Uranus Probe Entry and Descent Mission Concept

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Standing on the Shoulders of "Ice" Giants

In the past decade great strides have been made to address the challenges to close a design for an ice giant orbiter and descent probe mission that achieves high priority science tours and descent probe data collection

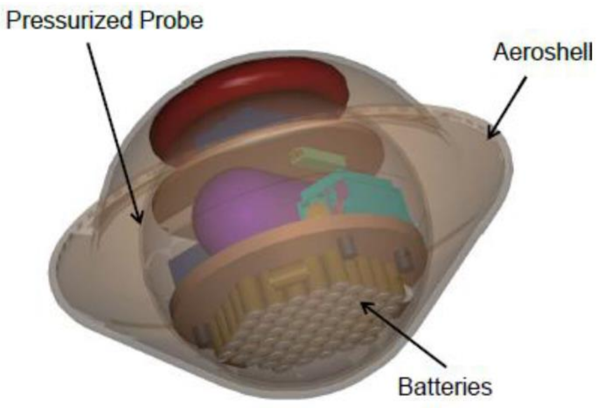
- **Vision and Voyages, Ice Giants Decadal Mission Study, (2010)**
  - William Hubbard (Lead, Univ of Arizona), Yanping Guo (APL), Chris Scott (APL), John Dankanich (GRC), Ryan Russell (Georgia Tech) https://nap.nationalacademies.org/read/13117/chapter/1
- **Uranus Atmospheric Entry Studies, funded by In-Space Propulsion, (2013 – 2014)**
  - Parul Agrawal (ERC), Gary Allen (ERC), Helen Hwang (ARC), Jose Aliaga (ARC), Evgeniy Sklyanskiy (JPL), Mark Marley (ARC), Kathy McGuire (ARC), Loc Huynh (STC), Joseph Garcia (ARC), Robert Moses (LaRC), Rick Winski (AMA)
  - P. Agrawal *et al*., "Atmospheric entry studies for Uranus," *2014 IEEE Aerospace Conference*, 2014, pp. 1-19,
  - doi: 10.1109/AERO.2014.6836417, https://ieeexplore.ieee.org/document/6836417
- **Ice Giants Pre-Decadal Study Final Report, (2017)**
  - Mark Hofstdater (JPL), Amy Simon (APL), Kim Reh (JPL), John Elliott (JPL),.. Parul Agrawal (ERC), Helen Hwang (ARC)
  - https://www.lpi.usra.edu/icegiants/mission_study/Full-Report.pdf
- **Neptune Odyssey: A Flagship Concept for the Exploration of the Neptune-Triton System , (2019- 2021)**
  - Cohen I. J. * Rymer A. M. Runyon K. D. Clyde B. A. Neptune-Odyssey PMCS Team [Content will be presented at 2:35pm]
  - https://iopscience.iop.org/article/10.3847/PSJ/abf654/pdf
- **Origins, Worlds, and Life, A Decadal Strategy for Planetary Science and Astrobiology 2023 – 2032, (2021)**
  - Uranus Orbiter and Probe, Richard Anderson (Lead, APL), Amy Simon (Science Champion, NASA GSFC)
  - Analysis teams Juan Arrieta (Nabla Zero Labs), Martin Ozimek (APL), Helen Hwang (ARC), Dinesh Prabhu (AMA), Gary Allen (AMA), Josh Monk (ARC), John Thornton (AMA), Soumyo Dutta (LaRC), Alejandro Pensado (AMA)
  - http://nap.edu/26522

This presentation will highlight lessons learned from the earlier studies and conclude with details about the design/analysis cycles used to successfully identify viable entry states, derive aerothermal environments, and size thermal protection systems for the OWL UOP entry vehicle

Vision and Voyages, Ice Giants Decadal Mission Study*

- Accelerated study that led to steep entry trajectory for probe resulted in peak deceleration that is too high for instruments to withstand, and a peak heat flux of ~2300 W/cm^2 and stagnation pressure ~18 bar
- Proposed concept limitations:
  - Full density carbon phenolic known to spall ~ 10 bar;
  - Arc jet testing limitations prevent testing above ~ 5 bar

Probe Type	Pioneer Venus Small probe
Entry Vehicle Diameter (m)	0.76
Cone Angle (deg)	45
Mass with margin (Kg)	127
Instruments	Mass spectrometer, temp-pressure sensors, USO and nephlometer
Entry Flight Path Angle (deg)	68
Entry Velocity (km/s)	22.35
Launch date	July-August 2020
Arrival Time	28-Jun-33
Peak Deceleration (g Load)	390



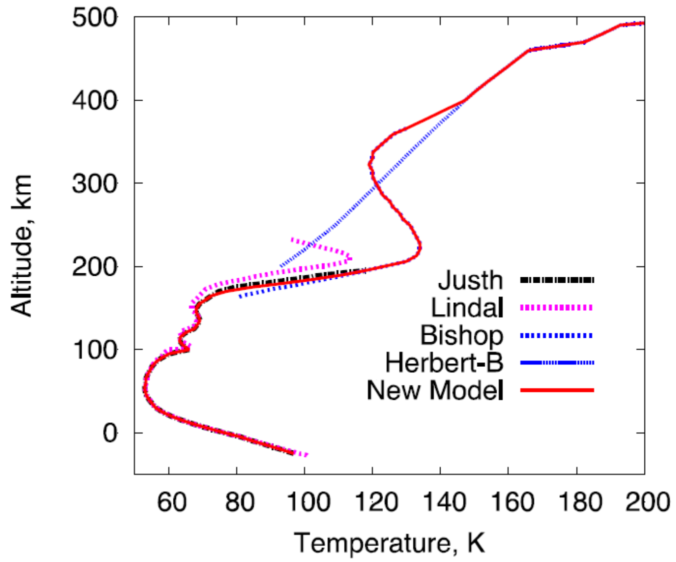
Altitude for descent : 550 Km
Shallow descent up to 5 bar pressure.

Future efforts began to include EDL teams earlier in entry probe design to identify relevant limitations of the proposed design

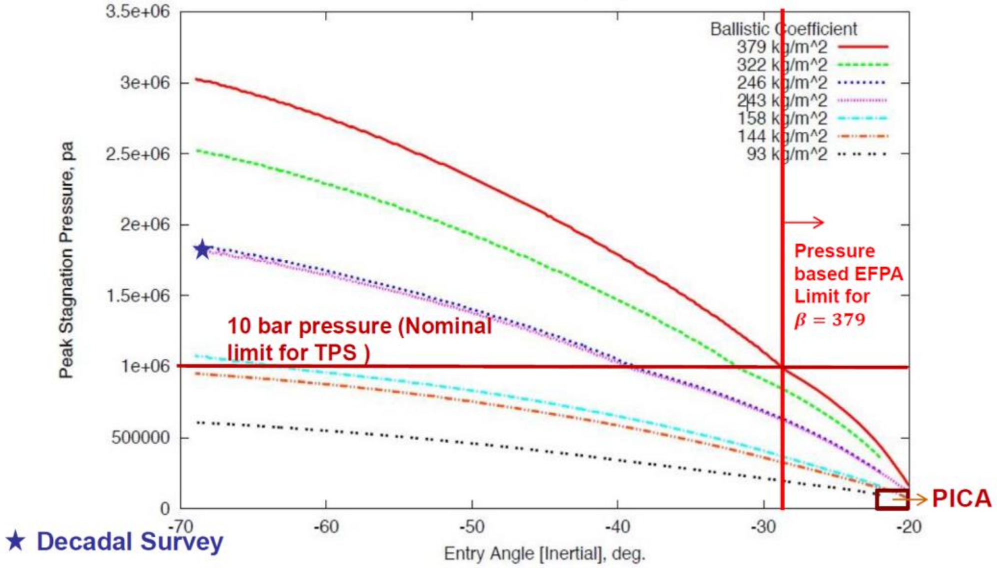
* W. Hubbard "Vision and Voyages for Planetary Science in the Decade 2013-2022"

Uranus Atmospheric Entry Studies, funded by In-Space Propulsion * (2013 – 2014)

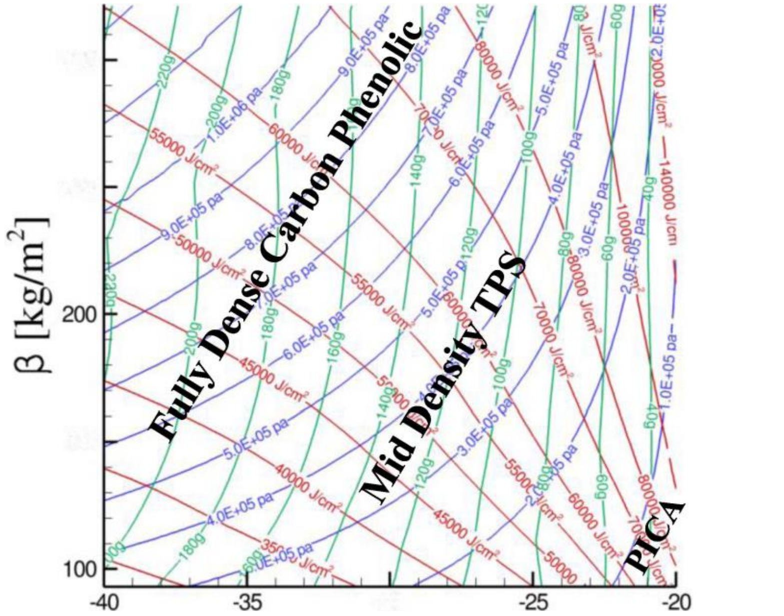
- Analysis focused on ballistic coefficient vs entry flight path angles for full density carbon phenolic, and based probe design on *Vision and Voyages* study
- Carrier spacecraft or communication link between probe and spacecraft not considered



Uranus-GRAM Developed and implemented into NASA Ames 3DOF code TRAJ+



Recommended reduced environments or new TPS option to close entry vehicle design



Opportunity for mid-density TPS realized

Findings led directly to NASA Ames development of woven TPS HEEET

+ Allen, Jr., G. A., Wright, M. J., and Gage, P., NASA/TM-2004-212847, 2005.

* P. Agrawal *et al*., "Atmospheric entry studies for Uranus," *2014 IEEE Aerospace Conference*, 2014, pp. 1-19,

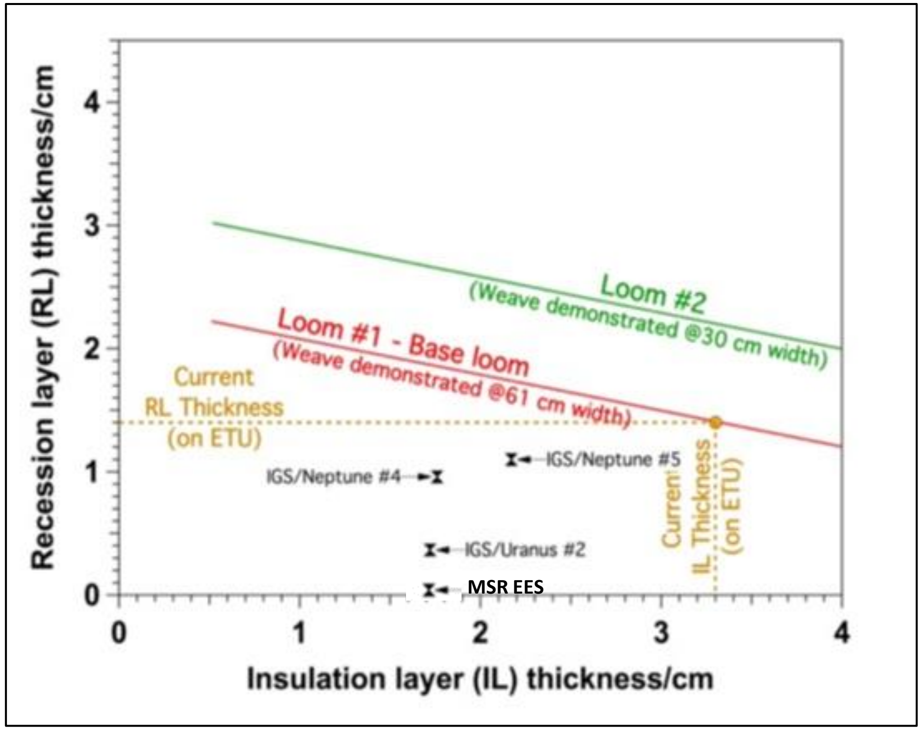
HEEET Overview
<u>H</u>eatshield for <u>E</u>xtreme <u>E</u>ntry <u>E</u>nvironments <u>T</u>echnology

- **HEEET is an integrally 3-D woven, dual-layer, resin infused, ablative system**
  - An efficient, optimized, carbon phenolic TPS using modern manufacturing & materials
- **Dense outer recession layer (RL)** is designed to be robust in highest heat flux & pressure environments
- **Inner insulation layer (IL)** handles the heat load with its lower density & thermal conductivity yielding reduced TPS mass fraction
- Existing 3D loom capabilities **constrain manufacturable layer thicknesses** (~5.5 cm)
- Dual layer HEEET has been funded by NASA and is at TRL 6 for a tiled configuration
- Single layer HEEET made up of only the insulative layer was chosen for MSR-EES engineering test unit. Current loom capabilities produce a single piece up to 200 cm width with 3.18 cm thickness

HEEET 3D Woven Preform

Mission designs need to consider manufacturing limitations (thickness)

HEEET Manufacturability - Weave Thickness Limitations



1.0-meter diameter tiled HEEET engineering test unit

1.25-meter diameter single piece 3MDCP MSR EES test unit

- Bally Ribbon Mill HEEET (2-Layer) loom can weave any combination of insulating and recession layer shown above at 61 cm (24") width
- NASA is establishing a newer Loom at T.E.A.M. Inc that can weave 3.18 cm (1.2") thick, single, Insulating Layer at 200 cm (80") width
- Single layer HEEET also referred to as 3MDCP (3D woven mid-density carbon phenolic) by MSR EES

New manufacturing capabilities of single layer 3MDCP could result in additional mass savings and removal of tiles/gaps

*E. Venkatapathy, Ice Giant II Workshop (7/13/22), D. Prabhu (FAR 2019, Monopoli, Italy)

Ice Giants Pre-Decadal Study (2017)*

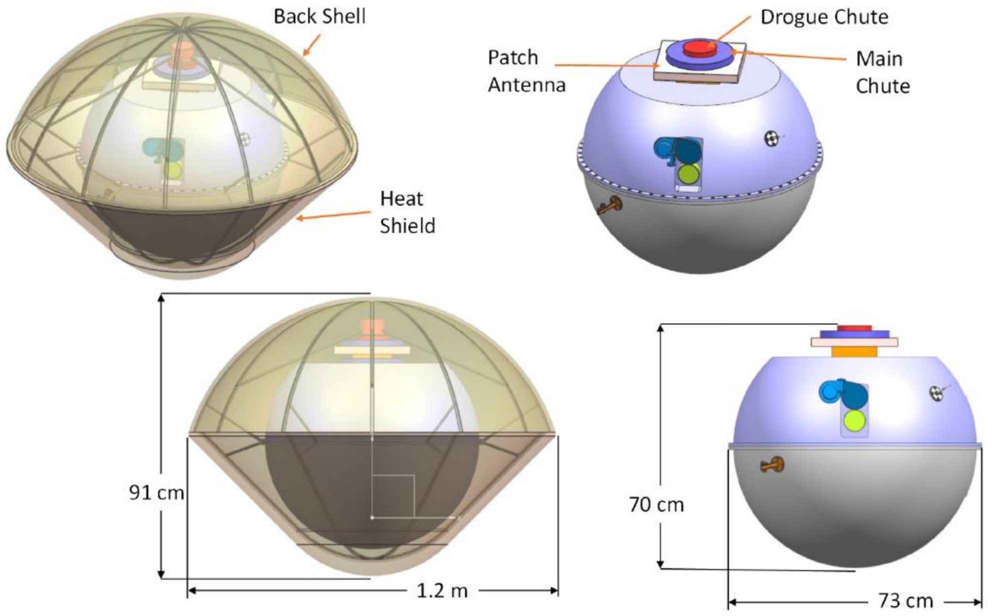
- NASA Ames 3D woven TPS material, dual layer HEEET, was under development
- Analysis showed > 50% mass savings over full density carbon phenolic

Table A-6. Entry parameters and environment for Uranus.

Entry Parameters	Point Design 1	Point Design 2
Hyperbolic excess velocity (km/s)	9.91	8.41
Entry interface altitude (km)	1015	1000
Radial distance (km)	26559	26553
Inertial velocity (km/s)	23.10	22.52
Entry Flight Path Angle, gamma (deg)	-35	-30
Inertial heading angle (deg)	-5.82	-20.02
Latitude (deg)	-9.22	-5.63
Max deceleration (g loads)	216.65	164.75
Stg pressure (bar)	12	9
Peak convective heat flux (W/cm^2)	3456	2498
Peak radiative heat flux (W/cm2)	N/A	N/A
Total heat load (J/cm^2)	43572	41114

Excessive g-loads and stagnation pressures ruled out point design 1

TPS Material	HEEET	Carbon-Phenolic
Aeroshell	Fore-Body	Fore-Body
Adhesive Type	HT-424	RTV-560
Adhesive Thickness (mm)	0.76	0.38
Adhesive Mass (kg)	2.42	0.84
Substructure Type	Aluminum Face sheet	Aluminum Face sheet
Substr Thickness *Thin* (mm)	0.762	0.762
Substr Mass (kg)		
Bondline Temperature (°C)	260	260
Unmargined TPS Thickness (cm)	RL - .244 IL – 1.5621	1.75
Unmargined TPS Mass (kg)	24.53	39.8
Margined TPS Thickness (cm)	RL - .366 IL – 1.72	2.625
Margined TPS Mass (kg)	28.67	59.7



Study identified potential entry states and showed mass saving using HEEET TPS option

*M. Hofstadter, et al. JPL D-100520 https://www.lpi.usra.edu/icegiants/mission_study/Full-Report.pdf

Origins, Worlds, and Life (OWL) Uranus Orbiter & Probe Mission (UOP)*
A Decadal Strategy for Planetary Science and Astrobiology 2023 – 2032

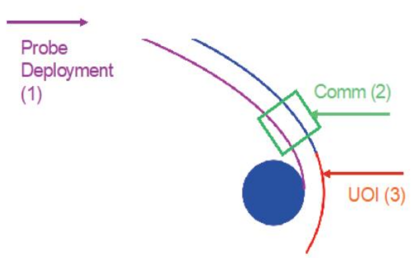
- OWL study led by Richard Anderson
- Direction from the Decadal Survey team (Amy Simon) aimed to "correct past errors and patch the 'holes'"
- Michelle Munk recommended EDL-study teams be associated with decadal studies
- Ames and Langley were involved in all EDL-study teams and were able to guide the mission architecture to consider both communications and TPS simultaneously when selecting trajectories
- Entry probe design and dimensions relied on Planetary Science Division of the Science Mission Directorate funded Common Probe study+
- Mission trajectories decided on a novel approach of spacecraft capturing Uranus in elliptic orbit and afterwards releasing the probe

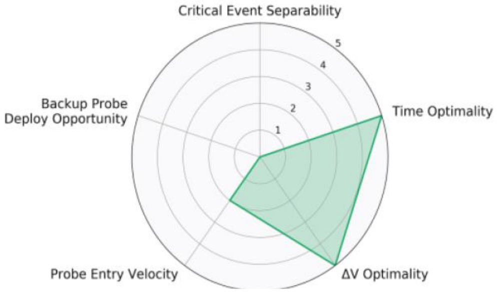
OWL UOP elliptical capture approach improved likelihood of probe delivery to high priority science target and data collection by separating Uranus orbit insertion and probe deployment operations

*Planetary Mission Concept Study for the 2023-2032 Decadal Survey: Uranus Orbiter & Probe (2021)
+H. Hwang et al. Common Probe Study Report (2019)

Origins, Worlds, and Life (OWL) Uranus Orbiter & Probe Mission (UOP)*
A Decadal Strategy for Planetary Science and Astrobiology 2023 – 2032

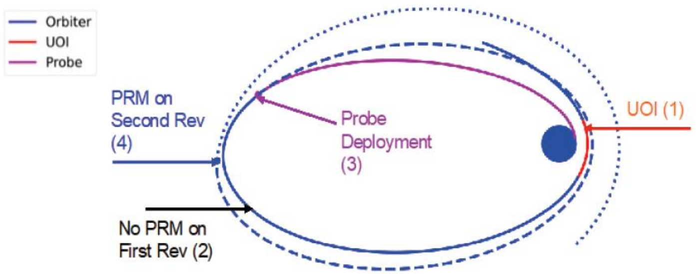
- Previous Neptune and Uranus studies used **Hyperbolic approach** with probe released for a ballistic flight along the hyperbolic trajectory

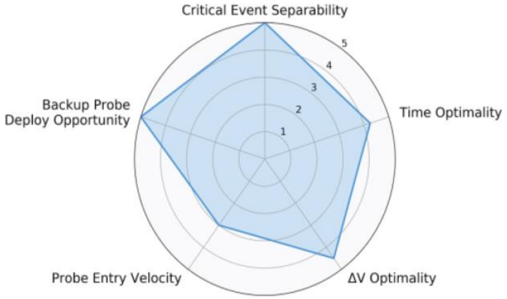




Advantages: Minimizes ΔV requirements and overall mission duration
Disadvantages: Results in higher probe entry velocities and the coupling of three critical events: approach targeting, the operation of the orbiter-probe communication link, and Uranus orbit insertion (UOI) execution

- OWL UOP study proposed probe deployment on **elliptic post-capture paradigm**, where the orbiter carries the probe through UOI.

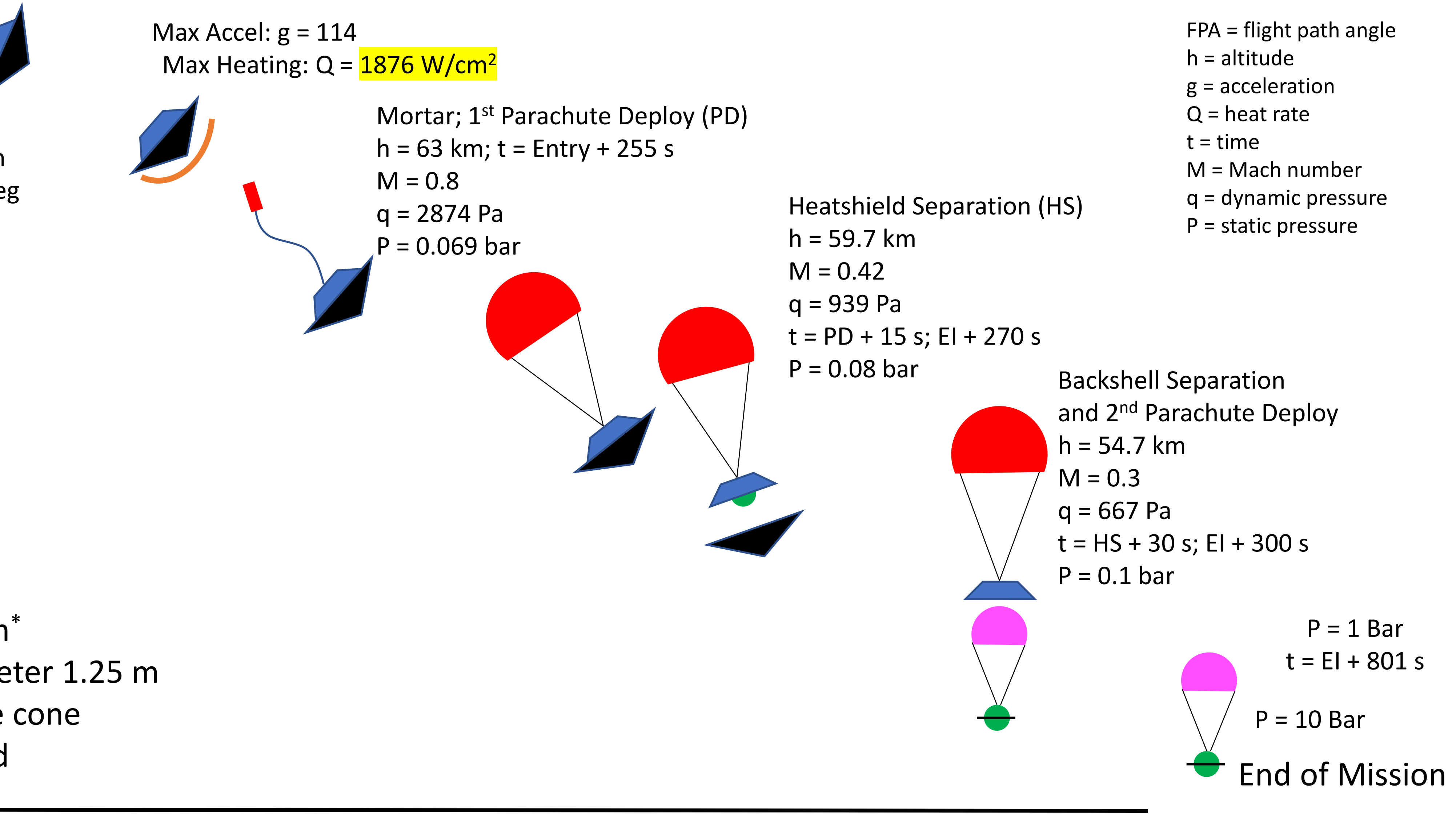




Advantages: Allows decoupling of the three critical events, reduced probe entry velocities, and provides flexibility for the release time of probe
Disadvantages: Extends overall mission by one period of capture (120 days) and requires additional ΔV maneuvers

*Planetary Mission Concept Study for the 2023-2032 Decadal Survey: Uranus Orbiter & Probe (2021)

OWL UOP Trajectory Concept of Operations and Entry Vehicle



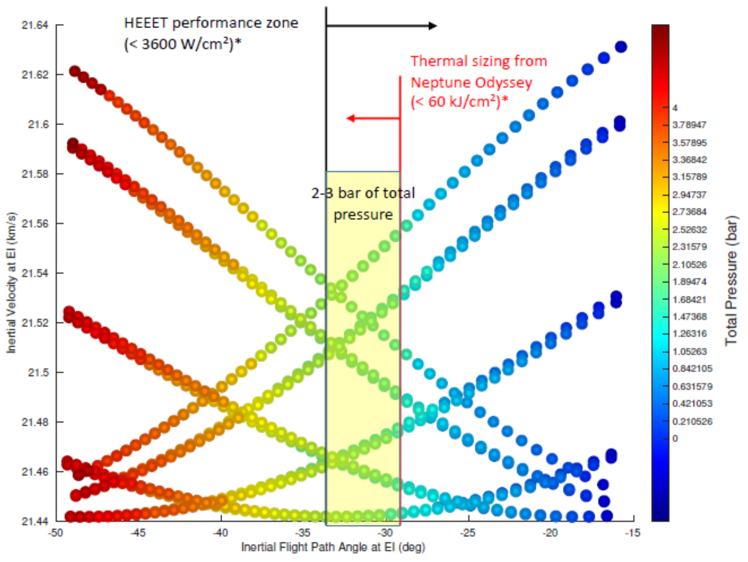
FPA = flight path angle
h = altitude
g = acceleration
Q = heat rate
t = time
M = Mach number
q = dynamic pressure
P = static pressure

- Nose 0.4 m*
- Base diameter 1.25 m
- 45° Sphere cone
- Heat shield

*ARC_Odyssey-TPS-Summary-Final Presentation.pdf (Allen Jr, Prabhu, Feldman, Williams)

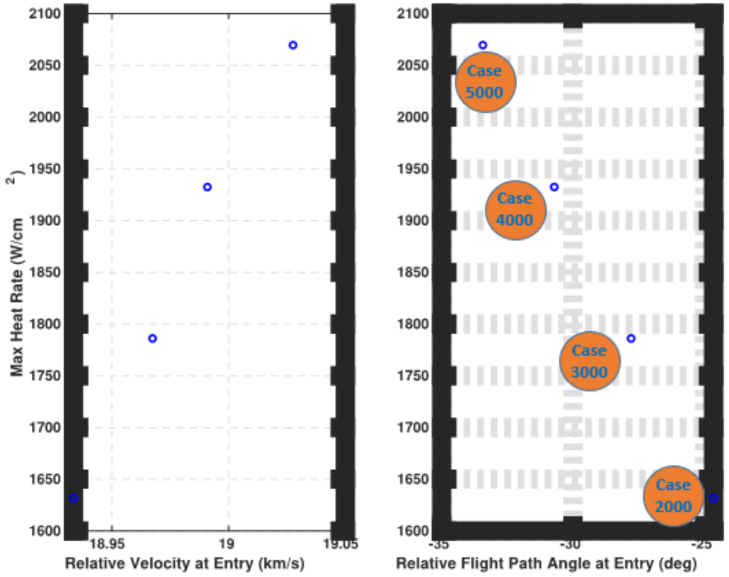
Case#2 shows blunter nose reduces the stagnation pressure and thereby lowers qualification risks and results in more manageable TPS thicknesses

Overview of 2021 OWL UOP EDL Team Design Analysis Cycles (DAC)



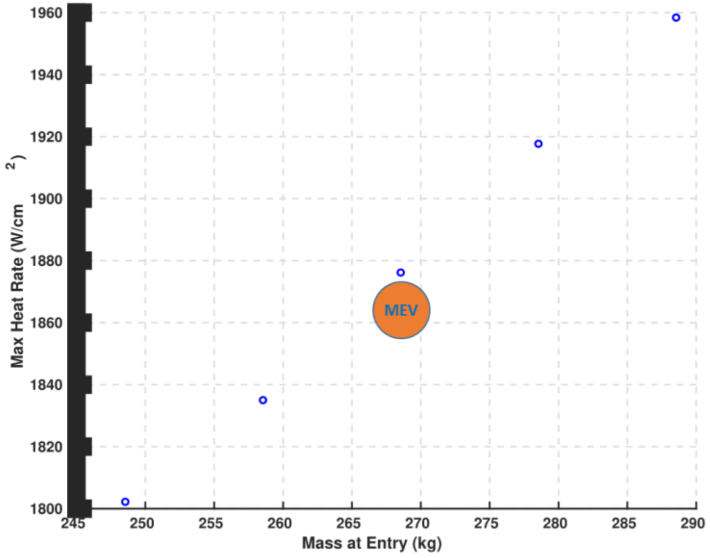
Uranus Study DAC 1

- POST2 used Sutton-Graves heating correlation*
- Ground test limitation and prior ice giant studies narrowed entry state options



Uranus Study DAC 2

- Selected subset of viable entry states for TRAJ, DPLR(CFD) and FIAT analysis
- Smooth, Turbulent, and Turbulent w/ roughness DPLR analysis completed
- TPS sizing conducted at five points along OML

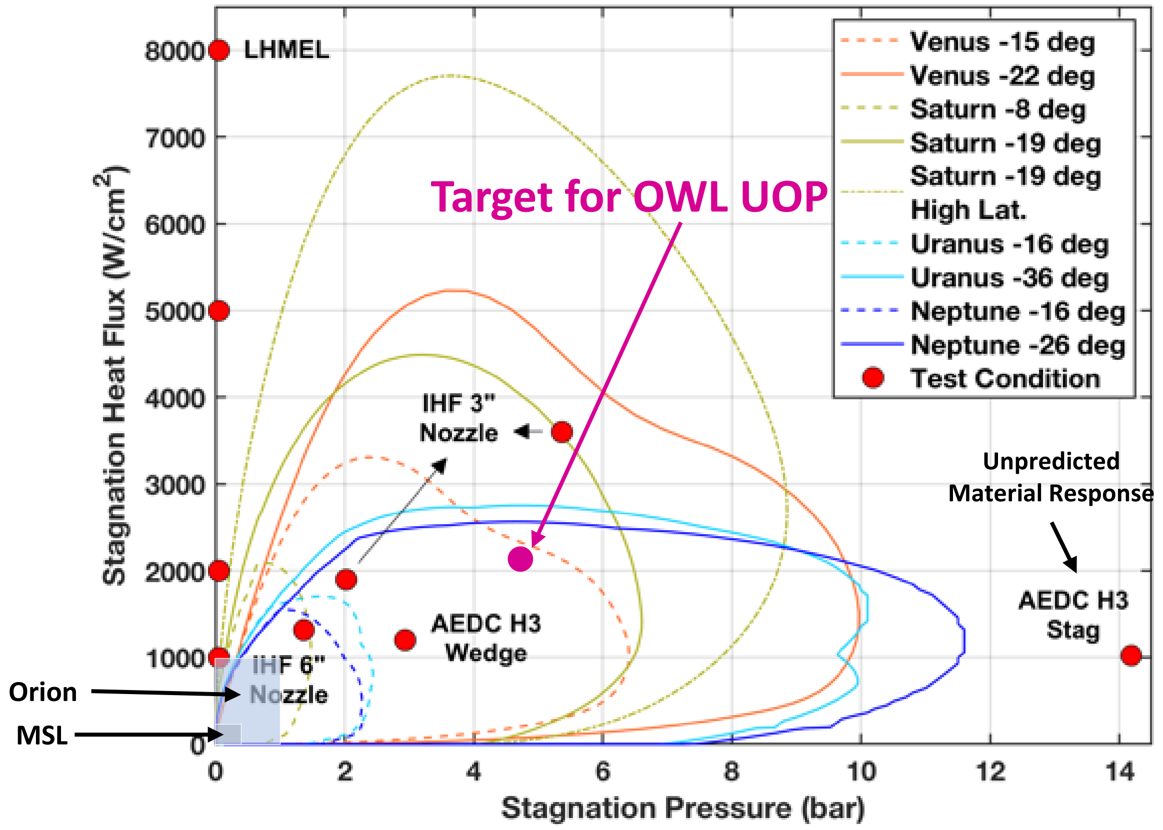


Uranus Study DAC 3

- Update Mass Expected Vehicle (MEV) and complete COMM + EDL analysis
- Ran case with +/- 10, 20 kg for TPS mass sensitivity
- Completed TPS sizing for 3mdcp and dual-layer HEEET for mass estimates

*Sutton, K. and Graves, R. A., NASA TR T-376, November 1971

HEEET Arc Jet Testing Overview with Notional Mission Environments

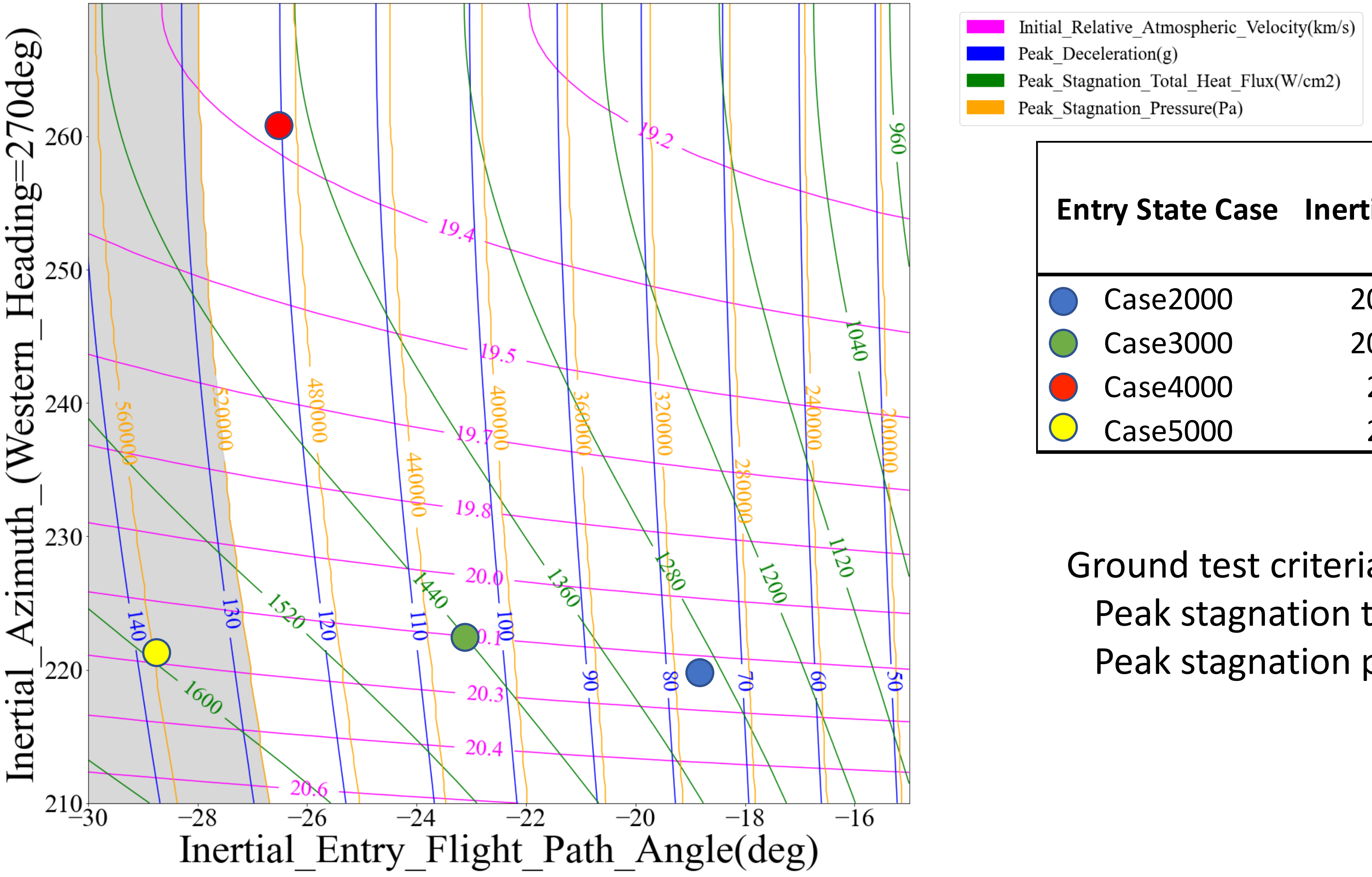


- Current testable heat fluxes and pressures in arc jets are shown
- HEEET (both dual layer and single layer) have been tested up to ~3600 W/cm^2 and ~5.4 bar

Down-selected trajectories considered for UOP are within bounds of arc jet environments

*G. Allen Jr. et al. ARC_Odyssey-TPS-Summary-Final Presentation.pdf

DAC2 OWL UOP Down Selected Entry Conditions in 2021



	Entry State Case	Inertial Velocity km/s	Inertial EFPA deg	Inertial Azimuth deg
● (blue)	Case2000	20.83539	-19.8858	219.9282
● (green)	Case3000	20.83526	-23.1934	220.0459
● (red)	Case4000	20.838	-26.17	260.61
● (yellow)	Case5000	20.845	-28.92	221.8

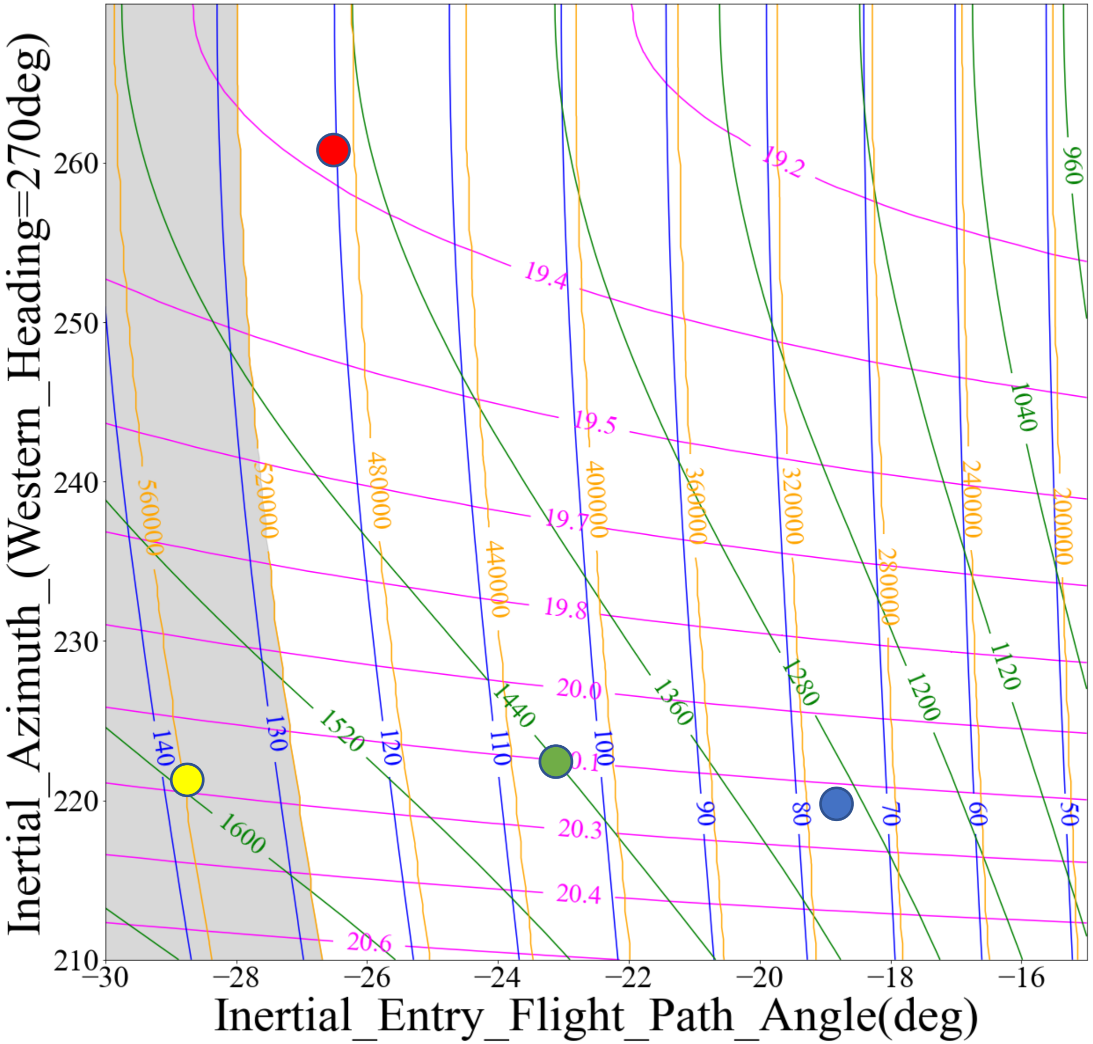
Ground test criteria

Peak stagnation total heat flux < 3600 W/cm^2

Peak stagnation pressure < 5.4 bar

Shaded area on contour does not meet criteria for current TPS ground testing

DAC2 OWL UOP 3MDCP Heatshield TPS Sizing Results



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Entry State Case	TPS Thickness* 3MDCP cm	TPS Thickness* 3MDCP in
Case2000	1.82	0.72
Case3000	1.65	0.65
Case4000	1.49	0.59
Case5000	1.44	0.57

*Margined TPS thicknesses at stagnation point used an additional 1.3x convective heating for all three branches to properly margin nominal Traj environments[+]

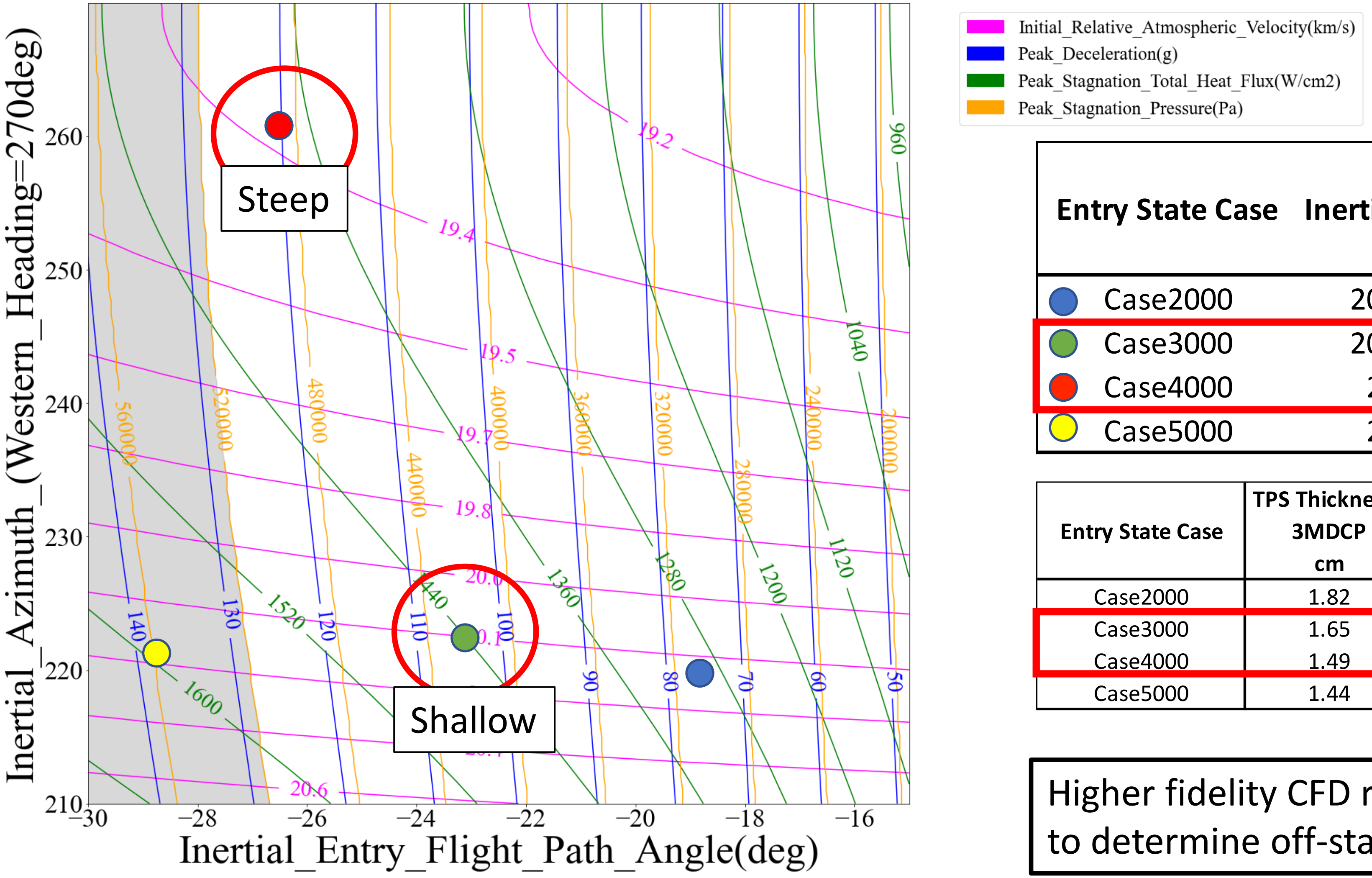
RSS sizing approach

$$T_{TPS} = \left(T_1 + \sqrt{(T_2 - T_1)^2 + (T_3 - T_1)^2}\right) + Max\{0.2 \times T_{rec} \,|\, 1.1 * T_{RSS}\}$$

Nominal (T_1), Aerothermal margin (T_2), Material margin (T_3), Recession (T_{rec})

[+] D. Prabhu (FAR 2019) identified the need for an additional 1.3x scaling factor to TRAJ heating correlations for H_2/He destinations

DAC2 OWL UOP 3MDCP Heatshield TPS Sizing Results



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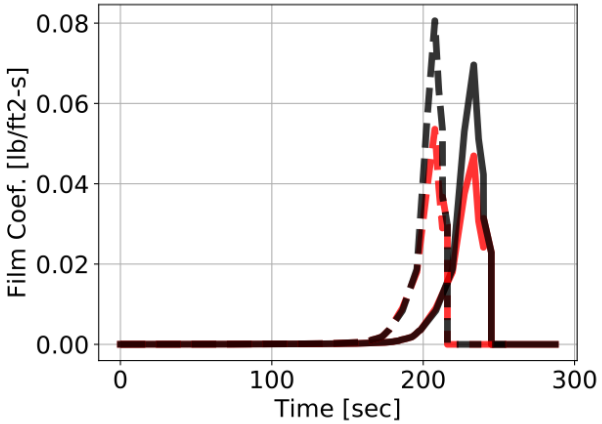
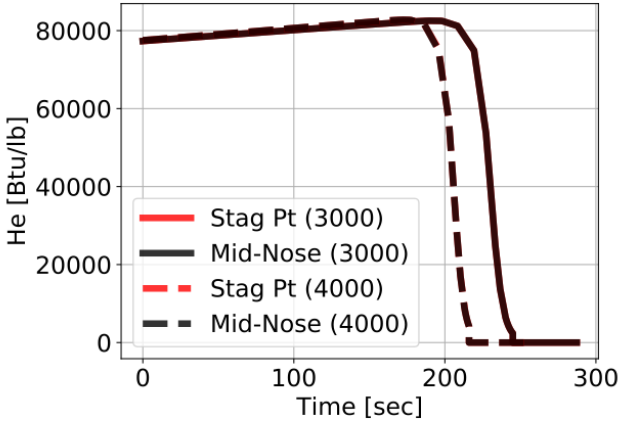
Higher fidelity CFD run for Case3000 and Case4000 to determine off-stag aerothermal environments

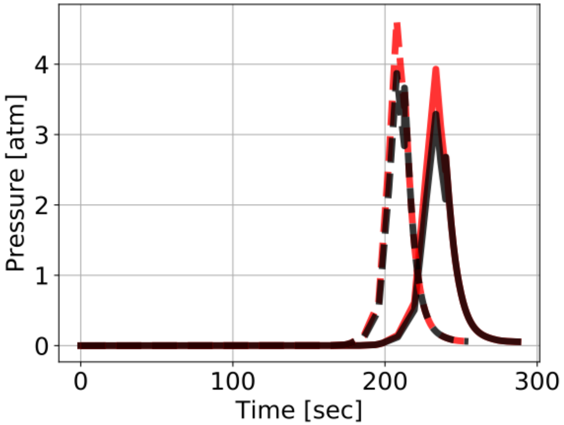
⁺ D. Prabhu (FAR 2019) identified the need for an additional 1.3x scaling factor to TRAJ heating correlations for H_2/He destinations

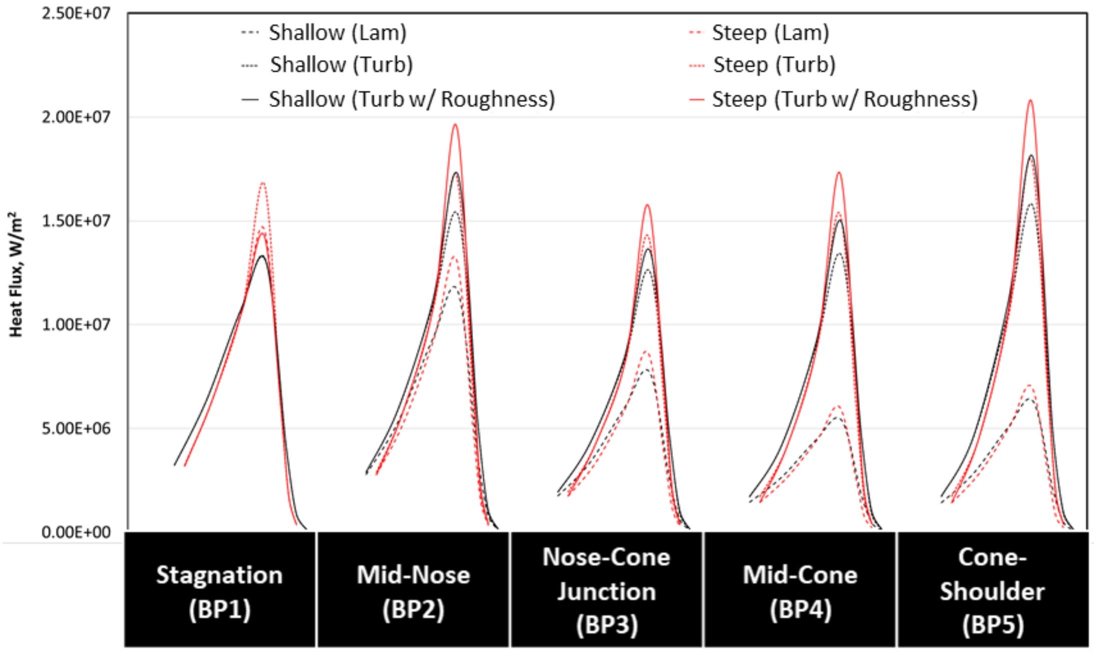
OWL UOP Aerothermal Environmental Inputs for TPS Sizing

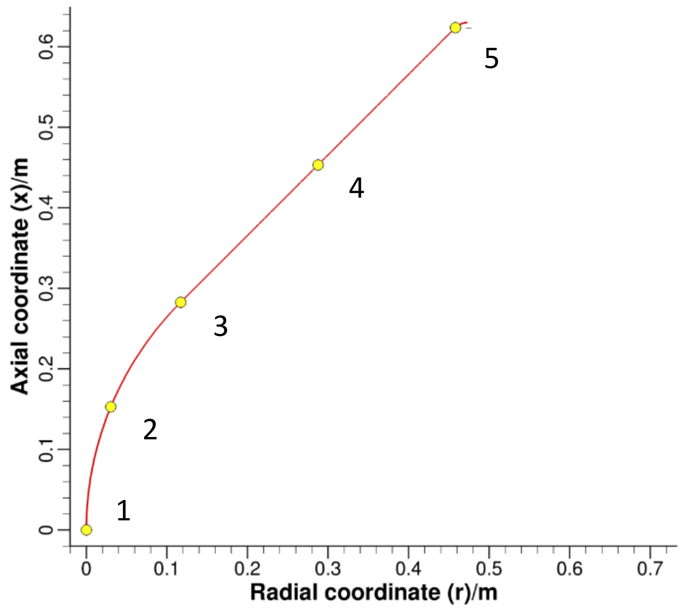
Results for Entry Mass = 275 kg











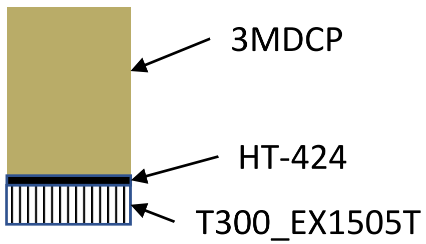
- Case4000 shows higher heating for slightly shorter duration than Case3000
- Heat load drives TPS sizing therefore Case3000 expected to require thicker TPS

*Shifted time for Case3000(shallow) to align peak heating with Case4000(steeper)

OWL UOP FIAT TPS Sizing Results using DPLR Environments (2021)

Results for 275 kg Trajectory: t = 152 s

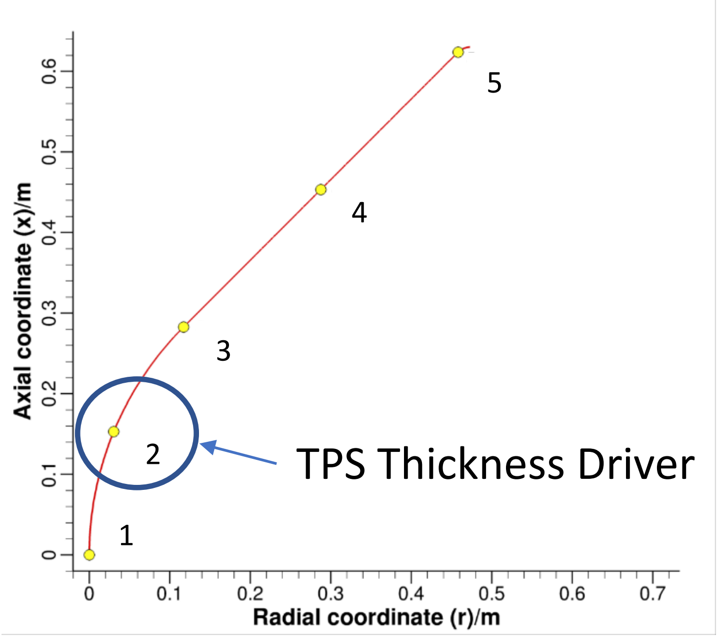
Case	Stagnation	Mid-Nose	Nose-Cone Junction	Mid-Cone	Cone-Shoulder Junction
4000	1.721 cm	1.783 cm	1.732 cm	1.739 cm	1.765 cm
3000	1.837 cm	1.892 cm	1.849 cm	1.854 cm	1.872 cm



- TPS thickness and masses are only for 3MDCP (single insulative HEEET)
- Aerothermal and material margins included for FIAT TPS sizing process
- Turbulent w/ roughness (0.4mm) aerothermal environments resulted in TPS sizing location at the mid-nose location

Case	Max Heat Flux	TPS Thickness	MEL Mass Estimate
4000	2080 W/cm^2	1.783 cm (0.70”)	25 kg
3000	1800 W/cm^2	1.892 cm (0.74”)	27 kg

(MVE = 1.3x MEL)



* More conservative Thermal Margin Policy and Sizing Guide HEEET project document HEEET-2012 used in 2021 TPS sizing

DAC3: Final Design/Analysis Cycle Summary

- One case was down selected for EDL and comm purposes – case4000
- Mass properties updated to MEV for UOP: 268.5 kg
  - Ran case with +/- 10, 20 kg for TPS mass sensitivity
  - Updated mass property simulations were comparable to early case4000 run
  - Very similar max g, max heating, and max heat rate predictions as before
  - Comm sensitivity – range, range rate, and backshell angles are very similar to case4000 (used the same case4000 orbiter trajectory)
  - Time to 10 bar has come down – from 53-55 mins to 48 mins

	Single-layer 3MDCP		Dual-layer HEEET	
Delta from Baseline Entry Mass (kg) based on stagnation point sizing	**Delta TPS Mass/kg**	**% Diff from Nominal**	**Delta TPS Mass/kg**	**% Diff from Nominal**
-20 kg	-0.1	-0.5%	1.6	7.7%
-10 kg	0	0.0%	1.8	8.4%
Baseline (268 kg MEV)	Nominal Baseline		1.9	8.9%
+10 kg	0	0.0%	2.0	9.3%
+20 kg	0.1	0.5%	2.1	9.8%

Origins, Worlds, and Life **UOP Study Summary**

After a decade of ice giant studies and lessons learned, UOP was encouraged to take a descent probe-centric approach which resulted in:

- The novel insertion of the spacecraft into elliptical orbit prior to probe release instead of releasing the probe upon hyperbolic approach which affords many advantages for mission design
- A robust mission concept, as the probe could be released after several orbits if problems were to arise while also allowing flexibility of tours around Uranus and the five major moons
- Entry trajectories identified to avoid rings while allowing for ~1 hour of communication between probe and spacecraft AND meeting TPS manufacturing and testing limitations
- A closed entry probe design using existing TPS manufacturing capabilities

OWL Recommendations

- Uranus Orbiter and Probe was named as the Highest Priority Flagship Mission
  - Mission execution to begin in FY24 / FY28 depending on funding level for Planetary Science
  - The public outbriefing slides cite reasons below for UOP being the highest priority:
    - Technically ready to start now (Neptune's heatshield outside of range of current weavable limitations)
    - Launch on Falcon Heavy Expendable (existing rocket)
    - Optimal launch in 2031 – 2032 would take advantage of Jupiter gravity assist
    - Potential partnership with ESA

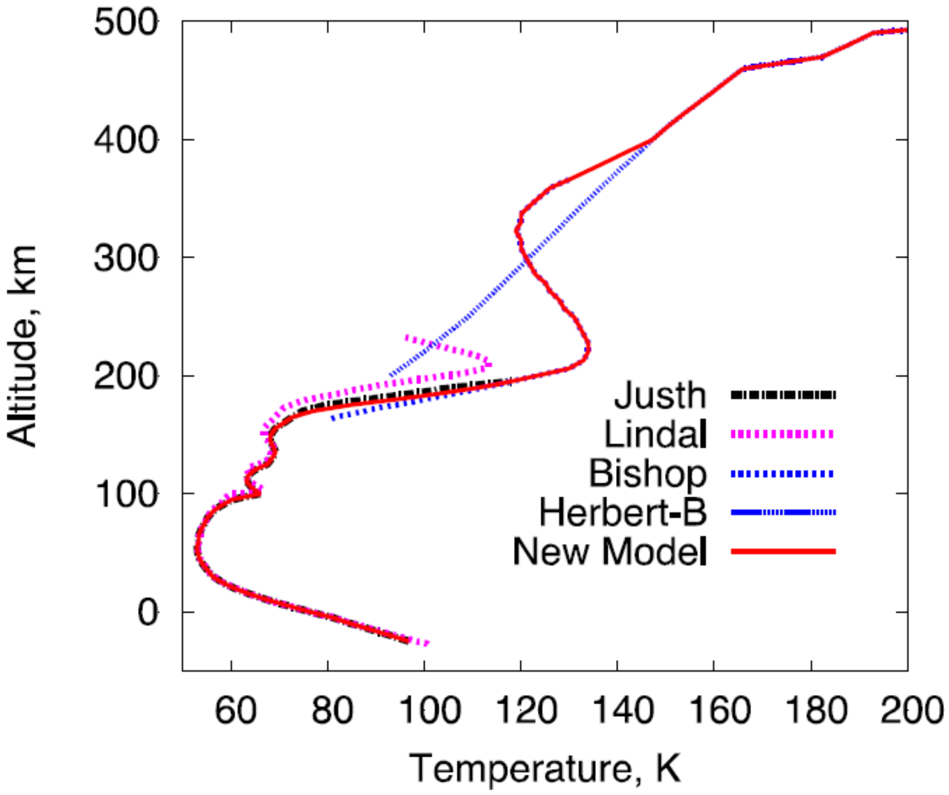
- Considering technology readiness was a major driver for prioritization, how do we sustain 3MDCP for UOP, if mission planning were to begin in FY28 (launch in ~FY35)?

Thank you kindly for your time and attention

Any Question?

NASA's In-Space Propulsion Uranus Study* (2013 – 2014)

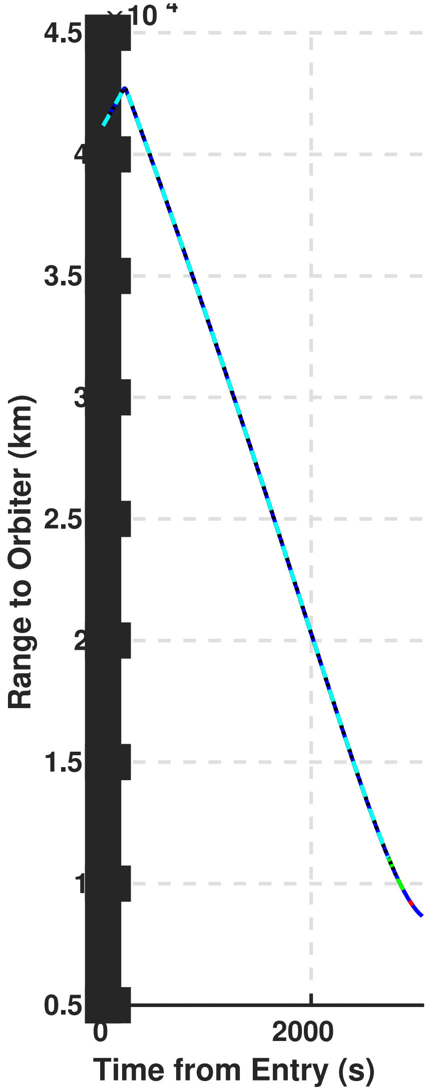
- Needed to develop an "engineering model" for Uranus's atmosphere (which is now Uranus-GRAM), as previous models did not cover the full range of atmospheric descent

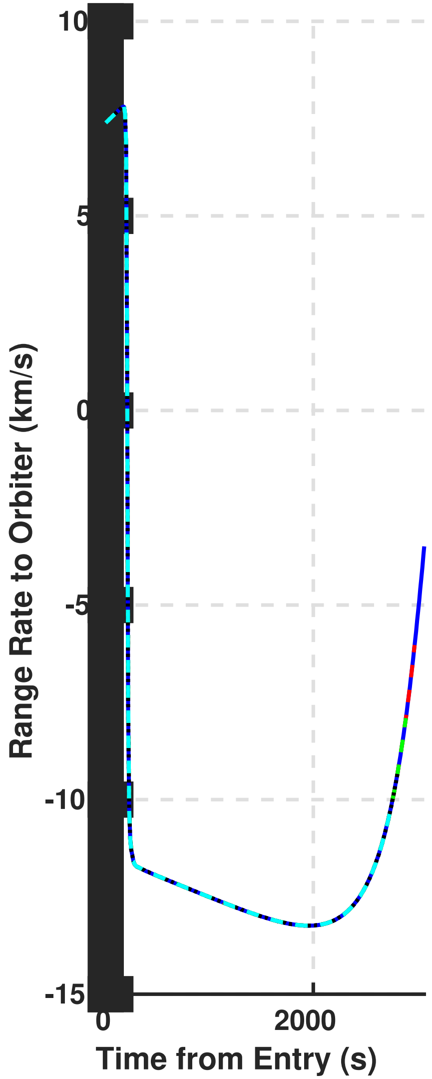


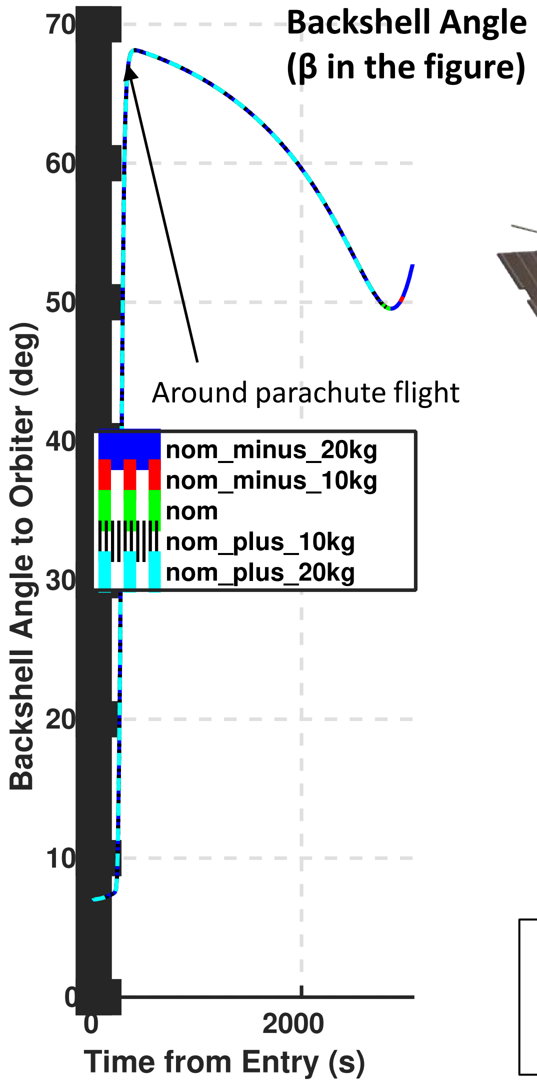
Uranus-hybrid model developed and included in NASA Ames 3DOF engineering tool TRAJ*

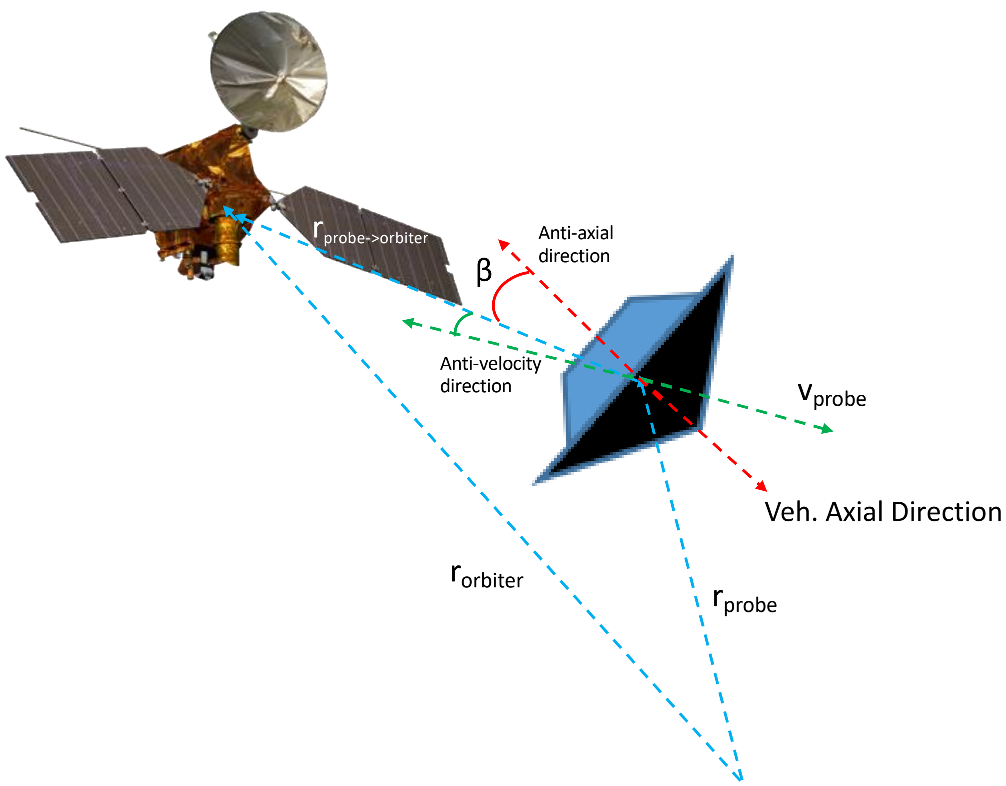
*Allen, Jr., G. A., Wright, M. J., and Gage, P., NASA/TM-2004-212847, 2005.

Communications to Orbiter









Note: Atmospheric effects and antenna pattern were not used for this analysis. This is purely geometric data

Assumptions

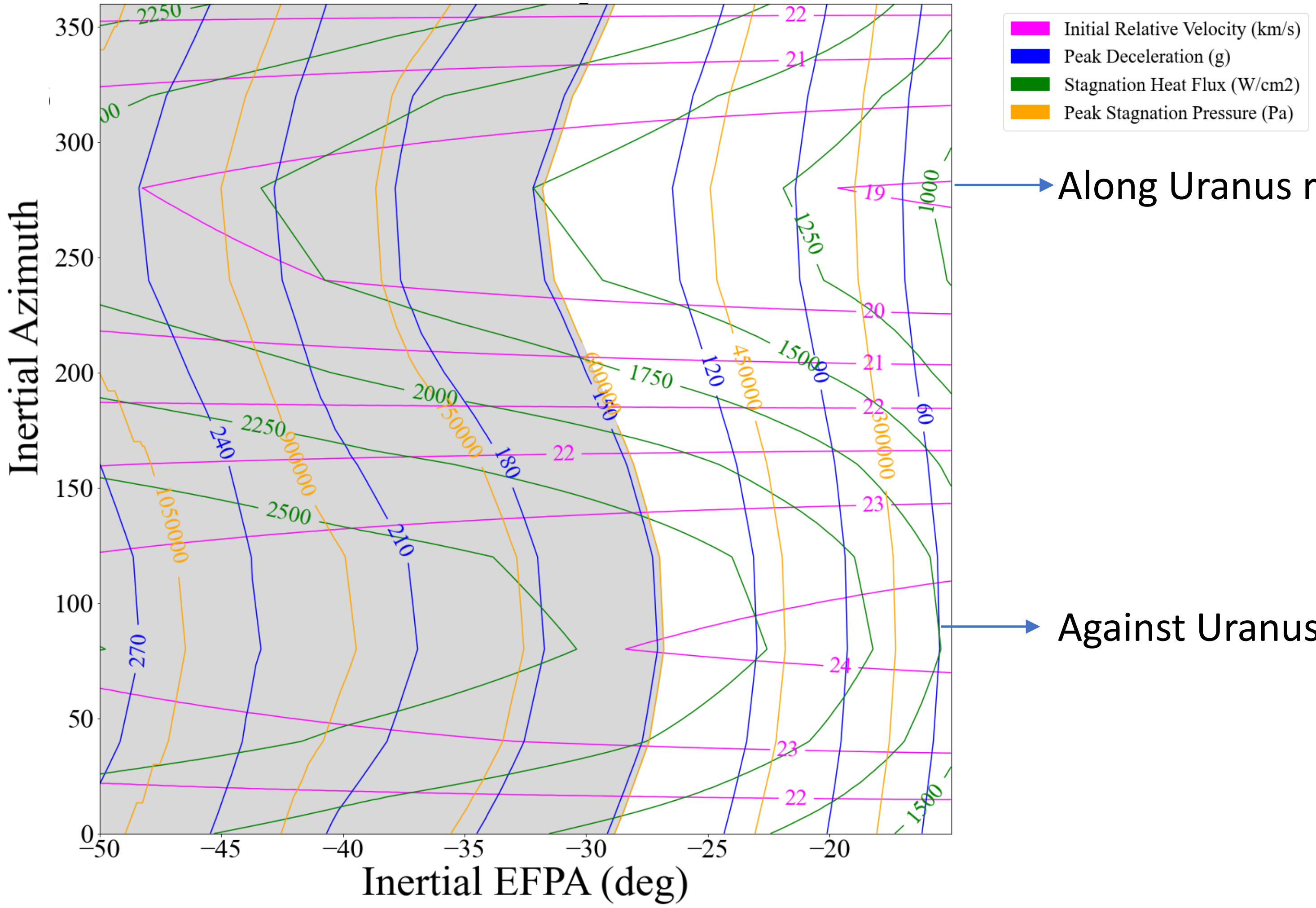
- 3 Degree-of-Freedom Trajectory Analysis
- Entry Vehicle
  - 45 deg. half-angle sphere-cone; heritage from Pioneer Venus and Galileo (Jupiter)
  - Entry Body Diameter: 1.26 m
  - Nose Radius: 0.4 m
  - Ballistic Coefficient: Approximately 220 kg/m^2
  - Assumed no shape change due to ablation; effect on trajectory of mass loss due to ablation will be quantified
- Parachutes
  - 1^{st} parachute: Conical Ribbon, Diameter: 2.5 m
    - Deploy at Mach 0.8
    - Mortar deployed
    - Used for separation system – separate heatshield and then probe from backshell
    - Conical Ribbon Parachute – heritage from Pioneer Venus and Galileo (Jupiter)
  - 2^{nd} parachute: Ringsail, Diameter: 1.8 m (updated)
    - Deploy at Mach 0.3
    - Increases descent time by 10 mins
    - Inflates as backshell separates (not mortar deployed)
    - Ringsail Parachute – heritage from Earth flights at low subsonic conditions
- Atmosphere: Uranus GRAM 2021 Atmosphere (Based on Lindal, Bishop, and Herbert)
  - Analysis includes Sromovsky's wind model to capture a notional impact on the trajectory
- Descent Probe: Diameter: 0.7 m

Conical Ribbon Parachute

Ringsail Parachute

DAC1 Re-exploring Uranus Entry States (ES) TRAJ/FIAT Analysis (2022)

Inertial Velocity: 20.8385 km/s (LARC suggested approach)
Geocentric Latitude: 6.671587 deg



Along Uranus rotation

Against Uranus rotation

Recommended approach

Reduced relative velocities with lower pressures and heating

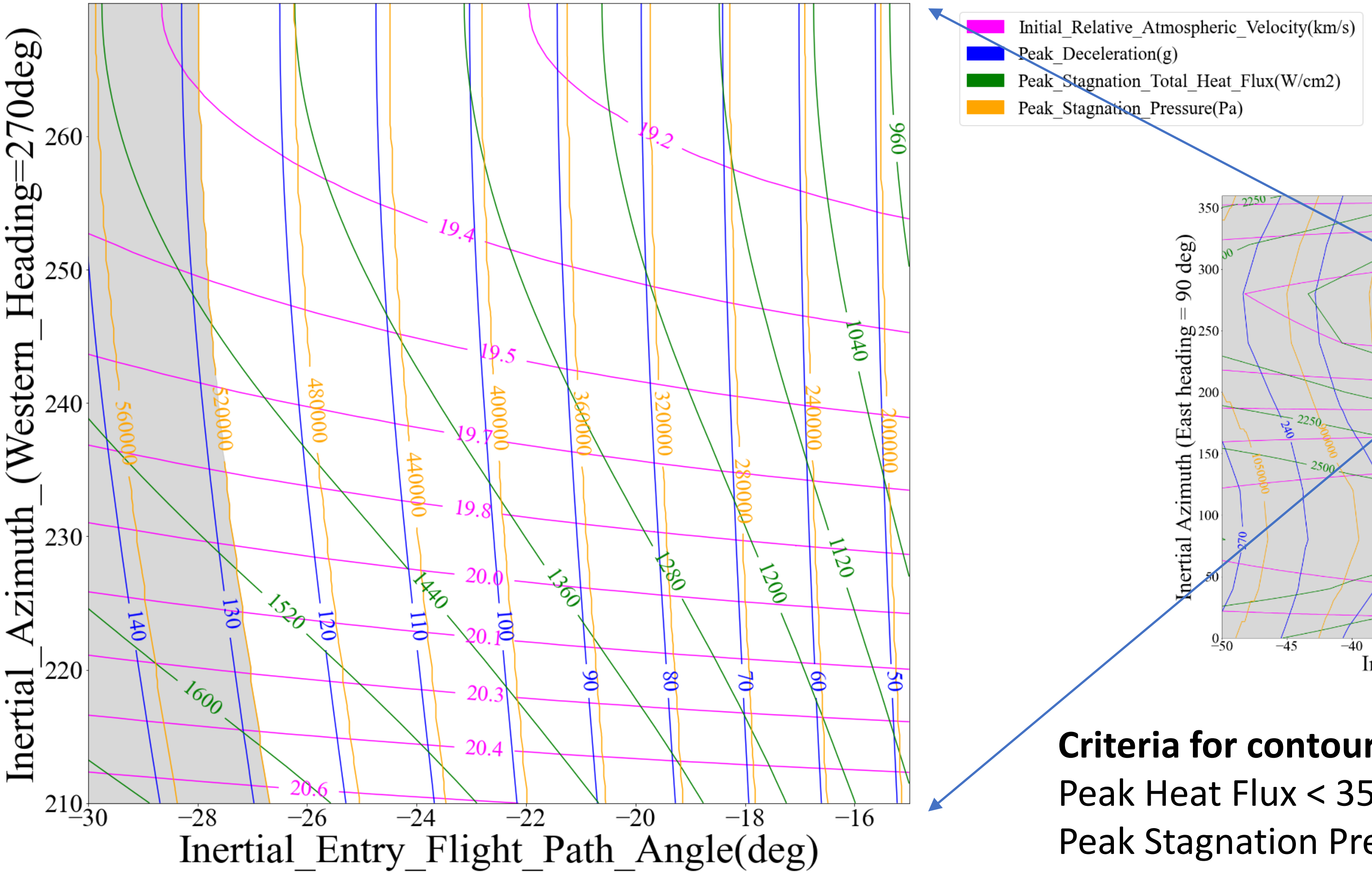
Not recommended approach

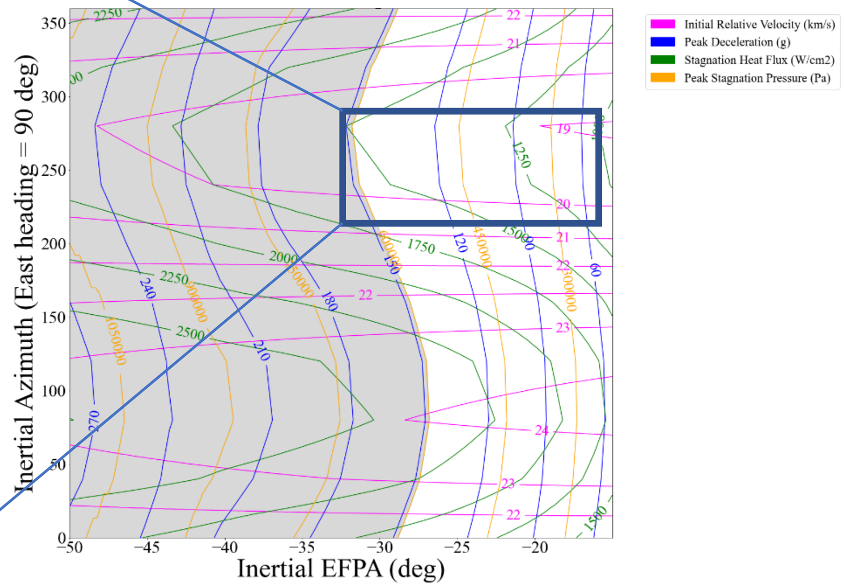
Increased relative velocities with higher pressure and heating

Peak g on the entry vehicle can also be a limiting factor depending on science instrumentation criteria

Shaded region indicates peak stagnation pressures that exceed ground test capabilities

Uranus Refined ES Analysis:
Focused On Subset of Entry States for Material Response





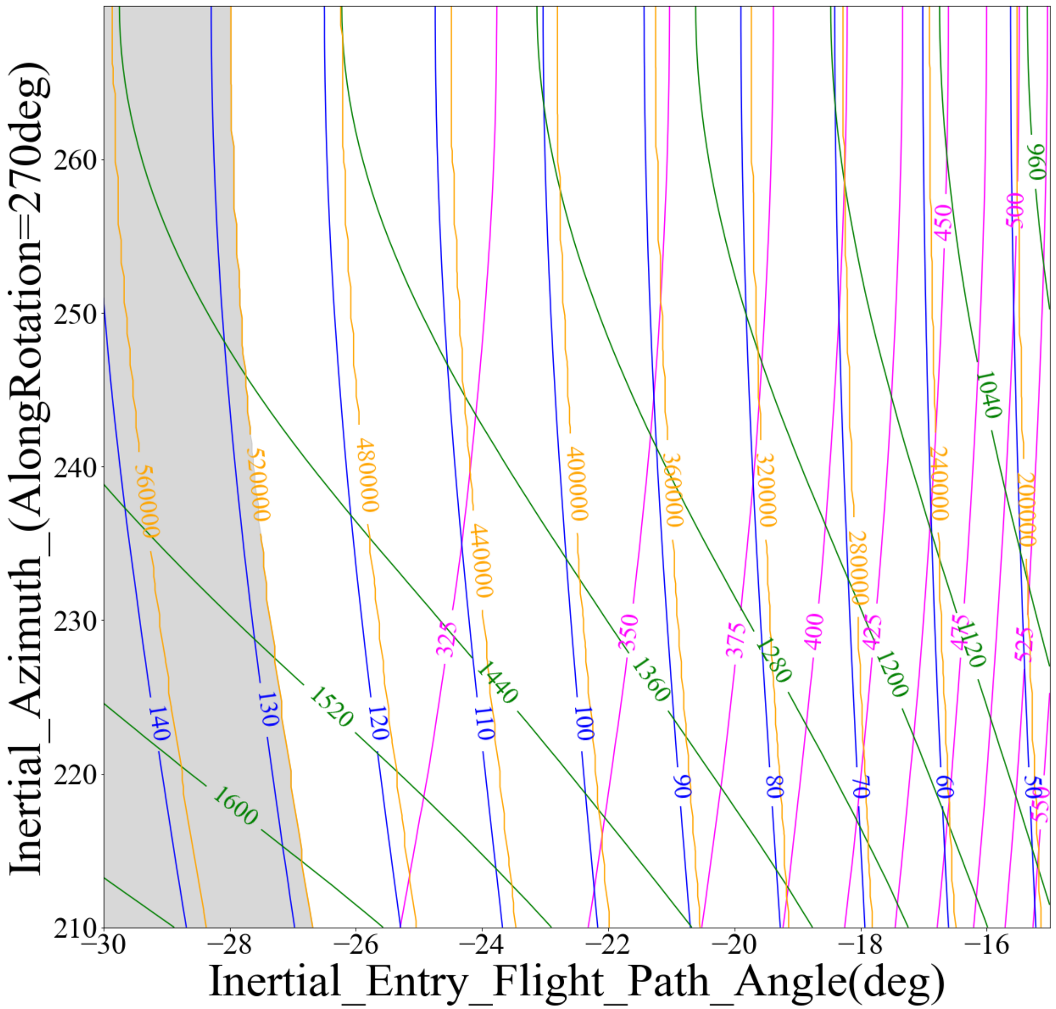
Criteria for contour plot

Peak Heat Flux < 3500 W/cm2

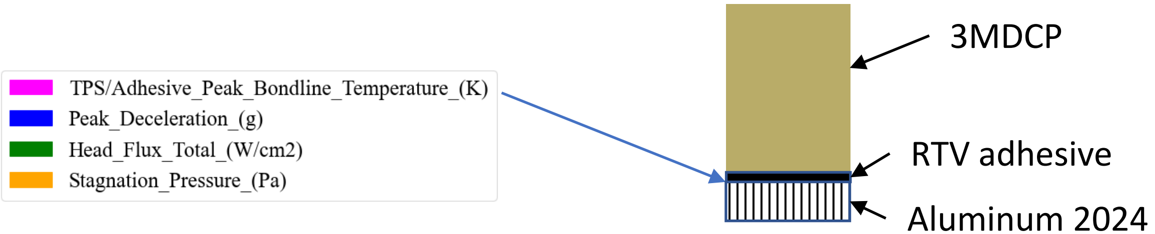
Peak Stagnation Pressure < 540,000 Pa (5.4 bar)

Shaded area does not meet ground test capability criteria

Uranus Refined ES Analysis:
TPS/Adhesive Bondline Temperatures



Shaded area does not meet criteria



Round1 of material response analysis

* Uses **fixed** TPS thickness simulations (0.8” for 3mdcp)
* Generic structure (0.015” RTV + 0.2” Aluminum)
* Margined TRAJ aerothermal environments
  - 1.25x Convective Heat flux
  - 1.1x Pressure

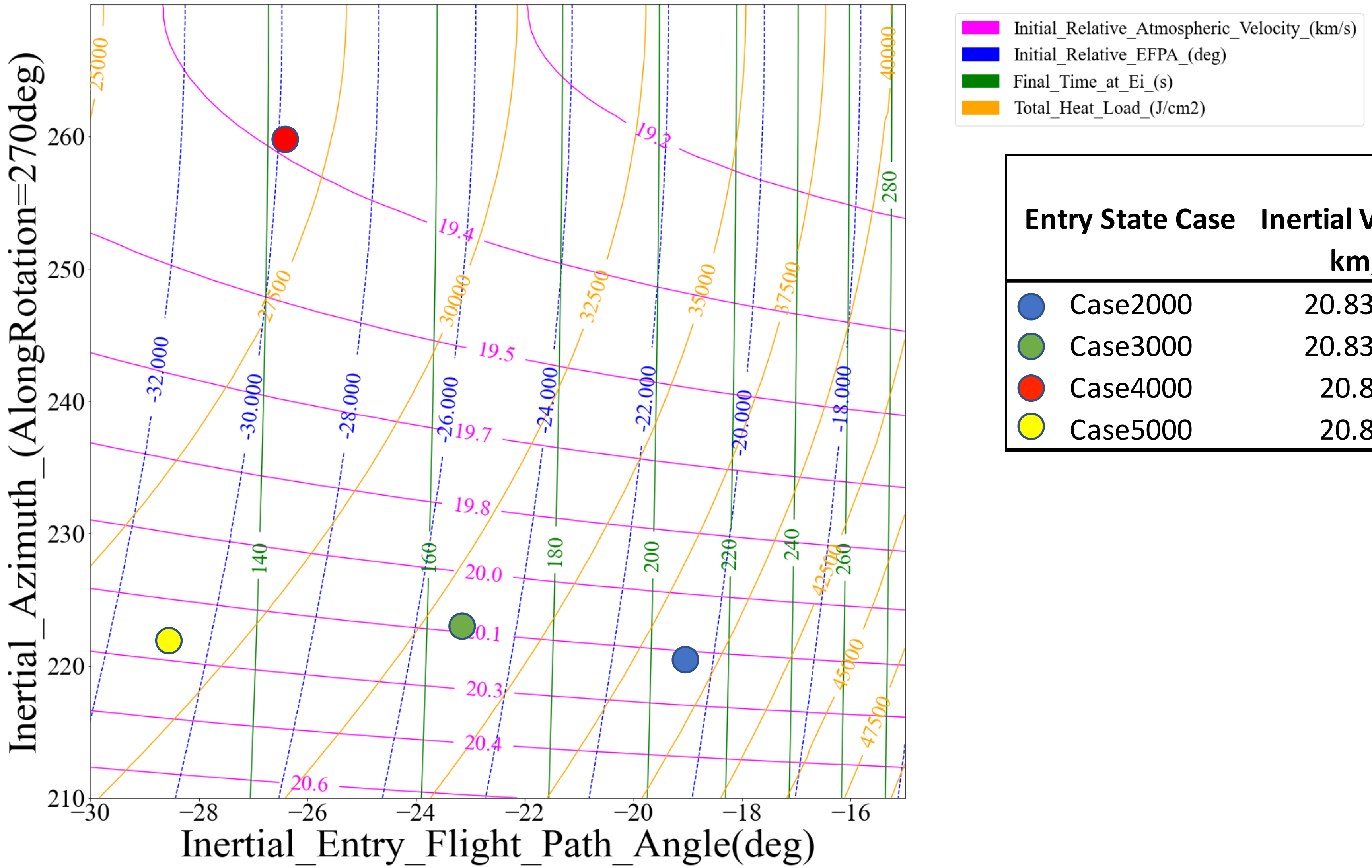
Criteria for contour plot

Peak Heat Flux < 3500 W/cm2

Peak Stagnation Pressure < 520,000 Pa (5.2 bar)

Bondline temperature < 540K (250C)

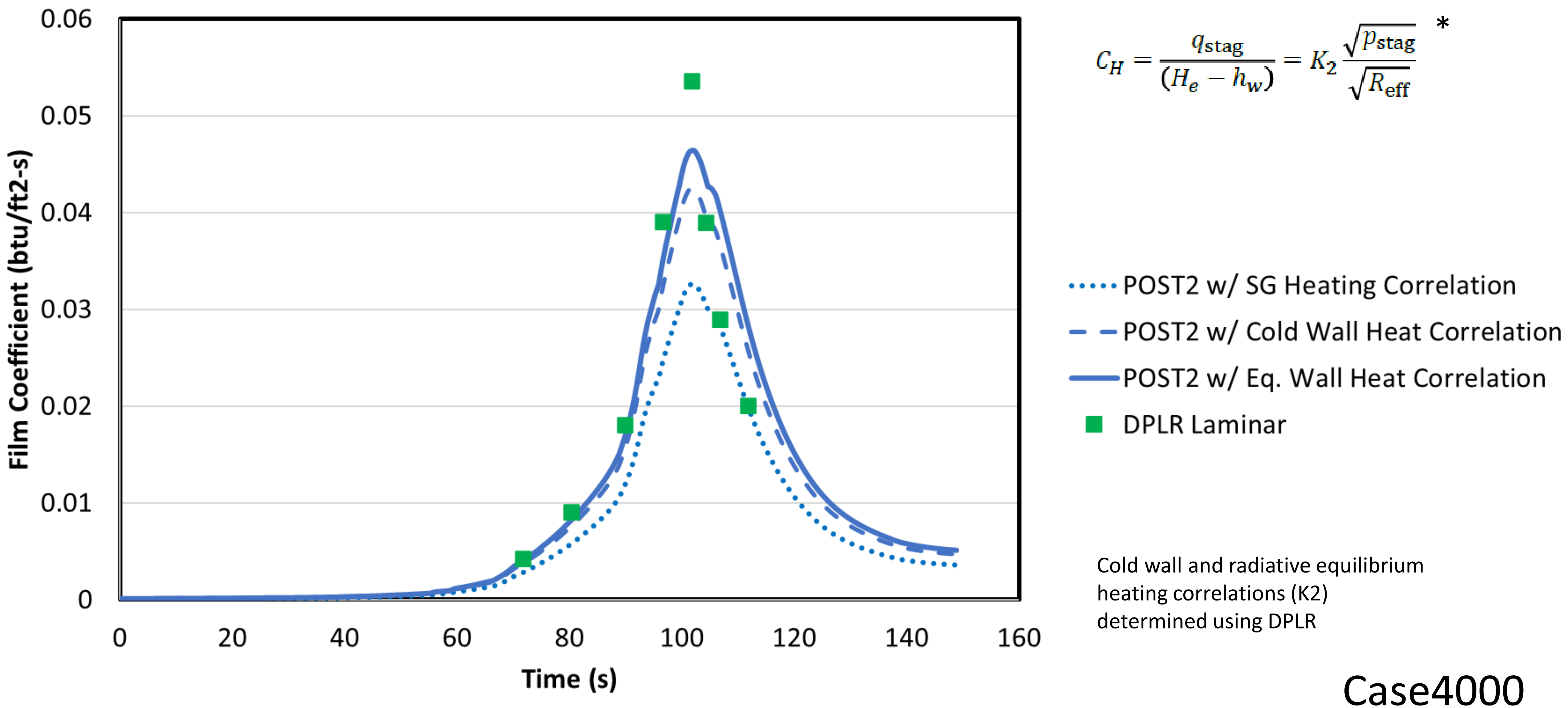
Additional parameters



Entry State Case	Inertial Velocity km/s	Inertial EFPA deg	Inertial Azimuth deg
Case2000	20.83539	-19.8858	219.9282
Case3000	20.83526	-23.1934	220.0459
Case4000	20.838	-26.17	260.61
Case5000	20.845	-28.92	221.8

CFD vs. Engineering Models For Heating Environments

Stagnation Point Aerothermal Environments



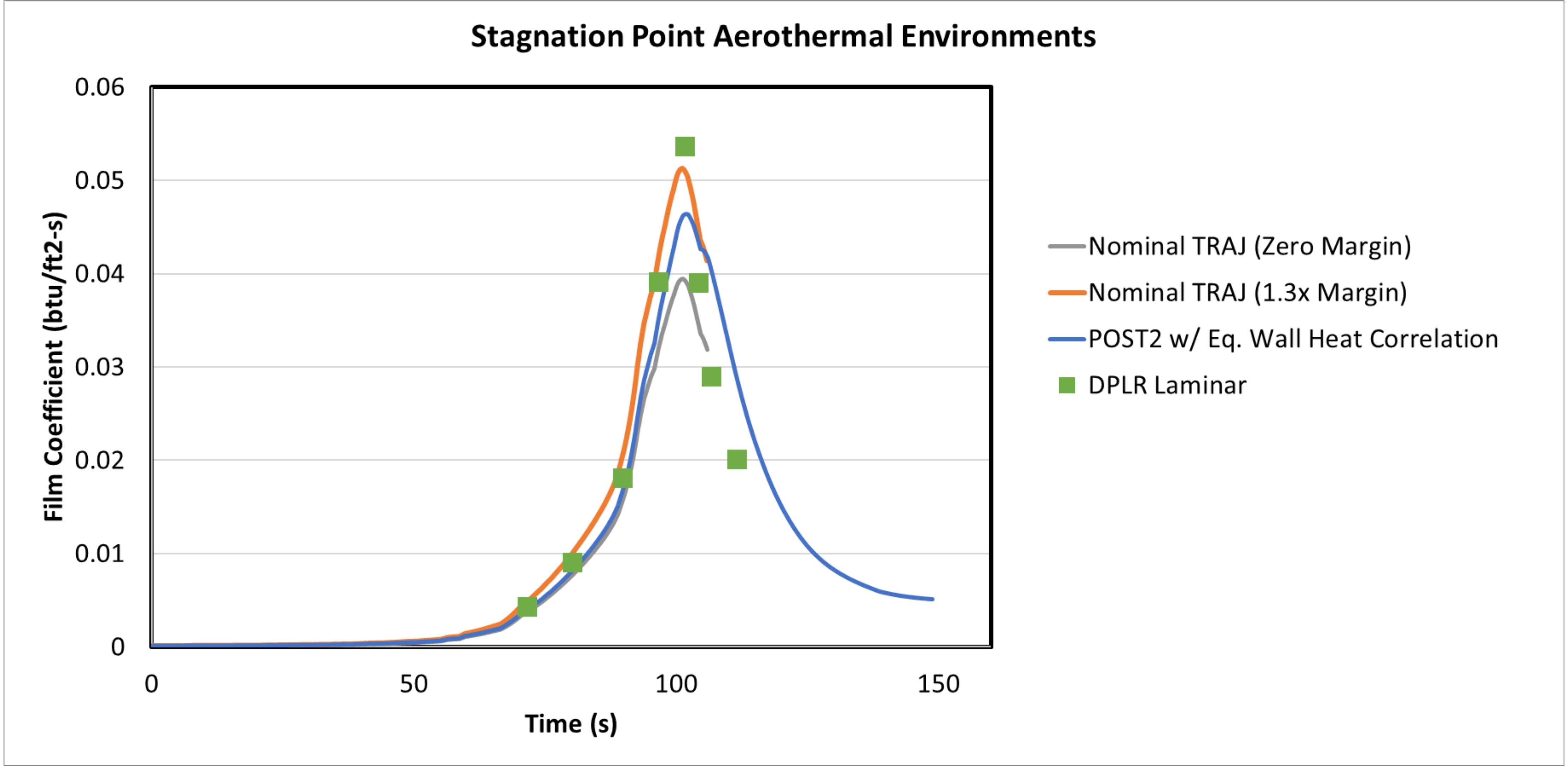
$$C_H = \frac{q_{\mathrm{stag}}}{(H_e - h_w)} = K_2 \frac{\sqrt{p_{\mathrm{stag}}}}{\sqrt{R_{\mathrm{eff}}}} \quad *$$

Cold wall and radiative equilibrium heating correlations (K2) determined using DPLR

Case4000

*D. Prabhu (FAR 2019)

CFD vs. Engineering Models For Heating Environments



Backshell

- **A rough estimate of a PICA backshell TPS sizing will be conducted, assuming ~15% aerothermal heating of the heatshield stagnation point**
- **Backshell shape will be assumed to be spherical for simplicity**
- **PICA was assumed to be a constant thickness**
- **PICA was sized to 0.8” using conservative estimates**
  - No substructure
  - Scaled down margined aerothemal HS stagnation point environment
- **Neptune Odyssey had a 9kg mass for PICA and adhesive**

Assumed Uranus Entry Probe