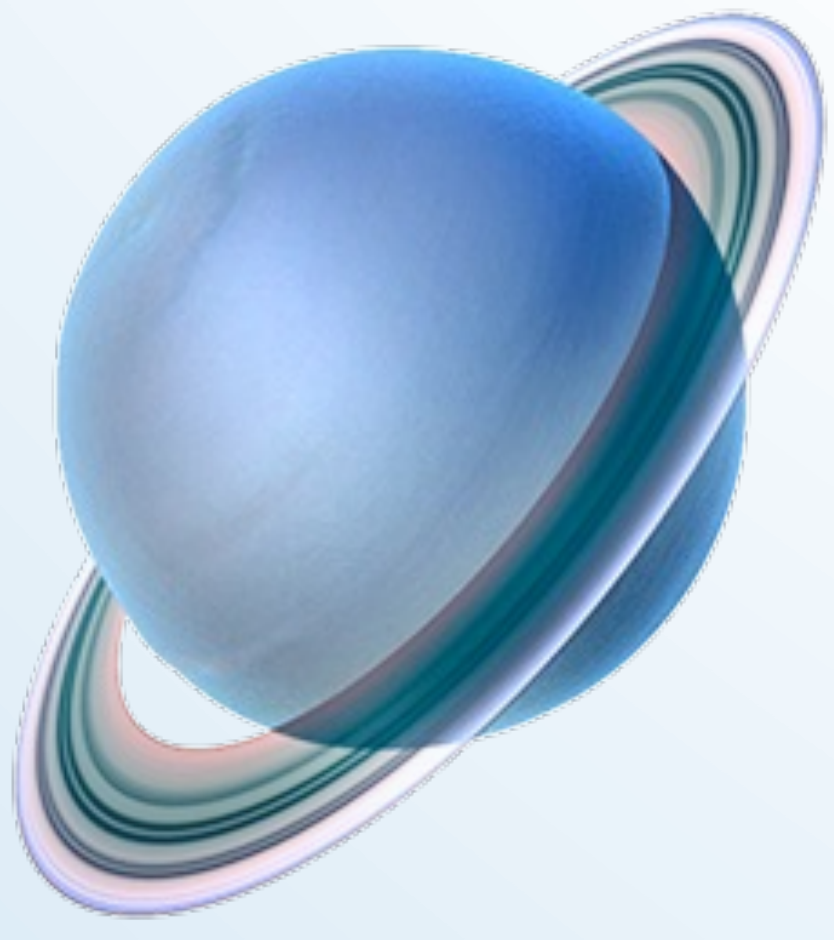


Developing & Sustaining Thermal Protection Systems for Uranus Flagship Mission

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NASA-developed TPS (3D Woven and C-PICA) needed for Uranus Orbiter and Probe missions are mature and ready today. They also enable other outer planet and sample return missions. We want to raise the awareness of the Science community that given the potential for a ~5 years of gap between now and NF-5/NF-6 or UOP mission, the potential for capability atrophy is a high risk that needs to be mitigated.

Aerocapture

Aerocapture, a method of orbit insertion, uses negligible propellant mass

- ΔV is achieved by dipping into the planet's atmosphere, slowing the spacecraft through atmospheric drag before exiting into a target orbit.

Performance Metrics of Aerocapture vs Propulsive Insertion:

- Aerocapture transit time of 8 years compared to propulsive insertion of (12 – 14 years) is a mission enabler for a later start

TPS for Aerocapture, C-PICA, has been flight demonstrated on a commercial mission (Varda – Feb 2024)

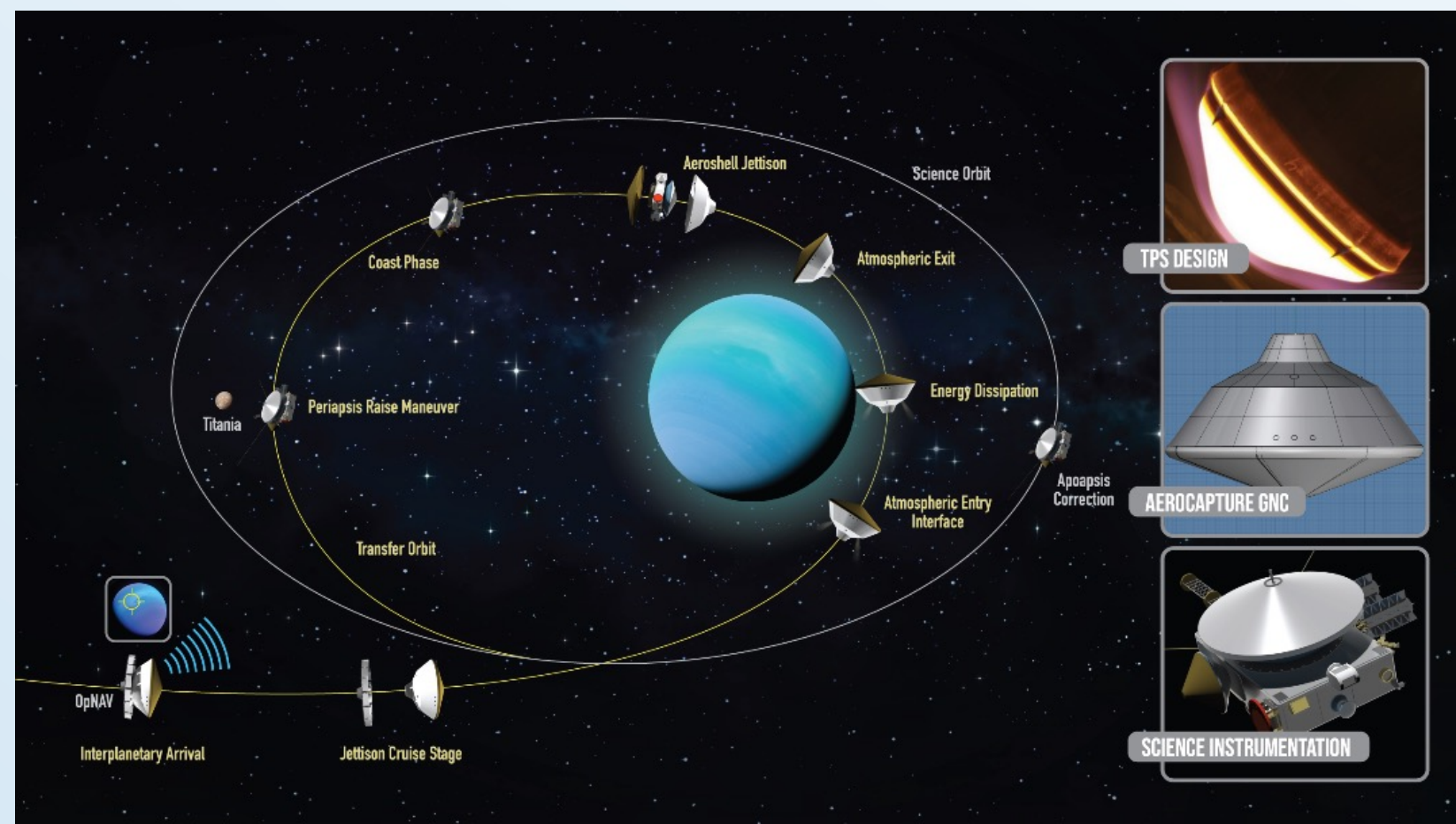
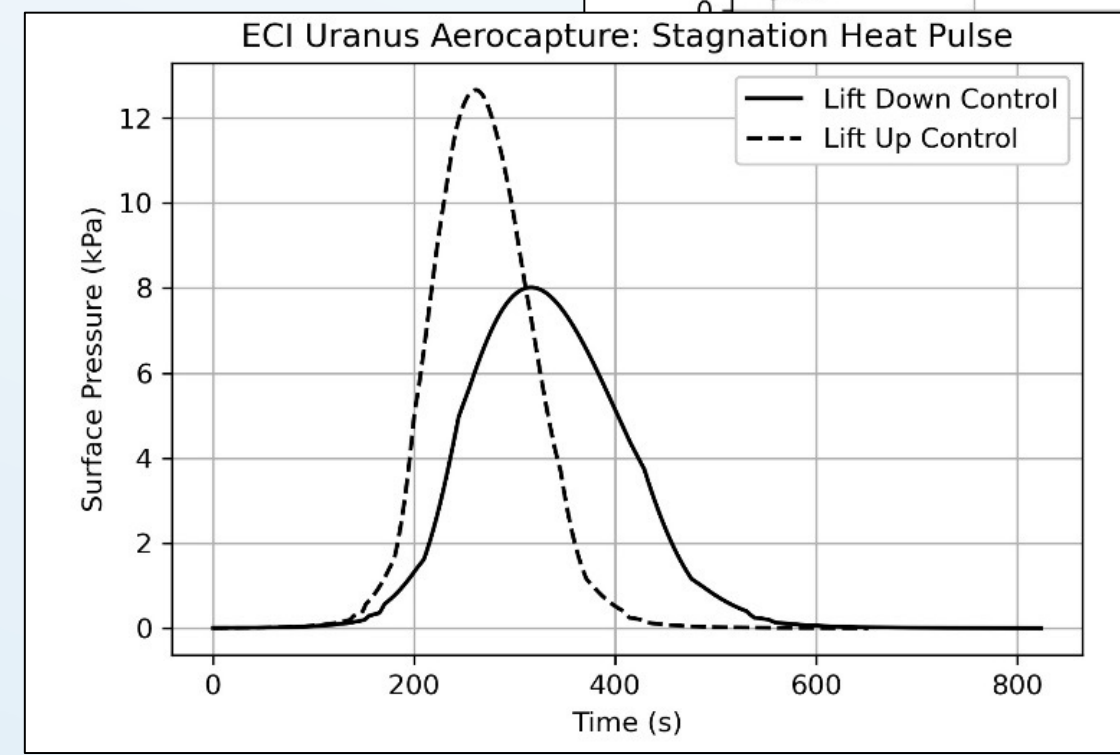
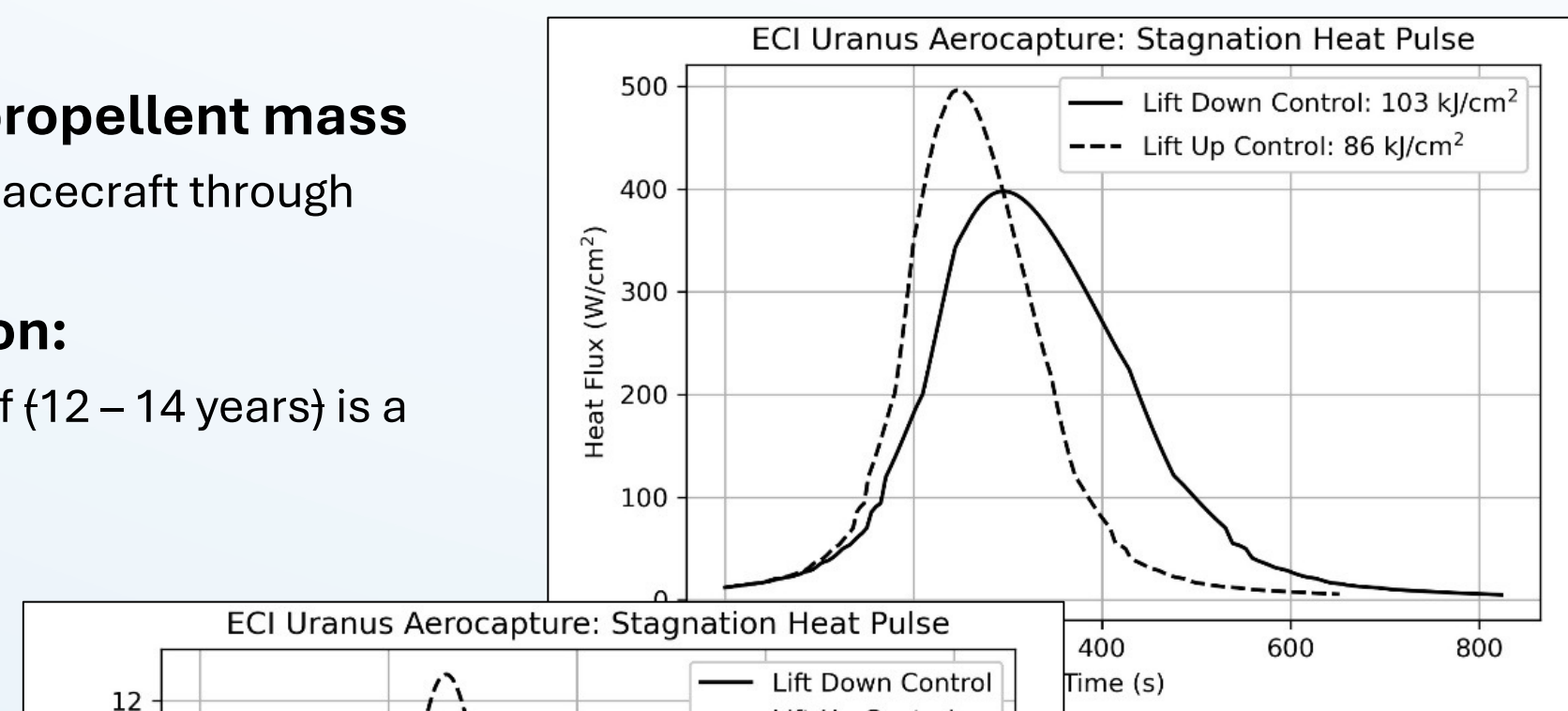
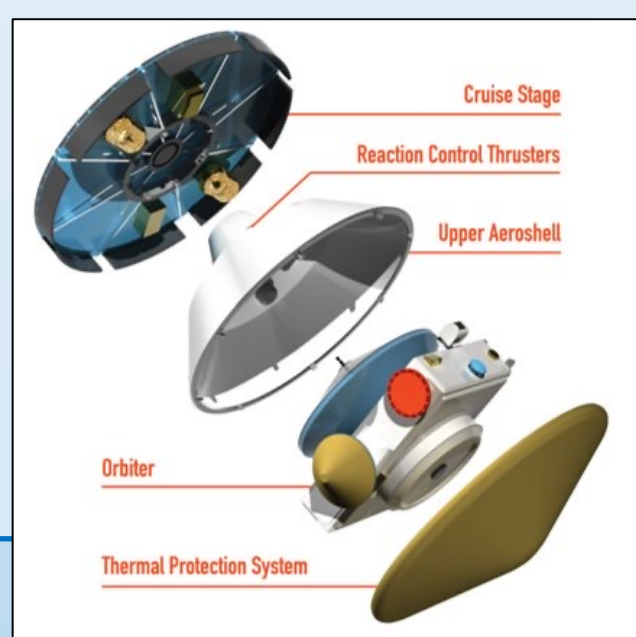


Image Uranus aerocapture paper
(<https://doi.org/10.2514/6.2024-0714>)



TPS	CPICA	PICA-D	3MDCP
Areal Mass* (kg/m²)	14	24	48

Entry Probe – Entry from Orbit (Post-Aerocapture)

The probe design from the UOP decadal survey study is quite different from the aerocapture problem due to diving much deeper into the atmosphere.

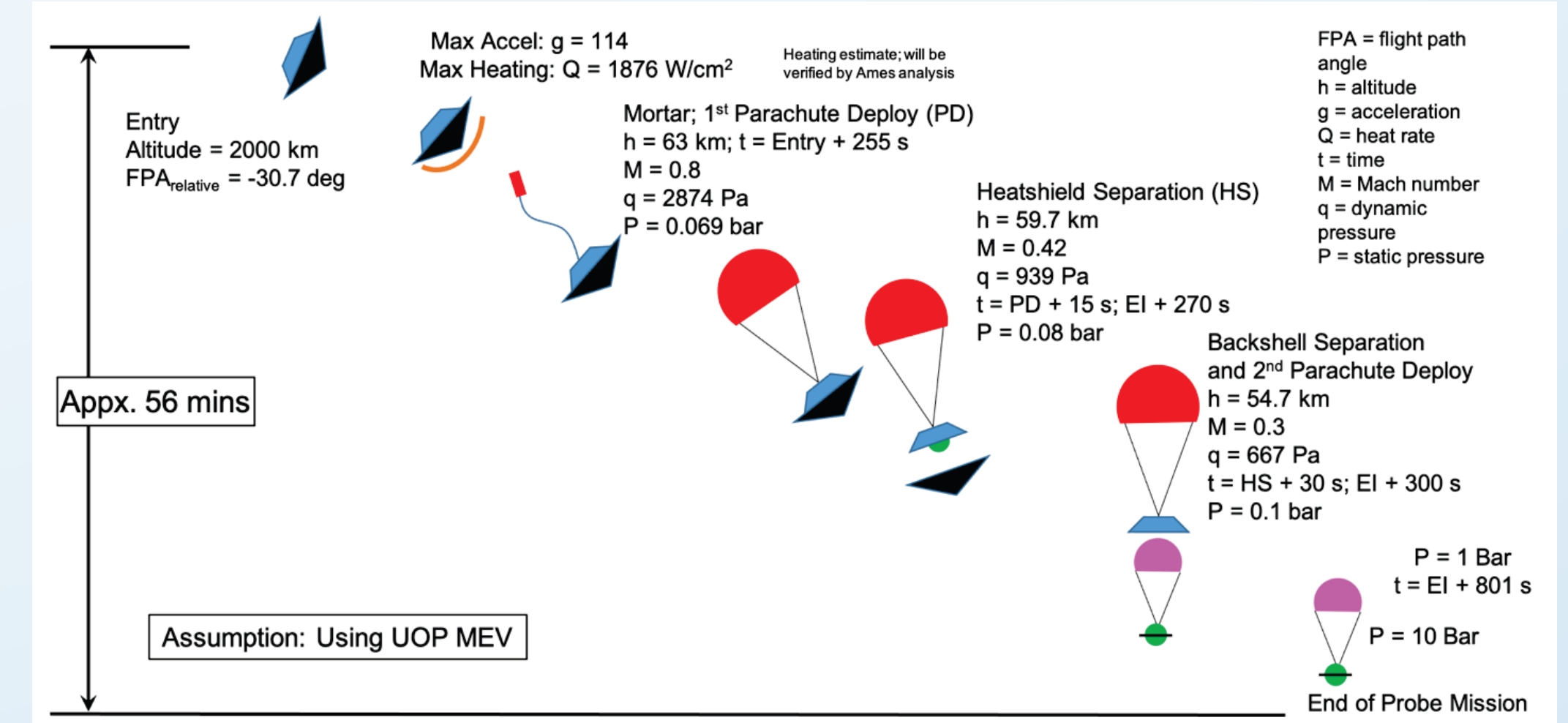
- Peak heating rates are nearly 1900 W/cm² and peak surface pressure during entry is ~450 kPa

TPS materials are ready for Flagship Uranus Probes

- Woven TPS – up to 3500 W/cm² & 540 kPa

Significant development in Woven TPS completed for these environments:

- The Earth Entry System for the Mars Sample Return mission has developed a HEEET-IL derivative called 3MDCP (3D Mid-Density Carbon Phenolic)
- Venus mission by Rocket Lab is using formed HEEET-IL TPS



TPS for Giant Planet In-Situ Missions: Probes and Aerocapture

3D Woven TPS (3MDCP and HEEET) are enabling for Saturn, Uranus, and Neptune probe missions.

TPS conclusions are result of the studies listed below for Outer Planet Probes:

- M. Hofstadter et al., "Ice Giant Pre-Decadal Mission Study Report," (2017)
- H. Hwang, "A Common Probe Design for Multiplanetary Destinations," VEXAG (2018)
- D. Prabhu, "Exploration of Atm. Entries at Saturn, Uranus & Neptune with HEEET as Heatshield TPS," FAR 2019.
- A. Rhymer et al., "Neptune Odyssey: Mission to the Neptune-Triton System," PCMS Study, 2020
- A. Simon, et al., "Uranus Orbiter and Probe 2023-2032 Planetary Mission Concept Study," PCMS Study, 2021

Conformal PICA is enabling for Uranus Orbiter + Probe Aerocapture:

Mass efficient TPS is required (~5m dia). Conformal PICA, a low-density TPS, due to its efficiency and robustness provides considerable mass savings for aerocapture and an enabler. (Delivery of probes from orbit is relatively easier but would require 3D Woven TPS.)

- Aerocapture Enabling Flagship-Class Uranus Orbiter and Probe
Authors: S. Dutta, R. Deshmukh, R. Restrepo, D. Mages, A. Gomez-Delrio, E. Shellabarger, J.B. Scoggins, J. Williams, J. Morgan, P.S. Chadalavada, D. Matz, S. Sandoval

Varda Successfully Demonstrated In-Space Manufacturing, Reentry and Recovery of the Sample – NASA-Developed Conformal PICA Enabled the Success

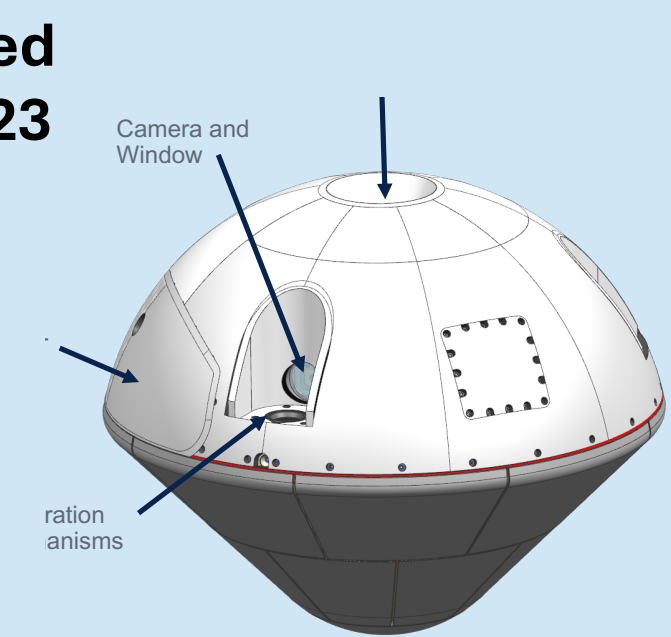
Varda, founded in 2021, launched their commercial mission in 2023 and returned the Ritonavir – in-space manufactured pharma product on Feb 21st at UTRR.

NASA Ames manufactured and provided Conformal PICA to Varda and enabled the first successful reentry

- NASA Ames is technology transferring C-PICA to Varda (STMD Tipping Point)
- Varda is planning to fly two flight demonstration missions in CY25 and CY26 under NASA-AFRL-VARDA public-private partnership

NASA has two flight opportunities

- Instrument and collect performance data on C-PICA and improve thermal modeling.



3D Woven TPS Efficient and Robust Materials for Extreme Entry

Advances in textile engineering allow us to weave single / multi-layer preforms, using different yarns, interconnected in all directions.

The dual-layer architecture was formulated to achieve mass efficiency and robust performance for extreme entry.

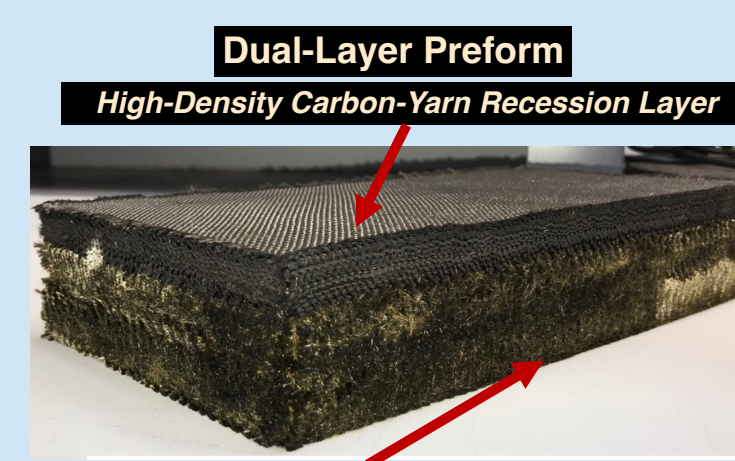
- The top-layer is optimized for recession performance, and the inner or insulating layer is optimized for lower thermal conductivity.
- The HEEET loom at Bally Ribbon Mills (BRM) is capable of weaving dual-layer at 24" width, recession layer up to 0.5", and insulating layer up to 1.3".

The MSR EES risk posture and mass allocation required development of 3MDCP (2019).

- The 3MDCP loom at SPIRIT Textiles (Formerly: Textile Engineering and Manufacturing: T.E.A.M) can weave a single-layer panel at greater than 1" thick and ~80" width. The weave is similar to the HEEET insulating layer.
- TRL 6 by 2025

3-D Woven TPS is capable of withstanding ~4000 W/cm² and ~6.0 atm pressure

- 3MDCP – seamless heatshield < 1.3 m dia.
- HEEET-DL (dual-layer) – tiled with seams – scalable to any diameter
- HEEET-IL (insulating layer) – seamless, single piece heatshield < 0.4m dia



Importance of Sustainability and Steps to Ensure It

Currently Conformal PICA is TRL 5+ for UOP though is flown by Varda. It is hoped that commercial mission cadence will maintain manufacturing capability within industry, but that is not guaranteed.

- To advance TRL of C-PICA for UOP additional Material Property testing is required as is testing of tiled/seams at relevant UOP heat flux/pressure

3MDCP/HEEET are applicable only for NASA Missions and hence at risk of atrophy (low mission cadence)

- MSR EES development will be completed by 2025. Depending on MSR EES timeline, 3MDCP manufacturing capability may atrophy.

In case of atrophy, critical knowledge, expertise, and capability within NASA needs to be maintained as NASA has knowledge of design tools and insight into manufacturing.

NASA can take mitigation steps to assess and minimize the extent of atrophy

- Perform periodic readiness risk assessment in coordination with vendors
- Develop risk mitigation strategies to be implement by SMD-PSD; e.g., perform manufacturing and lot acceptance testing of minimum quantity periodically (~3 years).

Concluding Remarks and Recommendations

3D Woven and C-PICA TPS are enablers for the Outer Planets including Uranus Missions:

- Mission proposers need to be aware of manufacturing as a long-lead item for 3D woven TPS
 - Weaving ~18 months and assembly and integration ~12 – 24 months
- 3D-Woven materials currently have single sources for the blended yarn raw material used in HEEET and 3MDCP, single suppliers for weavers (HEEET different than 3MDCP) and single vendor for infusion.
- It has already been 5 years since the end of the HEEET program and once the 3MDCP development is complete in FY25 it is unclear when additional 3MDCP work will be performed.
- Therefore, by the time NF or UOP missions are able to support TPS work it could be 5-10+ years since the materials will have been manufactured.

Recommendation:

- This science community needs to be aware of the potential for TPS atrophy and should advocate that NASA take steps to ensure TPS development continues sustainability.
- NASA should proactively engage vendors and perform TPS readiness assessments periodically.