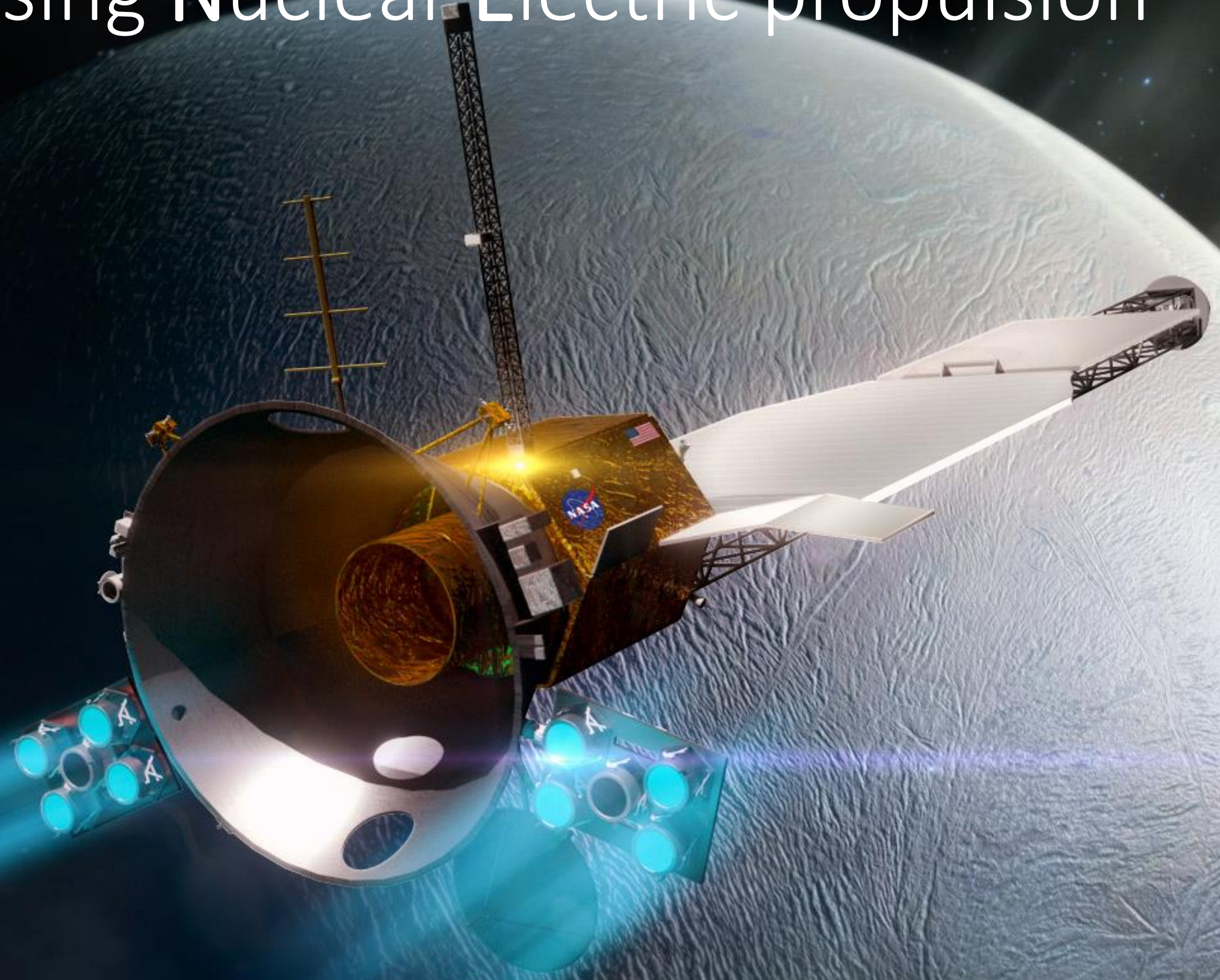
Saturn Enceladus-sample Return Explorer using Nuclear Electric propulsion



Steven Oleson, Elizabeth Turnbull, Steven McCarty, Zachary Zoloty, Geoffrey Landis, Lee Mason, Benjamin Abshire, Ryan McDonough, Bushara Dosa, Shadi Zogheib, Benjamin Wozniak, Cassandra Chang, and Maya Havens- NASA

Thomas Packard, Allison Fox, Anthony Colozza, John Gyekenyesi – HX5

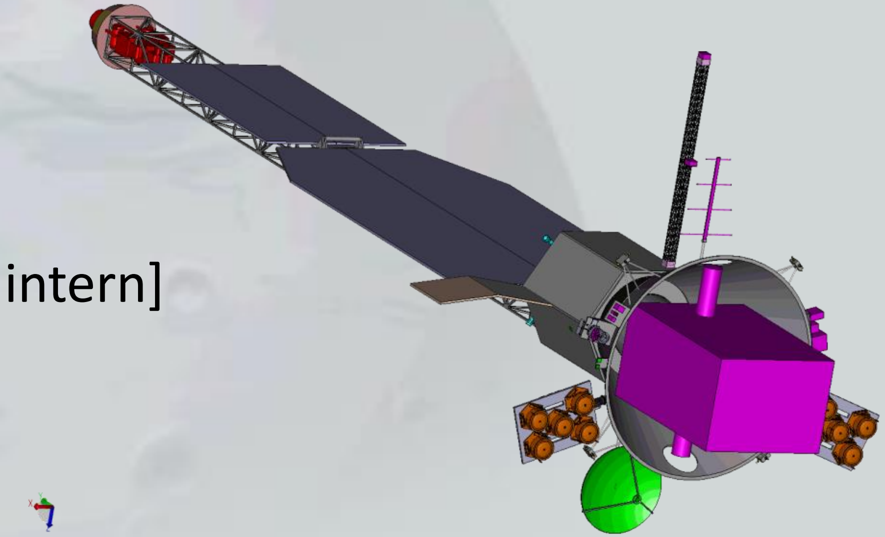
James Fittje - SAIC

COMPASS

ASCEND 2026 - Washington, D.C.

Team

- Customers: SNP: Kurt Polzin, Andy Presby, Tim Duquette, John Nowakowski
- Lead: Steve Oleson
- Lead Sys Engineer: Betsy Turnbull
- Science PI: Allie Fox, Geoffrey Landis, (Daniel Glavin - pre-work)
- Mission Design: Steve McCarty, Zach Zoloty, Maya Havens, Matt Duchek
- Power: Lee Mason, Ben Abshire, Chris Barth
- Propulsion: Jim Fittje
- Thermal: Tony Colozza
- AD&CS: Ben Wozniak
- Comms: Ryan Mcdonough, Bushara Dosa, Lewi Duressa [Comm intern]
- C&DH: Shadi Zogheib
- Mechanical: John Gyekenyesi
- Configuration: Tom Packard
- Cost: Cassandra Chang, Stephen Andryc

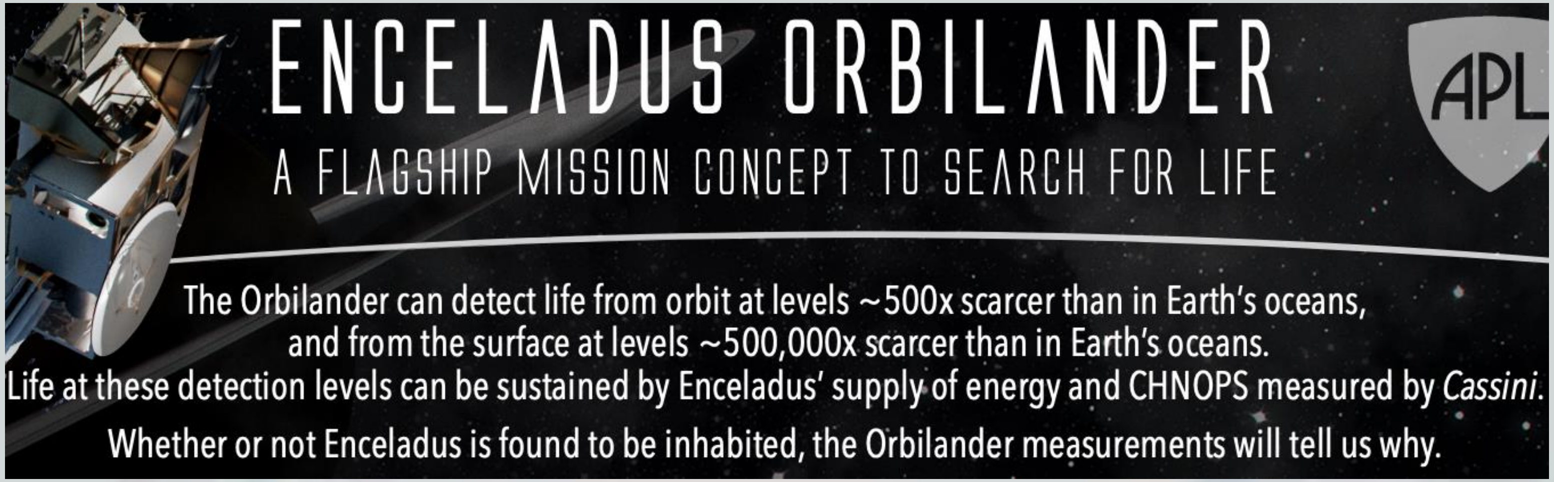


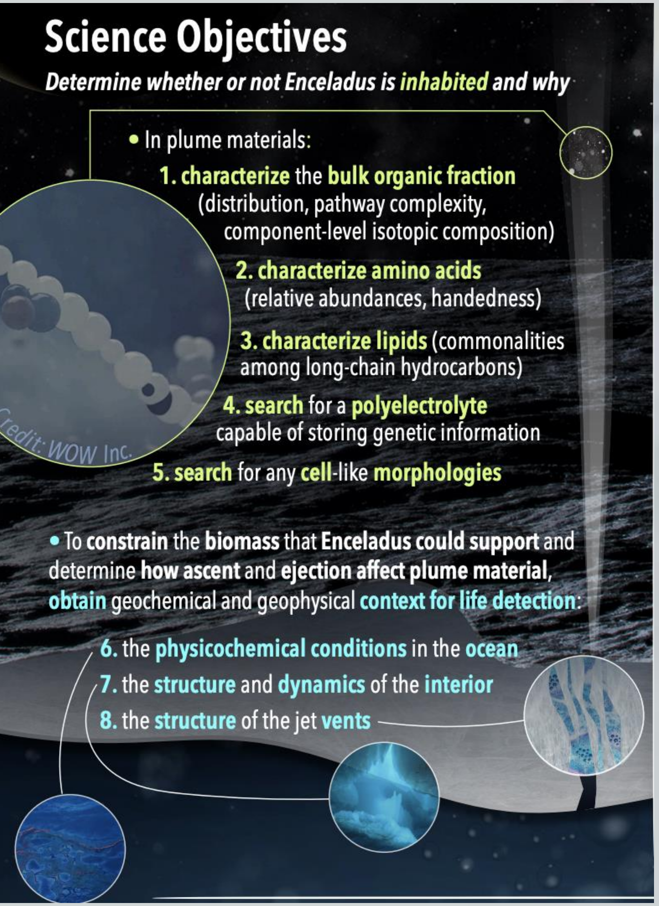
Purpose

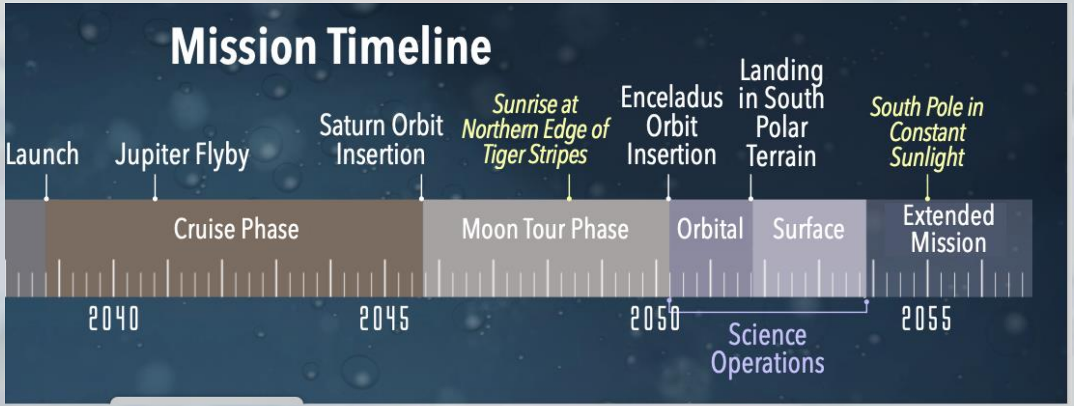
- Purpose:
  - *Develop a NEP conceptual vehicle design for returning a sample from Enceladus in under 20 years*
    - *Type(s) of samples to be defined by science PI*
    - *Use 2023 Accelerating Space Science with Nuclear Technologies Workshop guidelines: Use the NEP vehicle to ALSO deliver large landers, relay more data, power landers, radar map moons of Saturn*
- Scope
  - *Focus on the NEP design – utilize sample gathering from other designs*
    - *Trade HLS launchers and NEP/chem*
- Class A/B, Single Fault Tolerant
- Figures Of Merit: Round trip time, Launch opportunity, Mass delivered, Robustness, Cost
- 2026 Accelerating Space Science with Nuclear Technologies Workshop

Approach

- Minimize leg trip times to provide a <20 yr round trip
  - Use NEP and chem as needed: THIS IS THE FOCUS OF THE STUDY
  - Trade NEP power and alpha – effect of an advanced NEP system?
  - Utilize potential HLS performance (Starship or Blue Transporter)
  - Avoid flybys, if possible, to allow more launch opportunities
- Use the 2023 Accelerating Space Science with Nuclear Technologies Workshop science takeaways as guidelines for what science wants from nuclear propulsion
- Base sampling and science using the recent Orbilander design
  - Many Saturn/Enceladus environment data can also be gleaned from the design document. https://ntrs.nasa.gov/citations/20205008712
- For Comparison investigate an all-chem option based on Orbilander and first principles with storable propellants
  - Cryogenic options at Saturn are further work







Remove

Orbital instruments

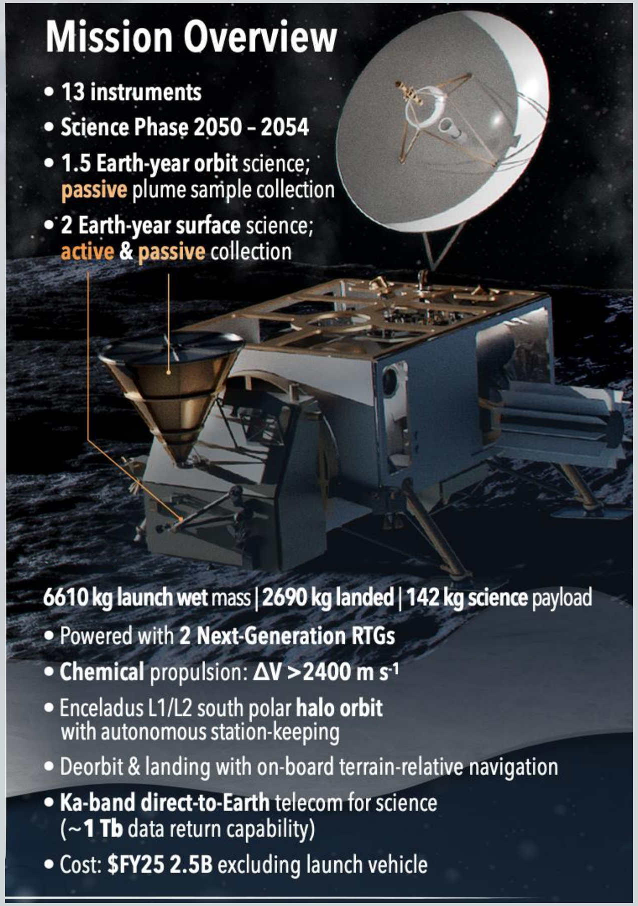
DTE comms to earth

Replace w UHF

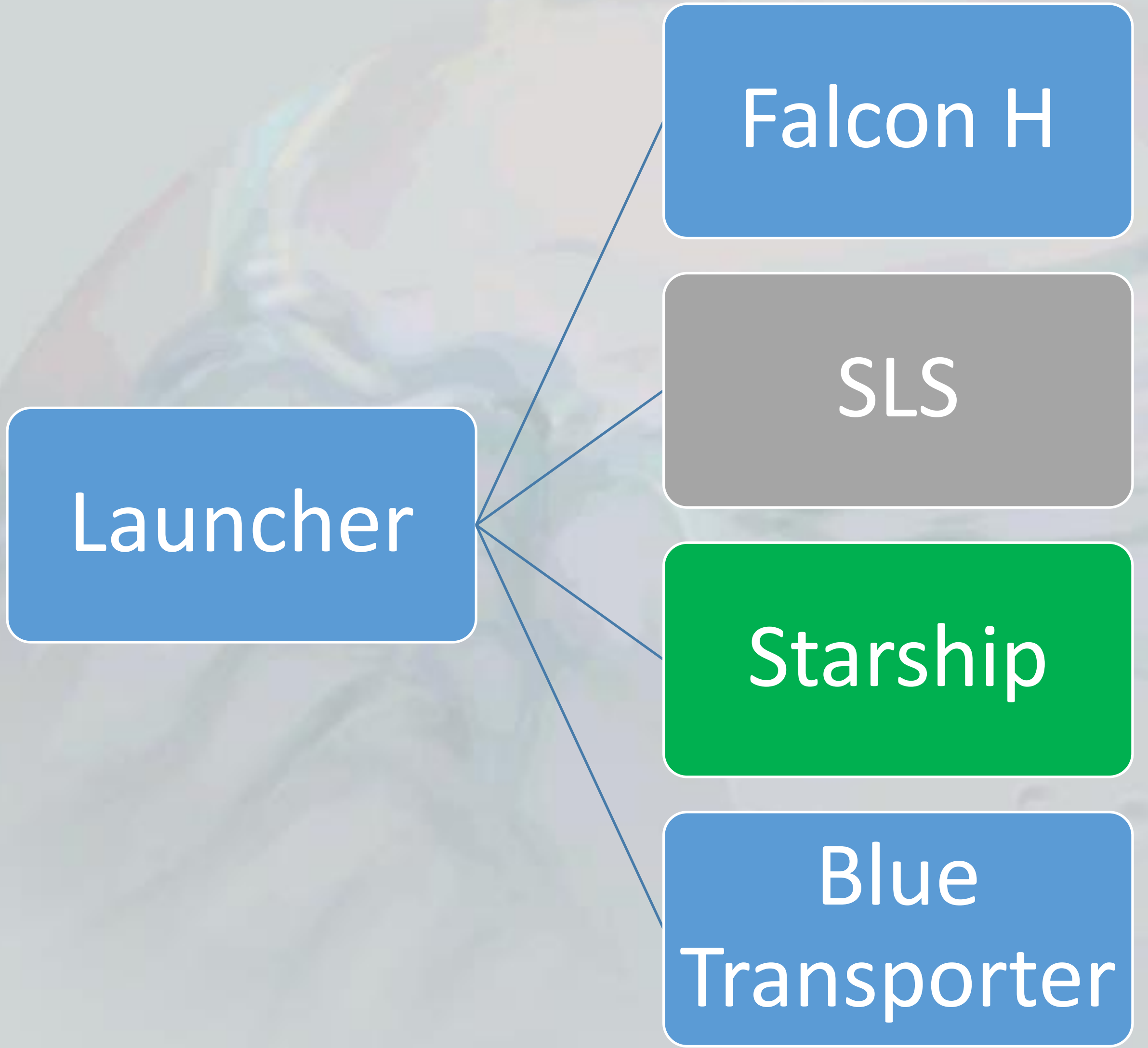
Add

Sample return Capsule

[Enceladus Orbilander: A Flagship Mission Concept for Astrobiology - NASA Technical Reports Server (NTRS)-https://ntrs.nasa.gov/citations/20205008712](https://ntrs.nasa.gov/citations/20205008712)

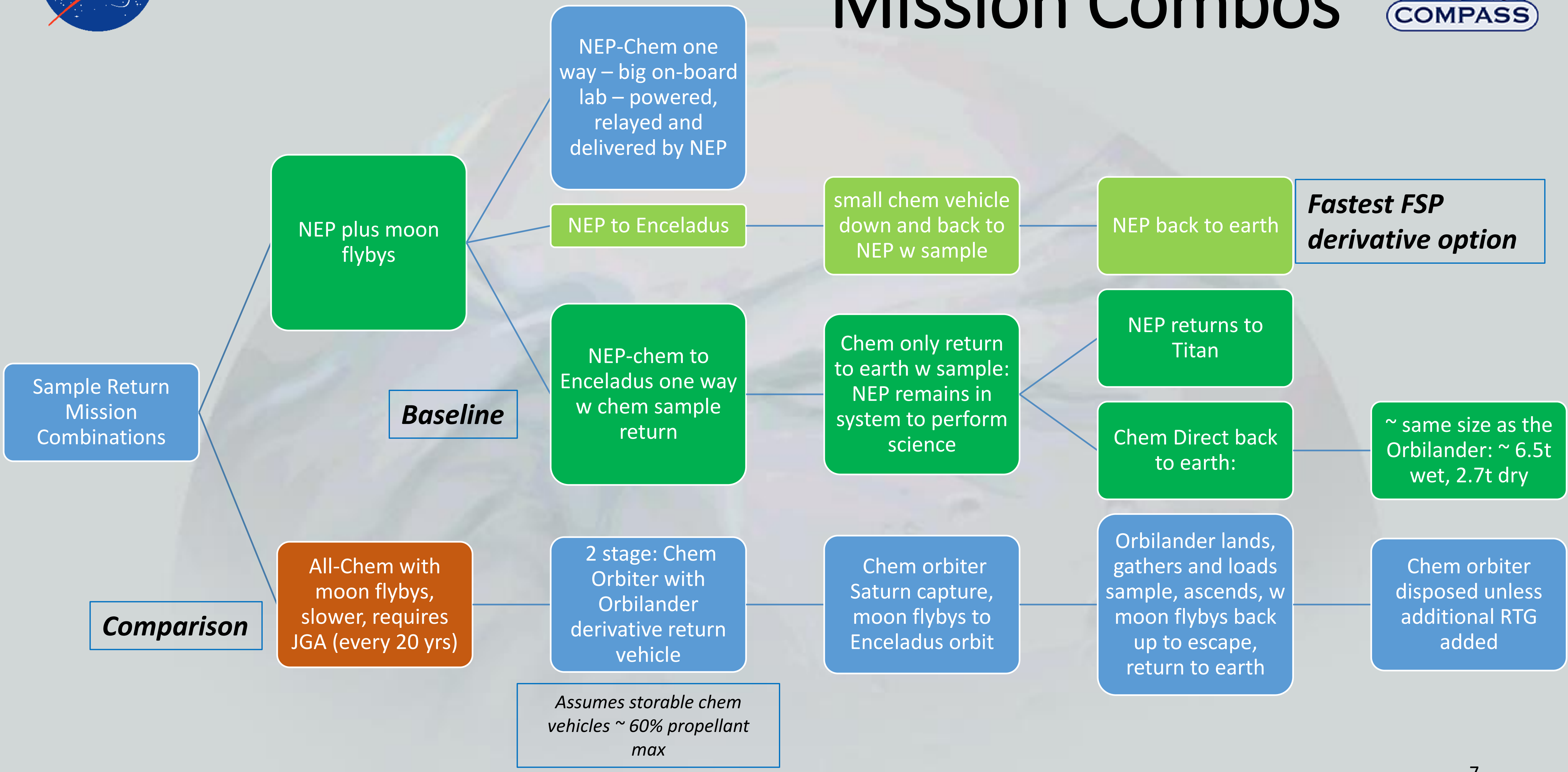


New Commercial Launchers

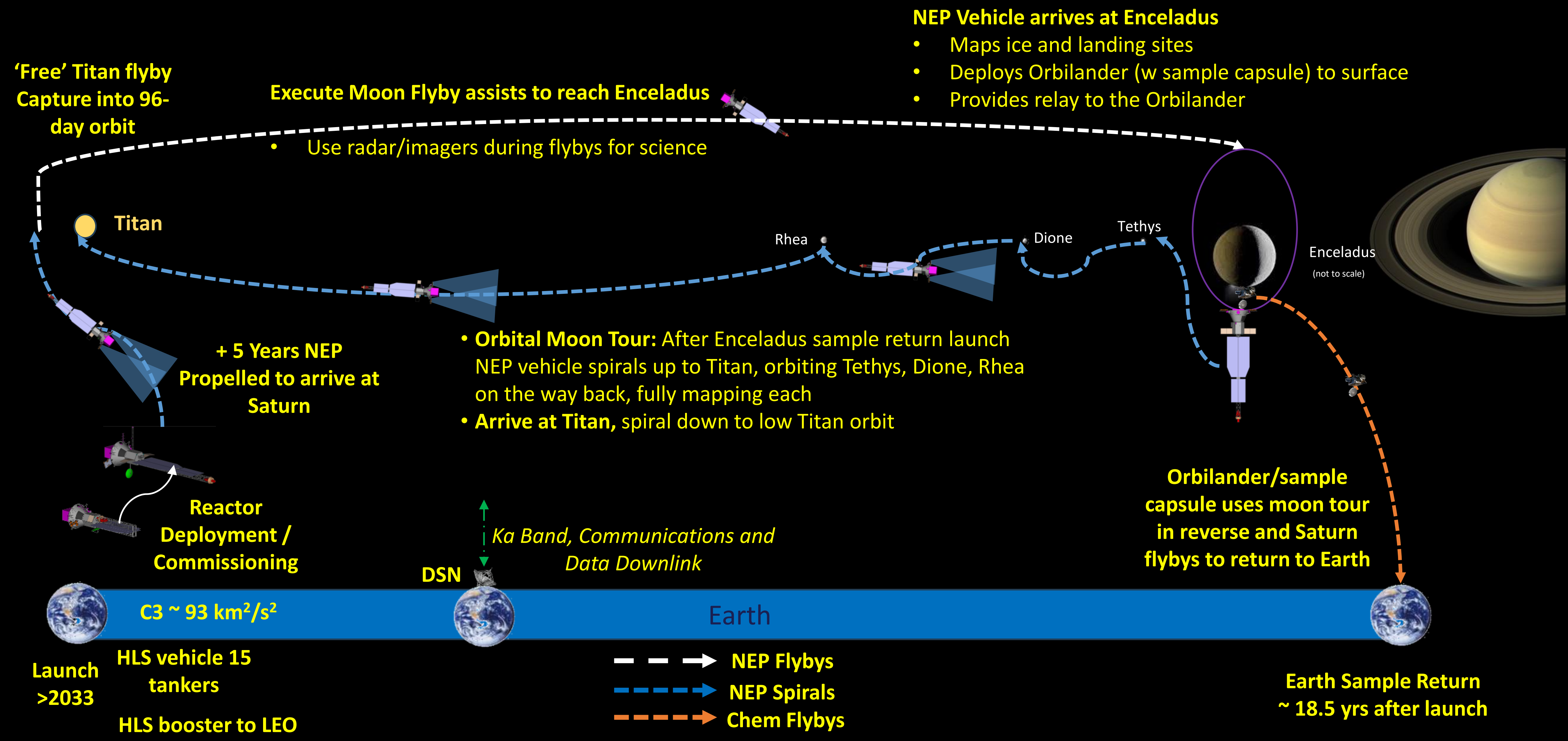


Mission Trades showed that Starship was by far the most capable at sending large payloads to high C_3s

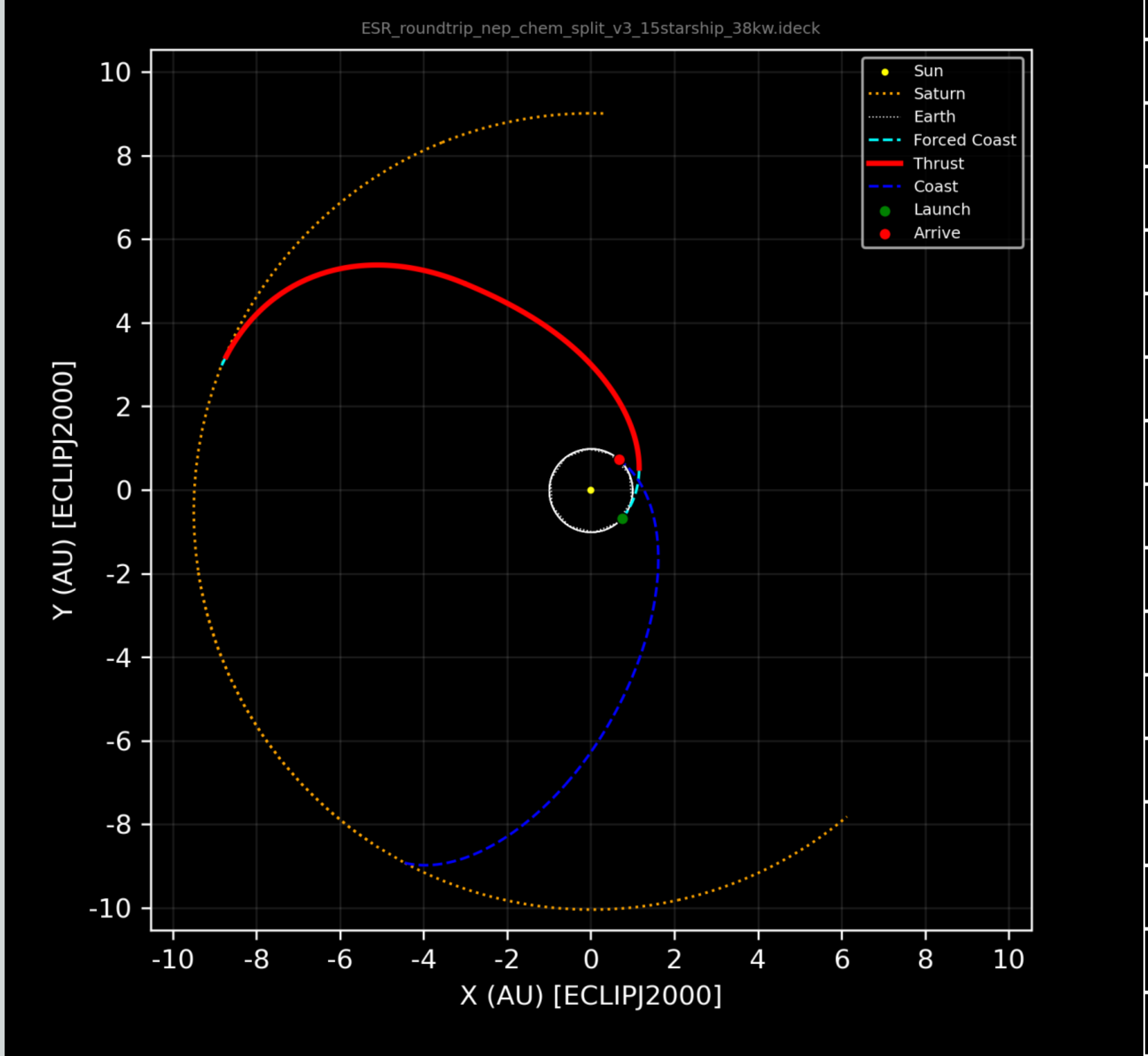
Mission Combos



Enceladus Sample Return: Concept of Operations Diagram

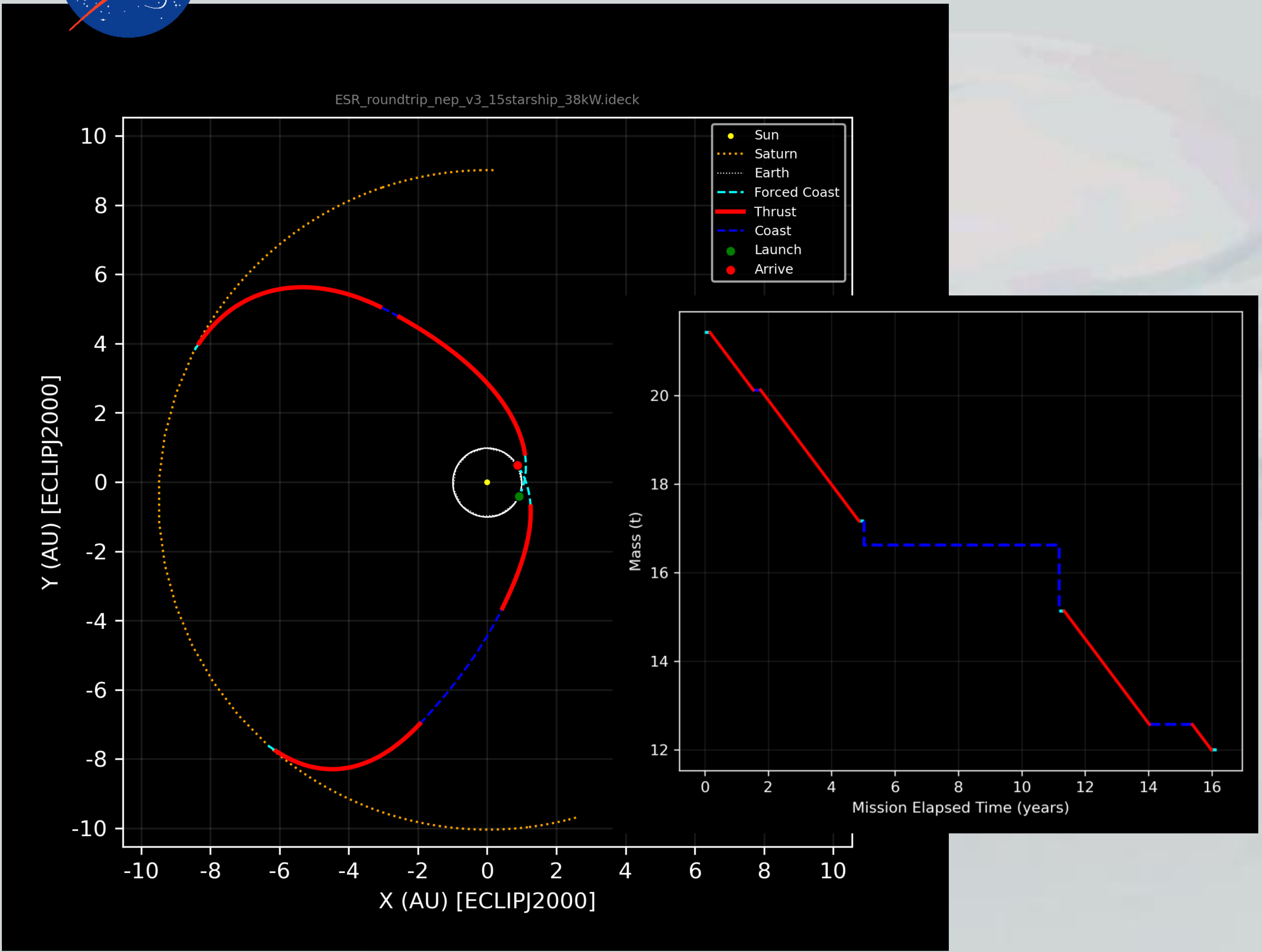


Mission Overview (38 kW NEP/Chem Split): Baseline



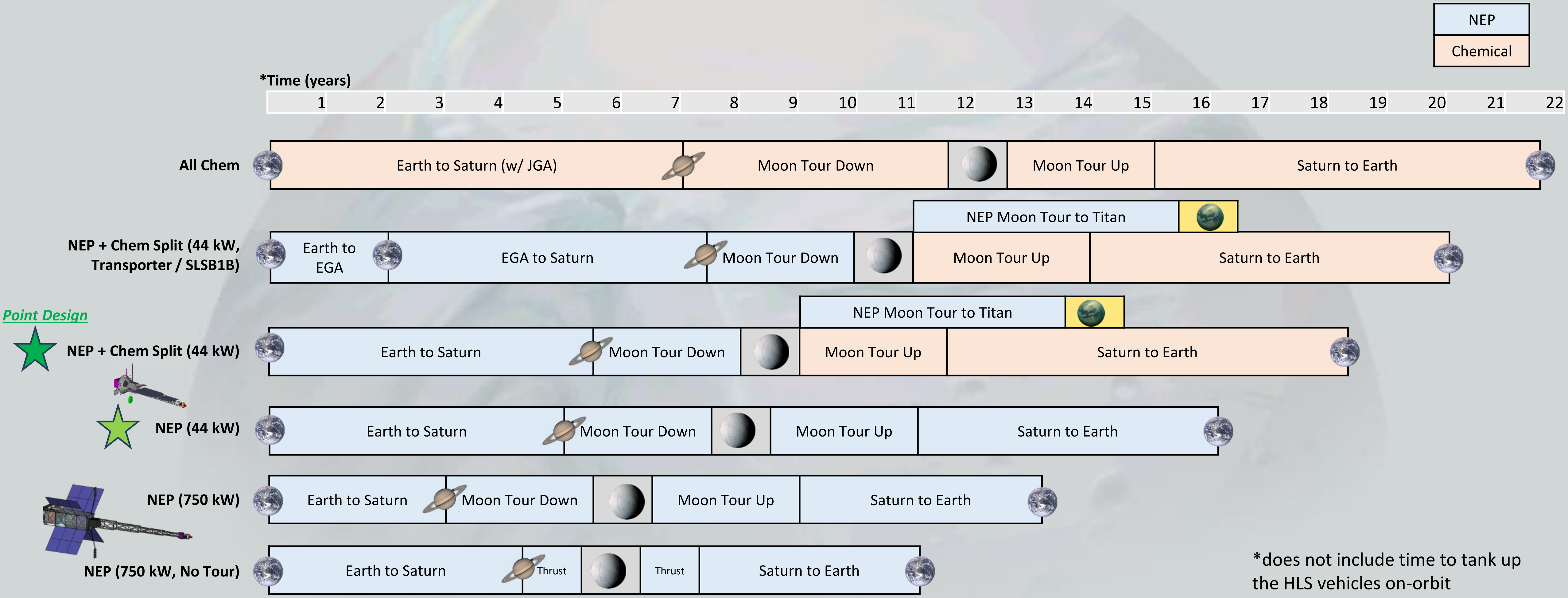
Launch C3 (km^2/s^2)	93.30
Launch Mass (t)	27.30
Saturn Arrival Mass (t)	22.38
Lander Mass (t)	6.60
Final Mass (NEP) (t)	12.00
Propellant Used (t)	8.70
NEP Isp (s)	4000.00
NEP Thrust (N)	1.19
NEP Mdot (kg/s)	3.02e-05
NEP Power (kW)	38.00
NEP ΔV Outbound (km/s)	7.79
NEP ΔV @ Saturn (km/s)	10.22
NEP ΔV Total (km/s)	18.01
Chem ΔV Total (km/s)	2.43
TOF Outbound (years)	5.51
TOF Inbound (years)	5.84
TOF Total (years)	18.25
Thruster On Time (years)	9.12

Mission Overview (38 kW NEP Roundtrip option)



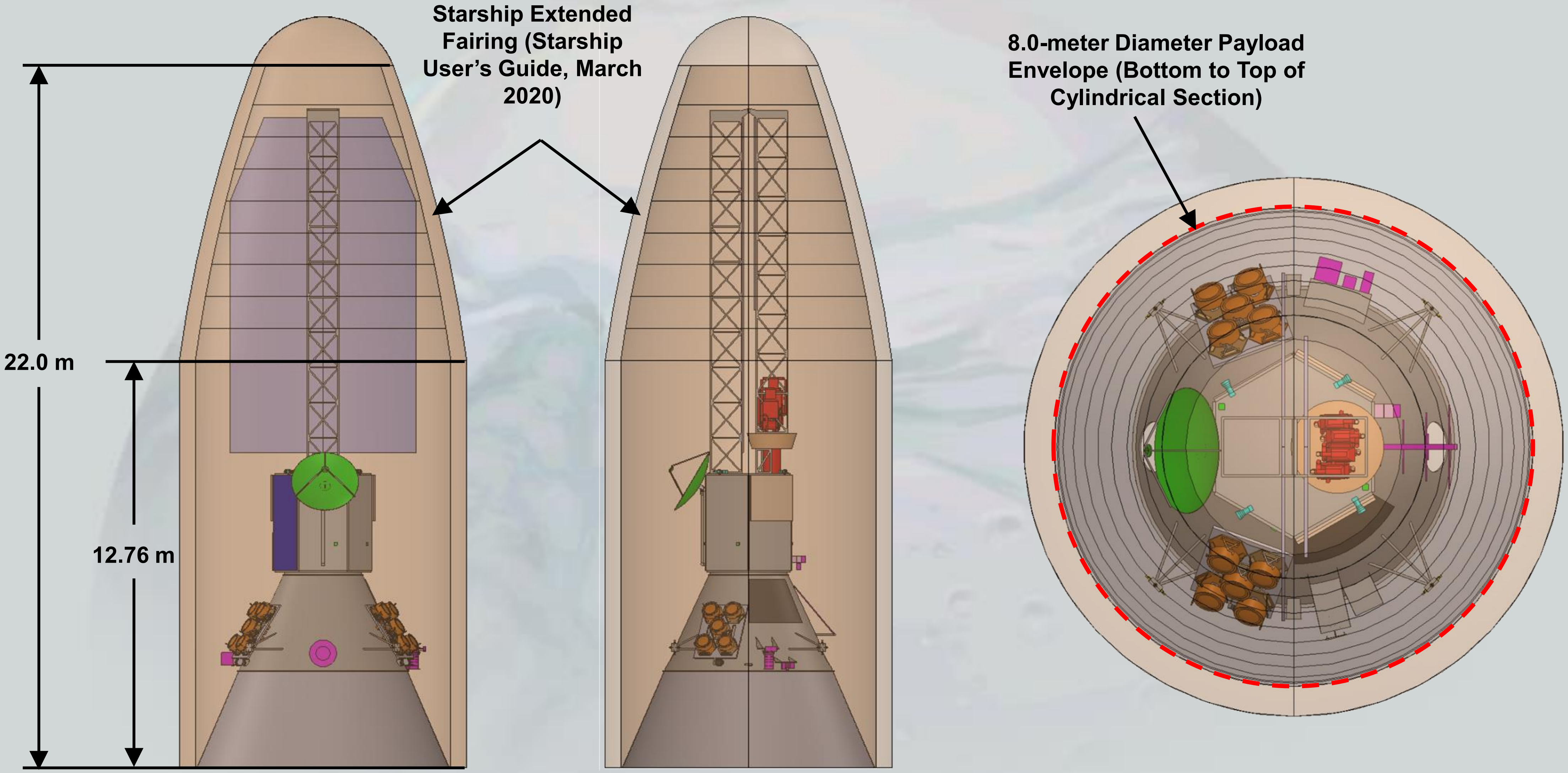
Launch C3 (km^2/s^2)	97.82
Launch Mass (t)	21.42
Saturn Arrival Mass (t)	17.17
Lander Mass (t)	1.00
Saturn Departure Mass (t)	15.13
Earth Returned Mass (t)	12.00
Propellant Used (t)	8.42
NEP Isp (s)	4000.00
NEP Thrust (N)	1.19
NEP Mdot (kg/s)	3.02e-05
NEP Power (kW)	38.00
NEP ΔV Outbound (km/s)	8.69
NEP ΔV @ Saturn (km/s)	2.51
NEP ΔV Inbound (km/s)	9.10
NEP ΔV Total (km/s)	20.30
NEP ΔV Effective (km/s)	19.60
TOF Outbound (years)	5.03
TOF at Saturn (years)	6.15
TOF Inbound (years)	4.97
TOF Total (years)	16.15
Thruster On Time (years)	8.83

Option Timeline Summary

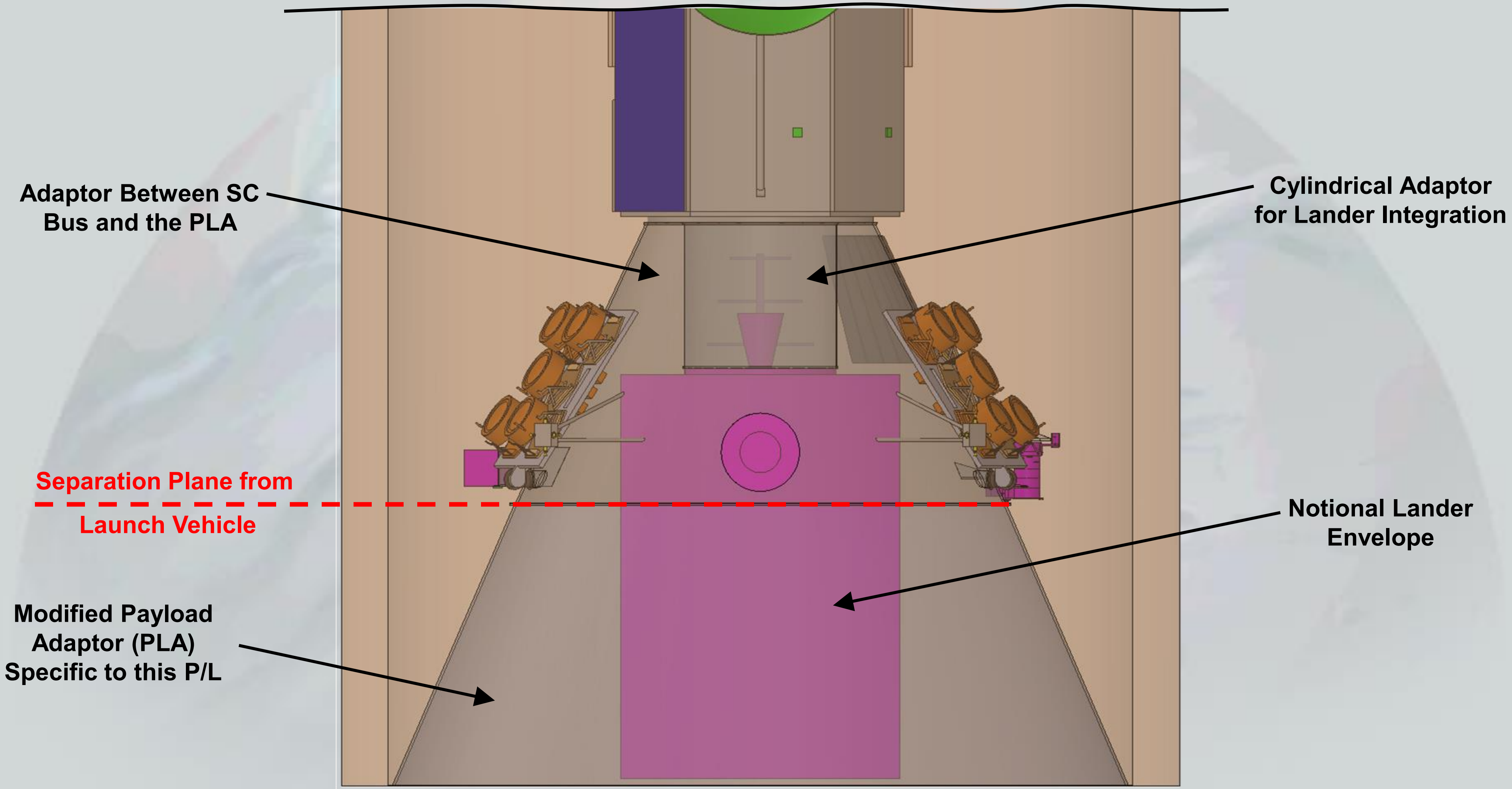


*does not include time to tank up the HLS vehicles on-orbit (~ 3 months estimated for 15 tankers)

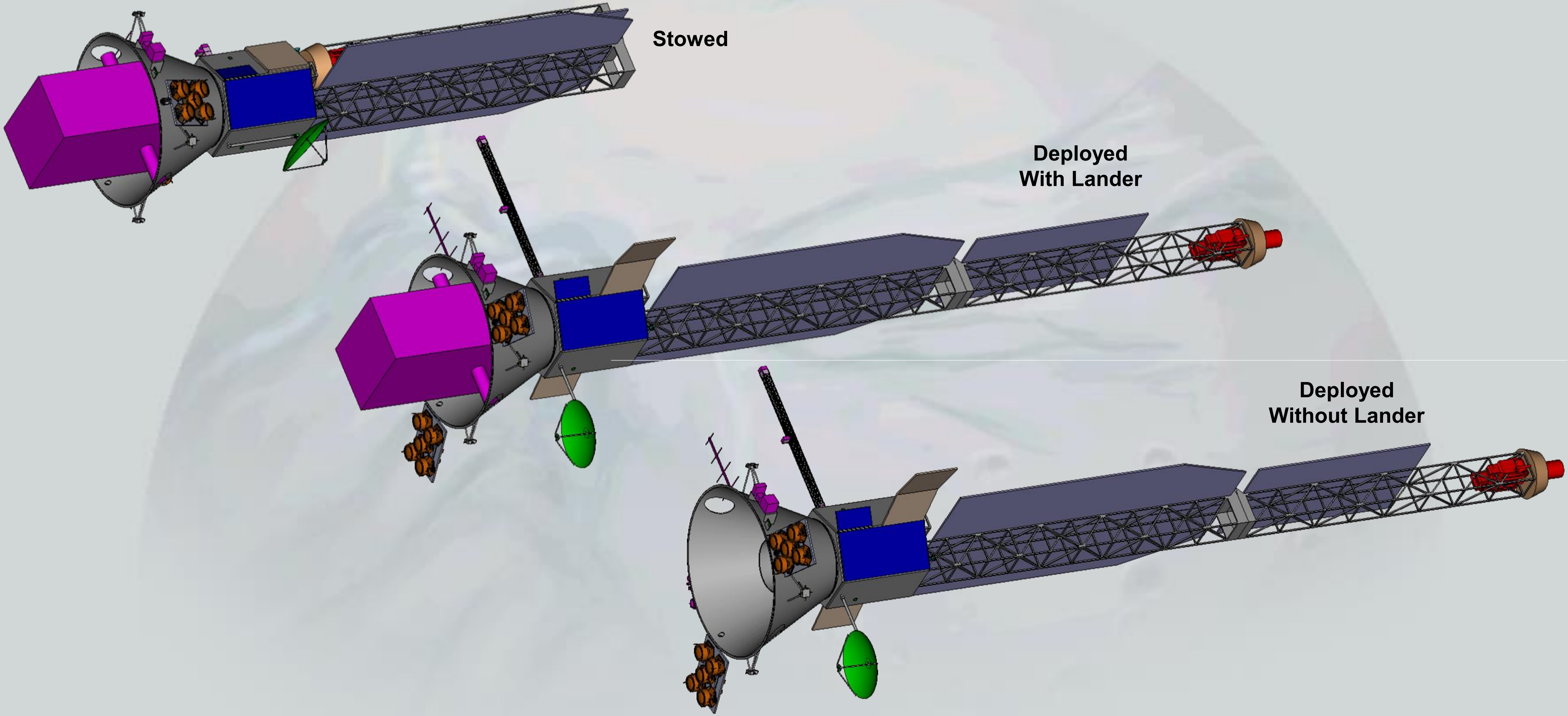
Enceladus Sample Return (ESR) Vehicle Inside the Starship Extended Fairing



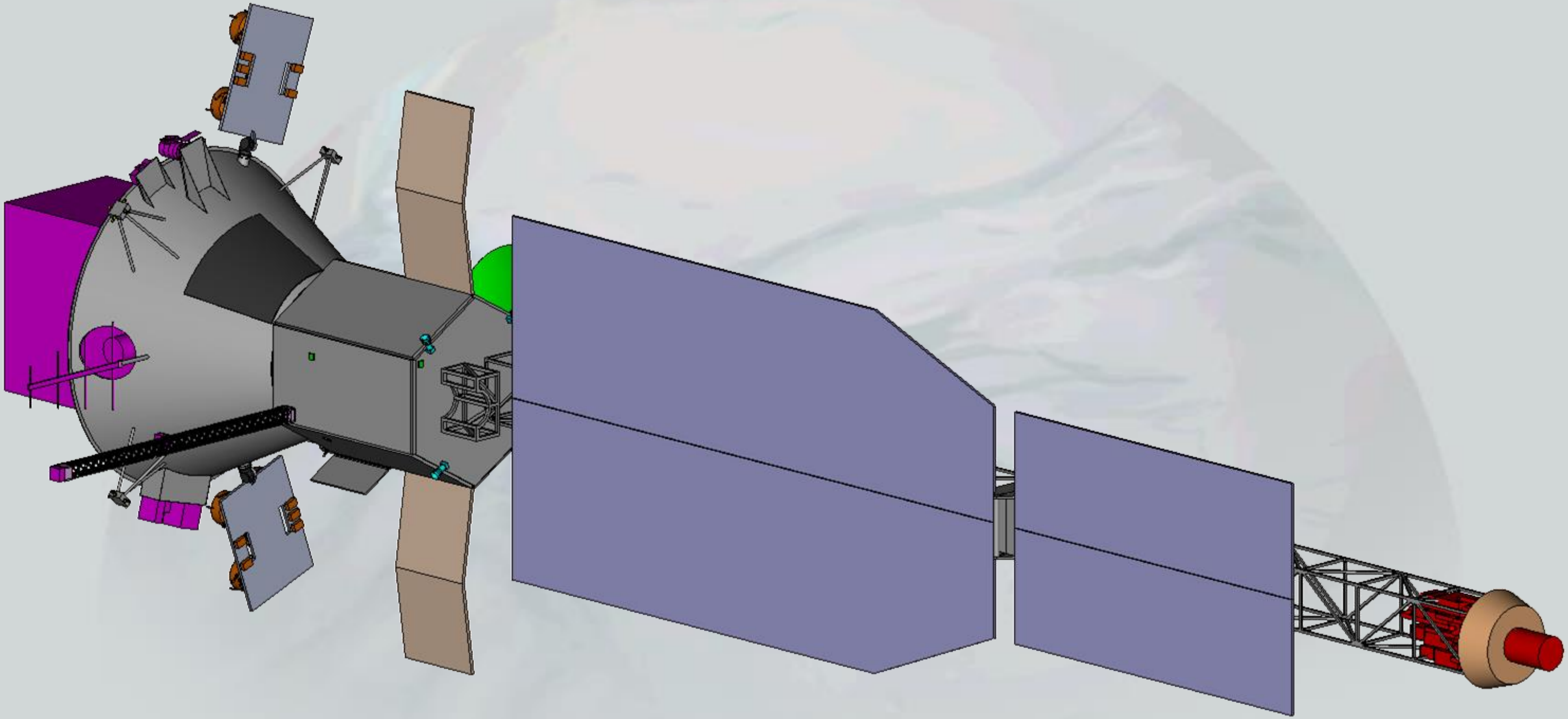
Various Adaptors for the ESR Vehicle



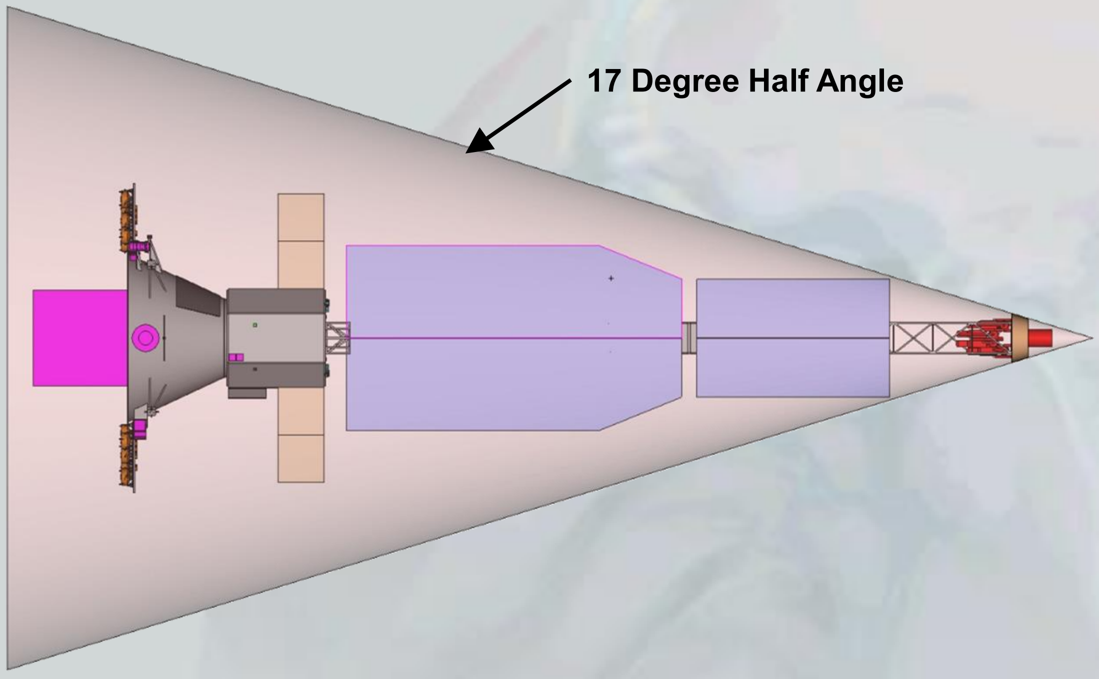
ESR Vehicle Configurations

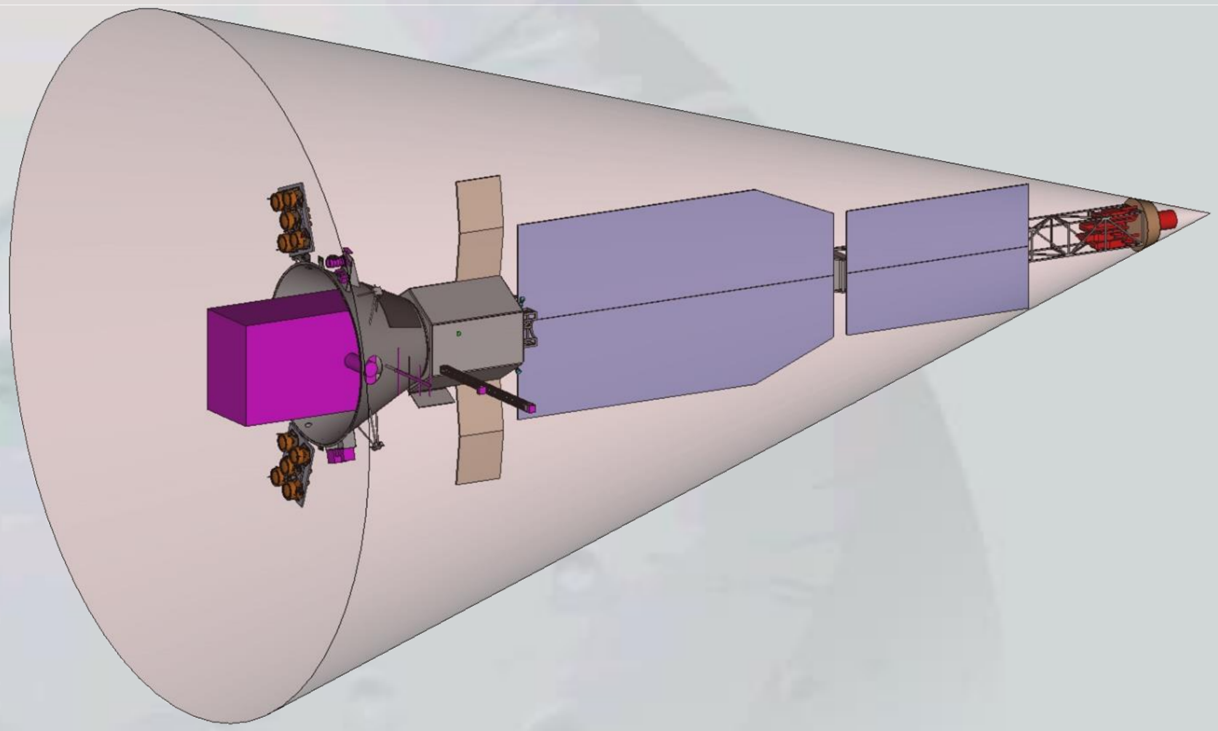


ESR Vehicle Deployed Configuration

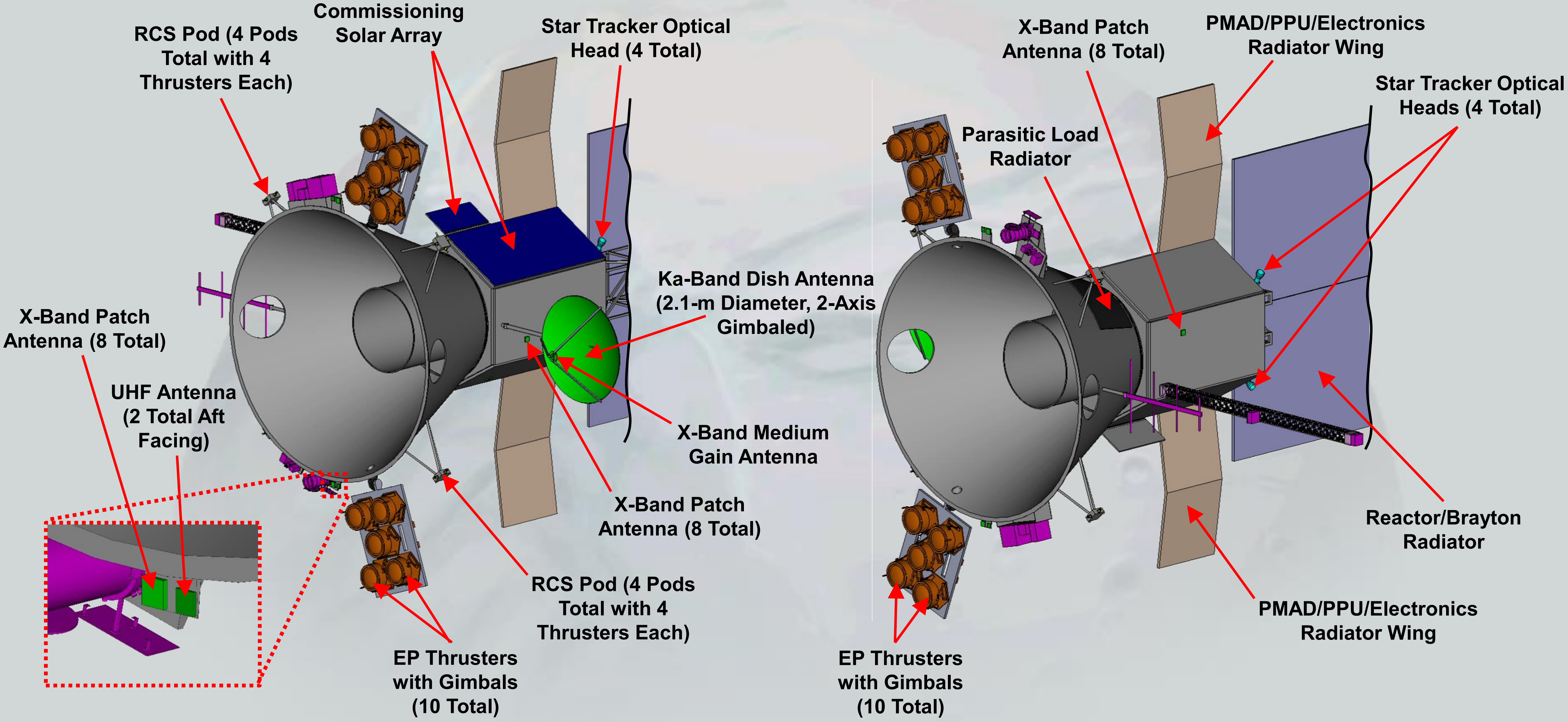


ESR Vehicle Reactor Shield Cone

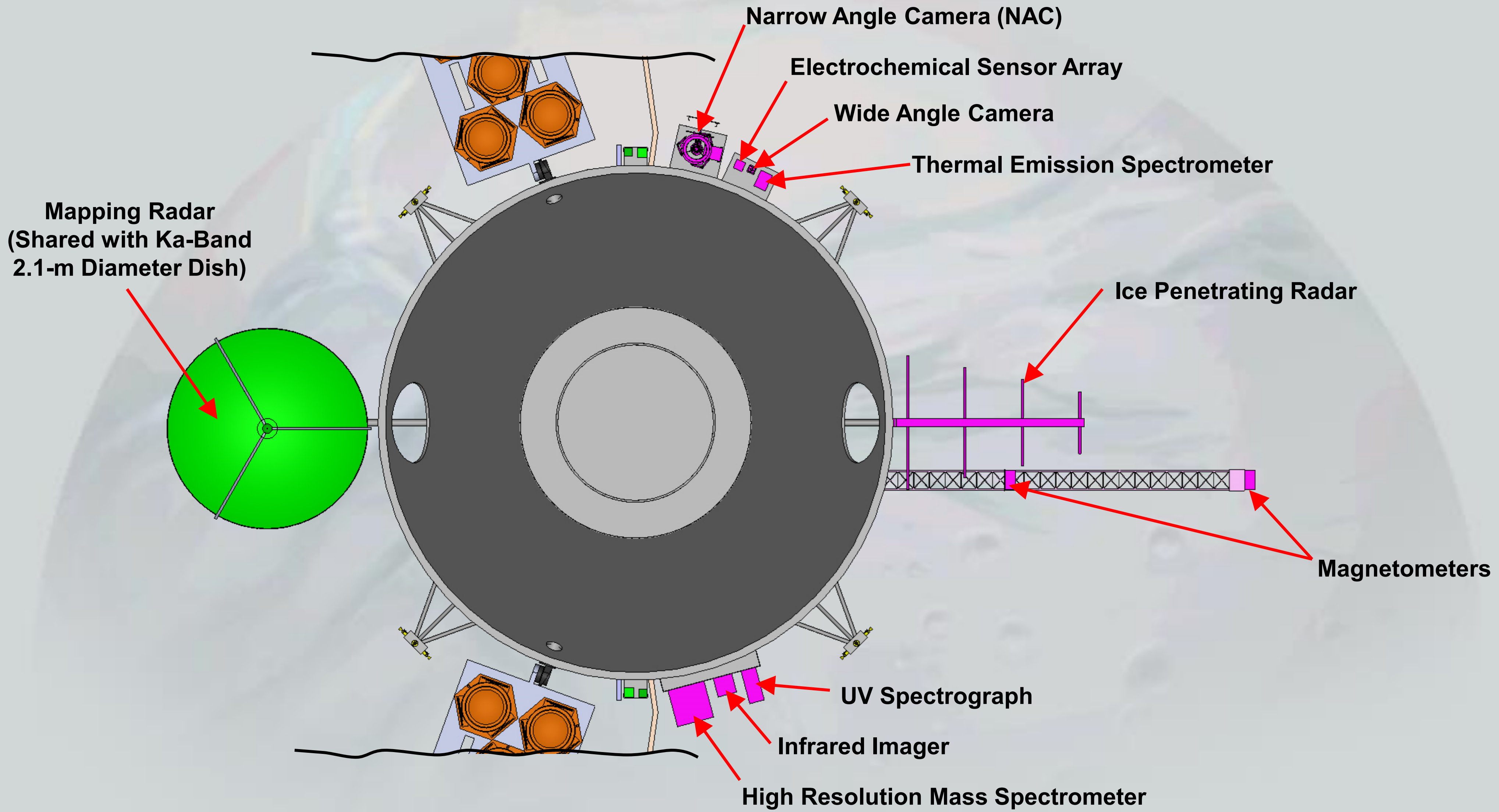




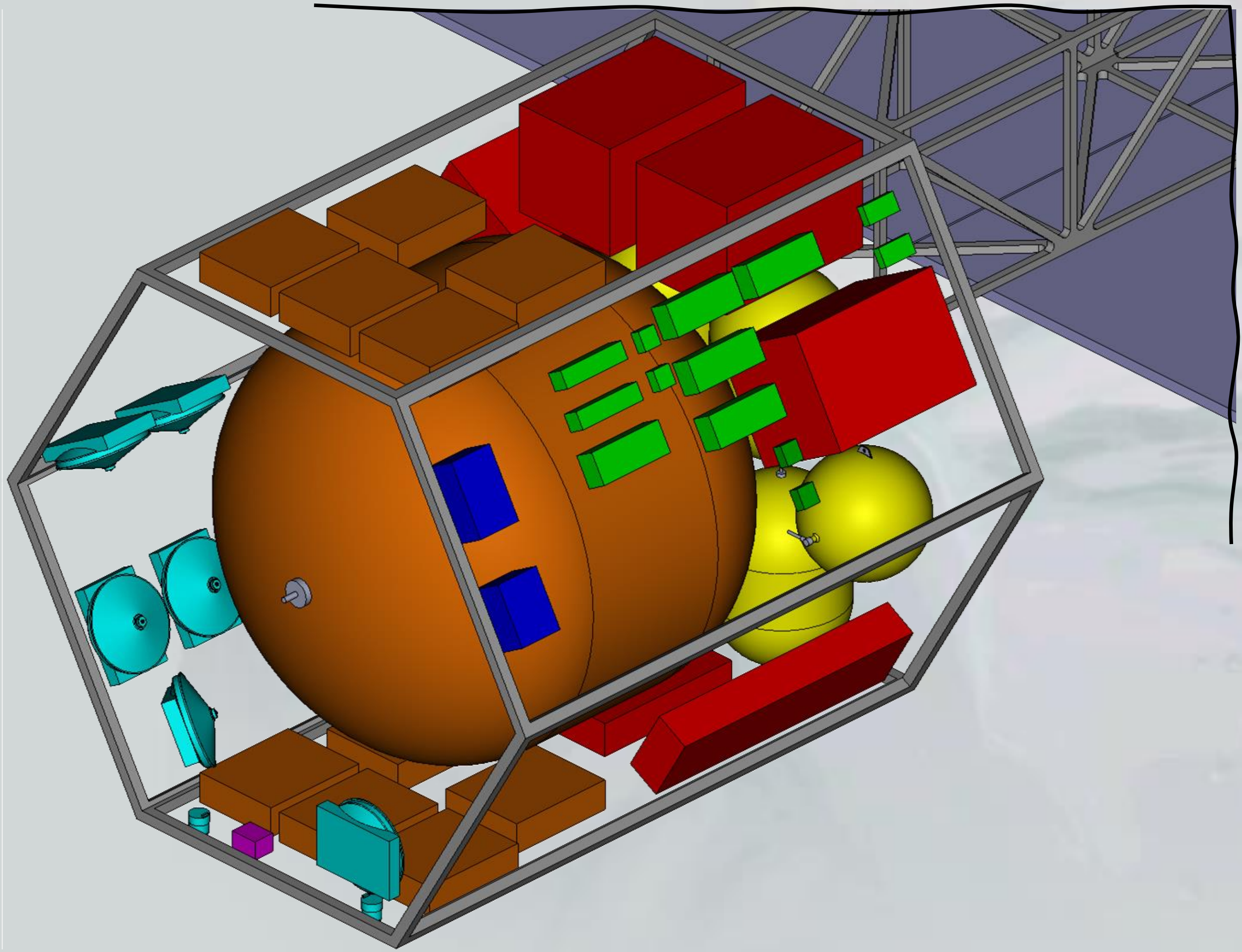
ESR Vehicle External Bus Components



ESR Vehicle Science Instruments



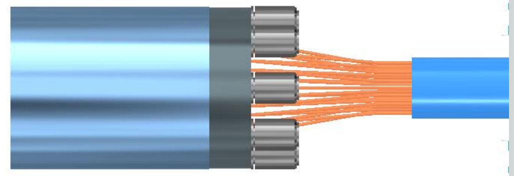
ESR Vehicle Internal Bus Components



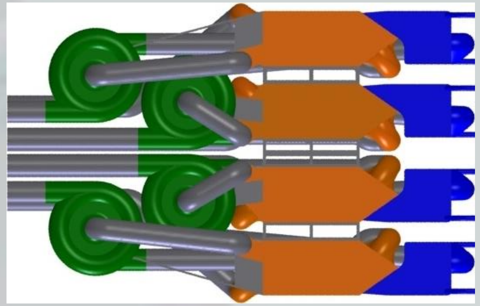
Subsystems:
EP System: Xenon Tank, PPU/DCIUs
Electrical Power: Power Electronics Boxes, Battery, Reactor PMAD
Communications: Ka-Band, S-Band, and UHF Electronics
Attitude Determination and Control: Reaction Wheels, IMUs, Star Tracker Electronics
Command and Data Handling: C&DH Enclosure and Driver Enclosure
Science: Magnetometer Electronics
RCS Hydrazine Tanks
Structures

44 kW NEP Power System

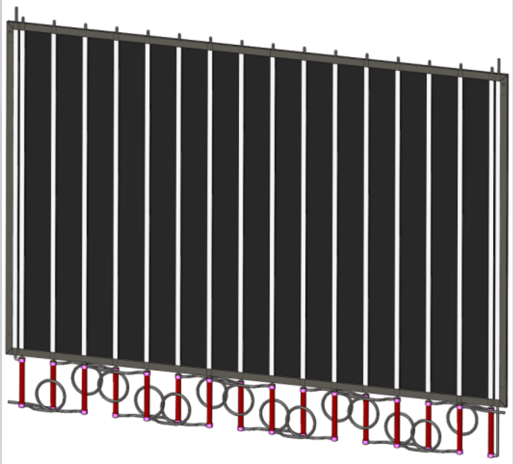
- **19.75% HALEU moderated reactor**, UN fuel, YH moderator, Na heat pipes, 1100K reactor supply temperature, 10 yr full-power design life
- **LiH/W shadow shield**, 10^{11} n/cm^2, 25 krad at 21.5 m separation, 17 deg half angle (~5 Mrad at 2m power conversion)
- **Four independent power strings** (PCS, HRS, PMAD) at 25% each; first fault results in no less than 75% power
- **HeXe Brayton power conversion**, four 12.8 kW converters, 1100K TIT, 390K CIT, 95% recuperator, 249 kWt thermal input, 21% conv efficiency
- **Pumped H_2O heat rejection**, fixed composite radiators with embedded Ti/H2O heat pipes, 193 kWt rejected, 504K Tin, 379K Tout, 0.09 kg/s per loop, 10% area margin, 4K sink, 157 m^2 total
- **240Vac/2 kHz/3Ø alternator** output converted to 120 Vdc at bus, 25m AC cabling, 91% efficiency, 323K/8.1 m^2 PMAD radiator, 950K/2.5 m^2 PLR
- **~4700 kg Baseline NEP Power System CBE mass**



Heat Pipe Reactor



Brayton Converter Assembly

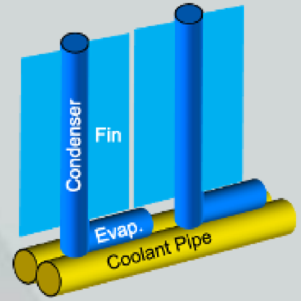


Composite Heat Pipe Radiator

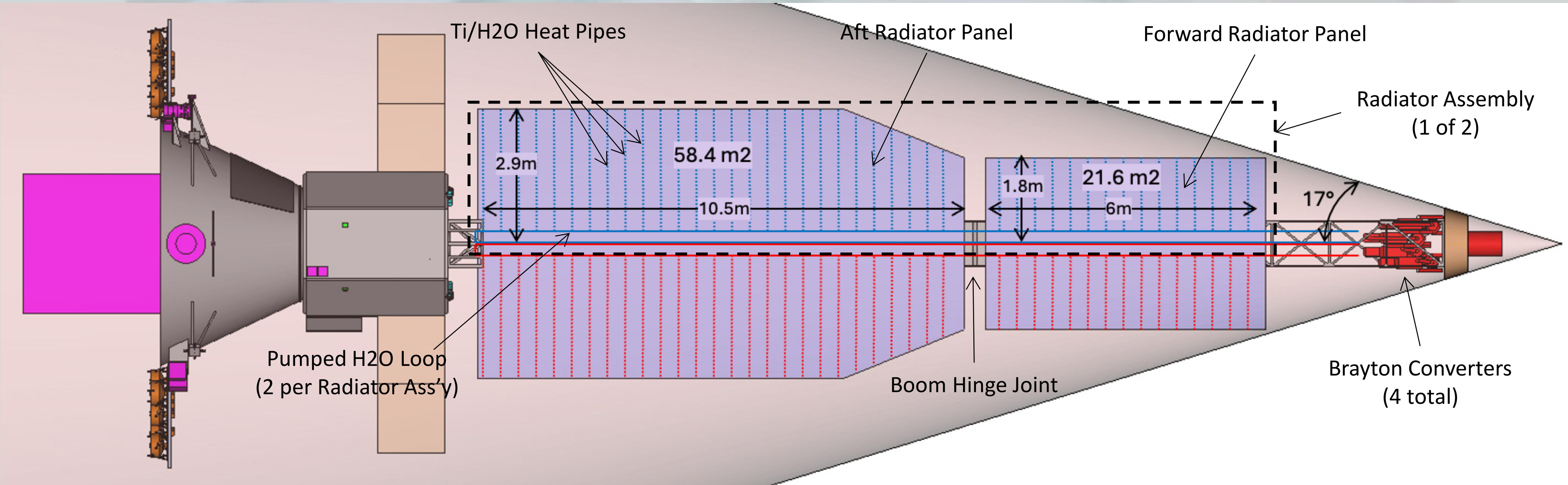
Radiator Configuration

- The main NEP heat rejection subsystem (HRS) includes two separate radiator assemblies
- Each radiator assembly includes a 22 m^2 forward panel and a 58 m^2 aft panel (separated by the boom hinge joint)
- The radiator panels include embedded Ti/H_2O heat pipes in a composite fin structure with two-sided heat rejection to an assumed 4K thermal sink
- Each radiator assembly includes two independent, pumped H_2O fluid loops that transfer the waste heat from two Brayton converters to the radiator heat pipes
- In the event of a Brayton converter or radiator fluid loop failure, the remaining Brayton can produce >25% power since the radiator is sized for two converters

Flexible Fluid Connectors at Boom Hinge

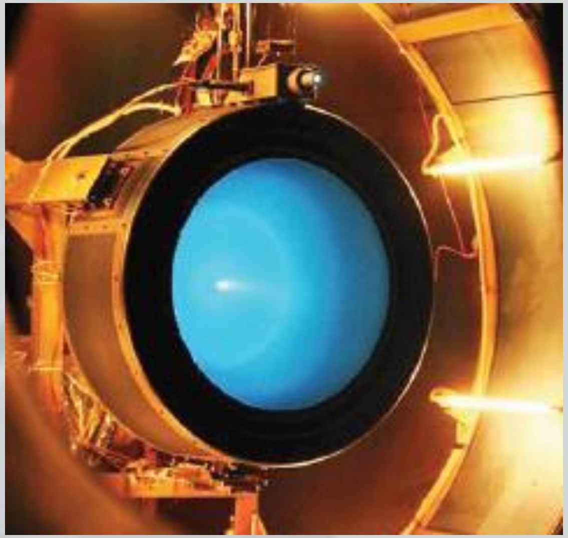


H_2O Loop & Radiator Integration

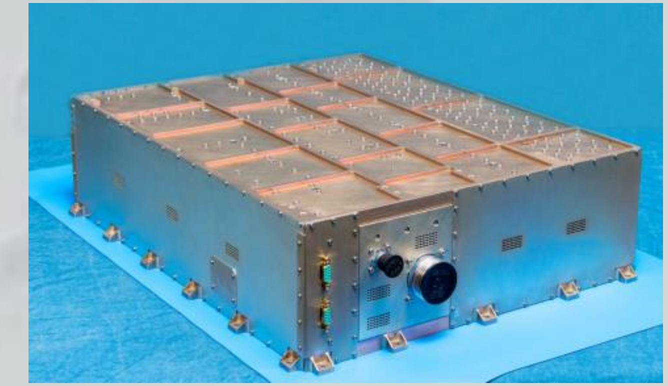


EP System Overview

- Ten NEXT-C Thrusters in 8+2 Configuration
- Thrusters Mounted on Two Panels Housing Five Thrusters Each
- NEXT-C Thrusters Mounted to Panels via Individual Gimbals
  - Three Strut Attachment to S/C Pannel
  - Provides Thruster Retention in Launch Position
  - +/- 19 Degrees in X-Axis, +/- 17 Degrees in Y-Axis
- Single 4,898 liter Supercritical Xenon Storage Tank
- Thrusters Operated at Nominal 4,000 s Isp, 4.5 kW
- Single 95% Efficient PPU per Thruster
  - Operates from 120V S/C Bus Power
  - Provides DCIU Functionality to Flow Controller



NEXT-C Thermal-Vacuum Testing

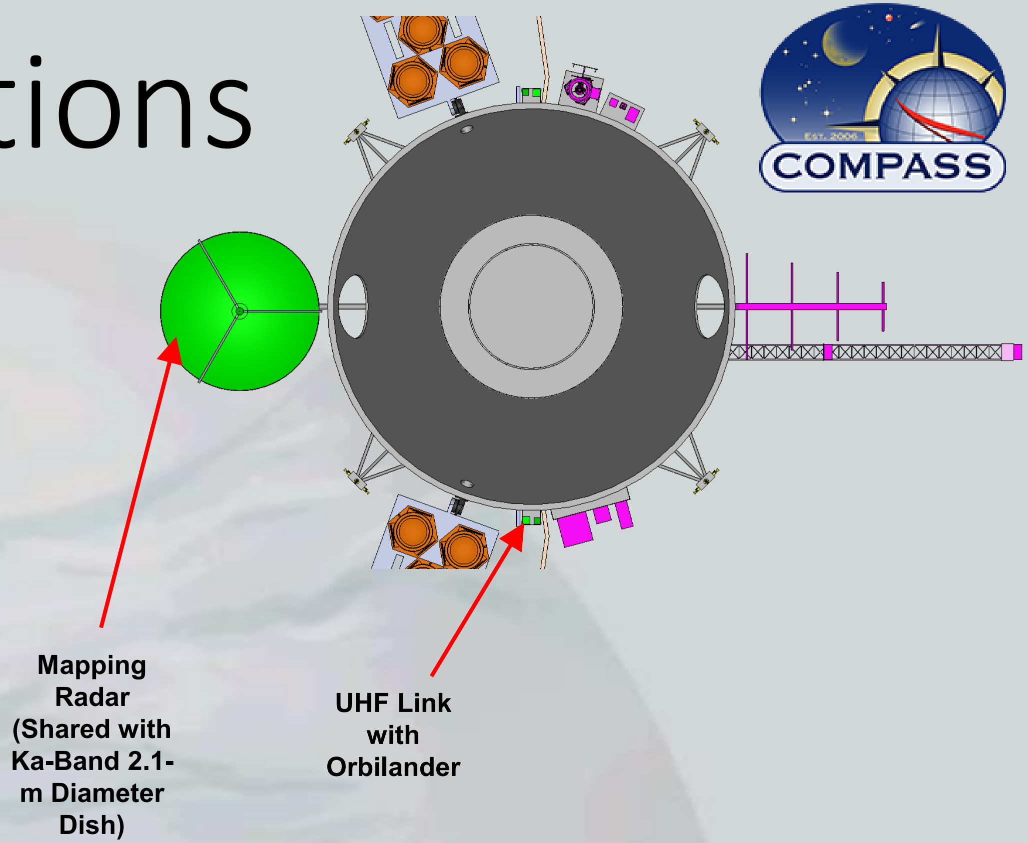


NEXT-C Power Processing Unit (PPU)

Communications

Comm Link Design:

- Ka-band high-gain antenna (HGA), for science data downlinks and X-band medium-gain antenna (MGA)
  - The HGA and MGA are co-bore sighted mounted, deployable reflectors, two–axis gimbal mechanism that allows for pointing toward Earth while on the surface.
  - 200/500 kbps w Ka-band (2.1 m antenna) DTE 11 AU
  - 2 kbps w x (0.5 m antenna) DTE 11 AU
  - 20 bps DTE 11 AU x-patch for EMS comm
- X-band Patch low-gain antennas (LGAs), 8x
  - Starting w the Orbilander (~2.1m dish) for NEP vehicle,
    - More power/Bigger or smaller Dish for higher rate
- UHF- band Antennas for uplink from lander
  - @ 4 Mbps UHF from Orbitlander to SERENE 1 hr per orbit (13.5 hr) can return ~14 Gb of data thru SERENE over a single 8hr Ka Band 500 kbps pass to DSN
- Single fault tolerance (when practical)



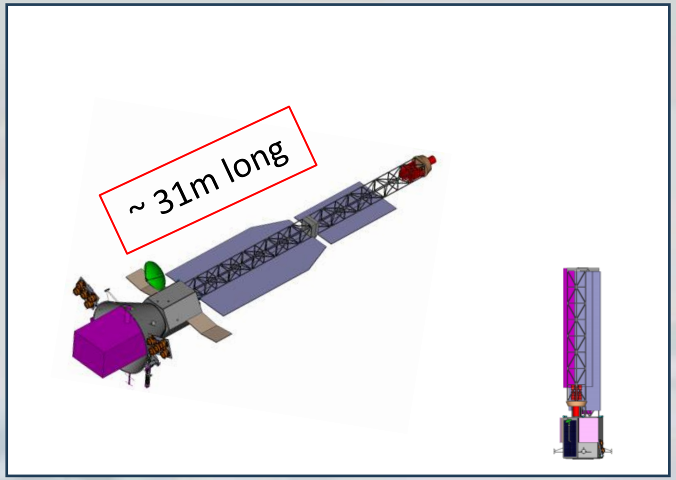
Comparison of Mission Options

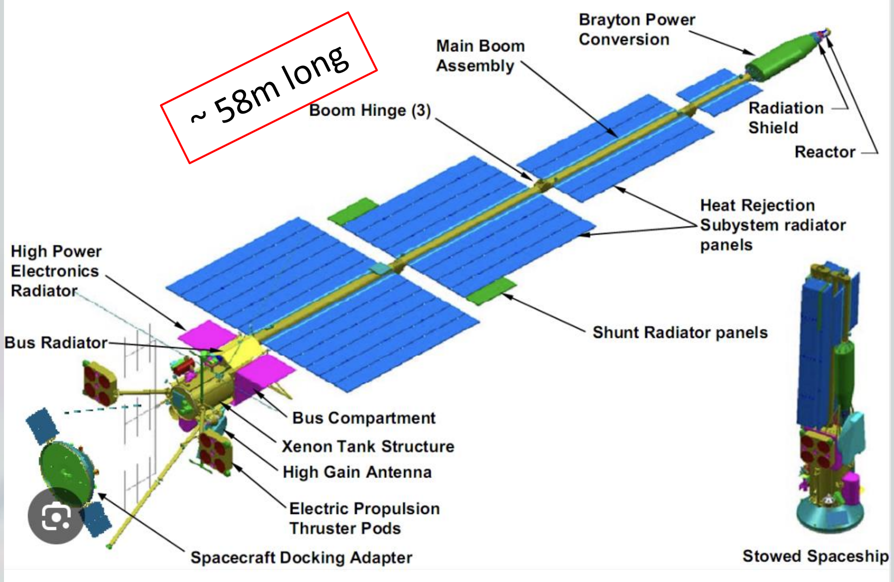
(2023Accelerating Space Science with Nuclear Technologies Workshop asks)

Option * Low thrust ΔVs are usually higher than impulsive BUT Isps are >10X higher ** IF a more capable radar is added the data returned is 29 Tb	NEP Round Trip	NEP/Chem Split (NEP w chem return & Moon Orbiting tours)	Chem Round trip (2-stage)
Use in concert with new large commercial rockets (Starship w x Tankers)	√ (15 tankers)	√(15 tankers)	√(17 tankers)
High DV destinations	~20 km/s*	~18/2.5 km/s*	1.89 / 2.4 km/s
Enabling much higher capability orbiters *and* landers		√	
Significantly reducing trip times	√ (~ 16.5 yrs)	√ (~18.5 yrs)	(~21.5 yr)
Sample return	√	√	√
Increase launch window flexibility by reducing or eliminating the need for gravity assists.	√	√	JGA (every ~ 20 yrs)
Increase communication rates	√ (>5-12X)	√ (>5-12X)	
Ground penetrating radar systems: icy moons/subsurface ice/liquid interface	√	√	
Enabling the delivery and landing of capable vehicles on the ocean worlds	√	√	√
40 kW provided significant improvements in trip time and delivered mass	√	√	N/A
Maximizing commonality between FSP and NEP subsystems (Time @ full power)	√ (9 yrs)	√ (9 yrs)	N/A
Nuclear architectures may enable missions to reach multiple destinations		√ (orbit multiple moons)	N/A
Data Returned	Sample & 0.7 Tb	Sample & 3 Tb**	Sample & 0.5 Tb

SERENE and JIMO

By using assumed OTS lunar surface power reactor and electric propulsion SERENE provides a more affordable option for deep space science

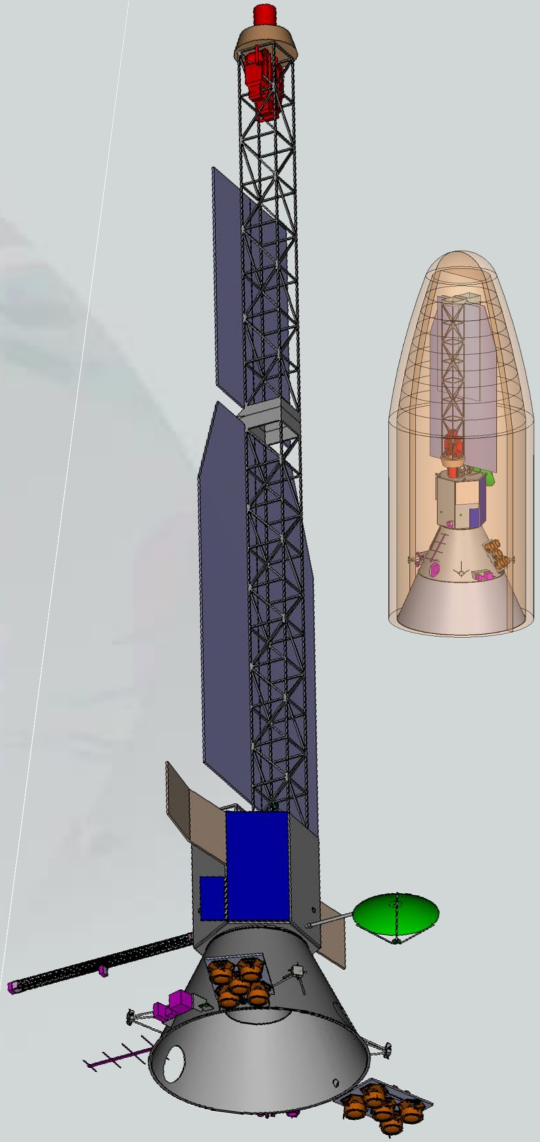




	SERENE (Saturn Sample return and Moon tour)	JIMO (Jupiter moon tour)
Reactor Power/source	44 kWe / FSP derivative	100 kWe / New design
Electric Propulsion	4000s, 7 kW NEXT Ion (flown)	New Ion: 8000s, 25 kW; New 50 kW Hall
Mass (wet, w lander)	~ 26t	~36 t
Mass (dry)	~ 11t	~ 16t
Reactor mass	~ 4t	~ 6t
Payload (includes 6.6t lander)	~6.8t	~1.5t
Launchers	1 Starship + 15 tankers	3 Delta IV Hs

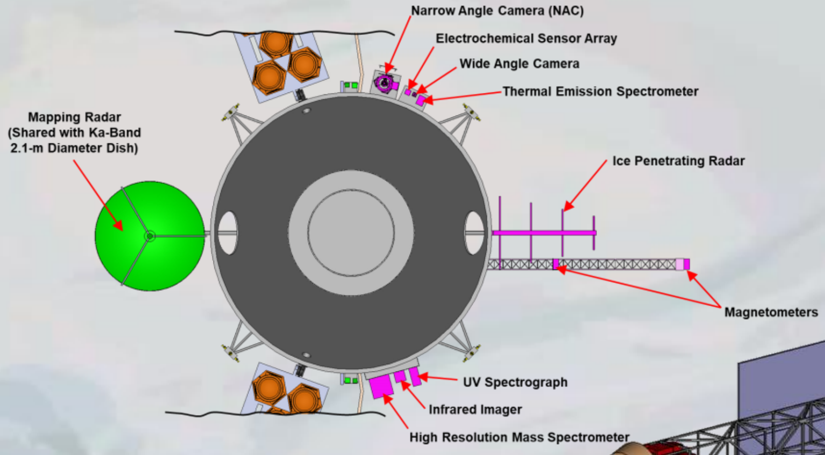
Lessons Learned

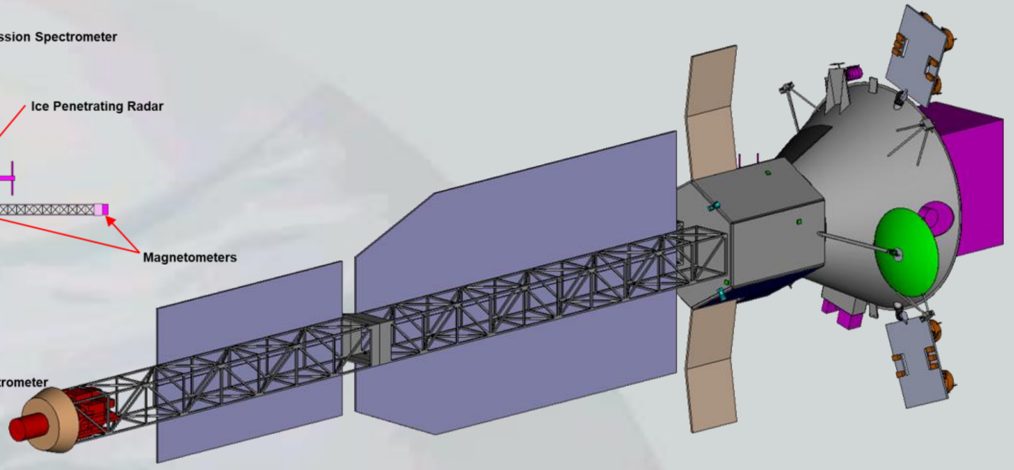
- A 40-kW-class NEP vehicle using the Lunar/Mars Fission Surface Power system, when used in combination with new, commercial launch systems was found to *enable* an Enceladus mission which:
  - Was quicker than an all-chem mission
  - Could be launched any year (all-chem requires a Jupiter gravity assist)
  - Could either return a sample in ~**16 yrs** from launch OR return the sample chemically in ~**18 yrs** from launch while staying at Saturn, orbiting four more moons (including Titan)
  - Can carry a 6.5t lander
  - While not adding large amounts of science instruments, can apply those instruments to 5x the number of moons
    - Can carry both ice-penetrating and surface mapping radars
  - Increased communication rates by 5-10 x
- The flown NEXT ion propulsion system was found to adequately propel the vehicle
- A 40-kW-class vehicle can be carried in a Starship, fully fueled and with only one boom fold, no additional reactor radiator deployments are required
- Impact of increasing reactor technology (temperature and materials) didn't show notable impact– *Quick mission investigation showed same ToF and ~700 kg less propellent*
- A separate, 750 kW NEP Mars exploration vehicle could perform the sample round trip in 11 yrs

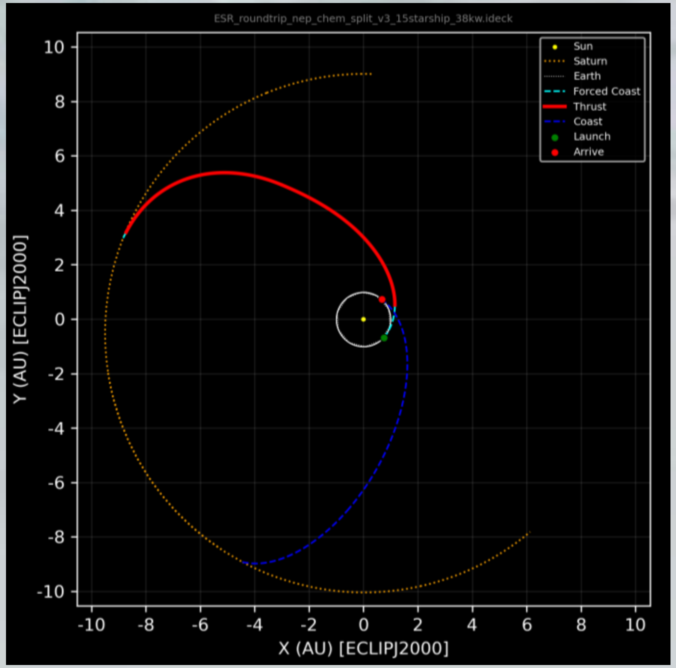


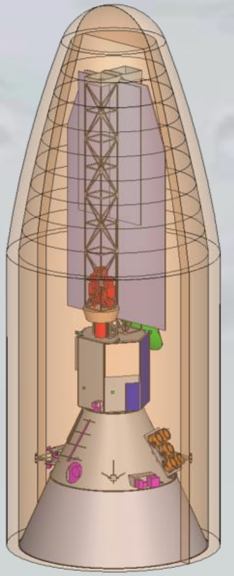
Saturn Enceladus Return Explorer with Nuclear Electric Propulsion – Executive Summary

- **Mission**: 40 kWe Class NEP Vehicle that delivers a ~6.6 t lander (Orbilander basis)/return vehicle to Enceladus to conduct a science/sample return mission. First science returned 5 years after launch with Sample return at launch +18.5 yrs. Conducts moon science tour of Saturn system.
- **Launch**: 2033, Starship, Extended Fairing, 15 Starship tankers refuel at 2000 km to give departure C3 of ~93 km^2/s^2
- **Science**: Vast science suite on lander and orbiter, to characterize surface and atmosphere, and search for cells/genetic materials.
- **Power**: 44 kWe HALEU reactor based on NASA Fission Surface Power System (planned 2030), Four Brayton convertors, ~2.3 kW for Bus, 25 krad shield
- **Electric Propulsion**: 9 +1, 4.5 kWe (derated) NEXT-C Thrusters, ~9000 kg Xenon propellant Load, stored in single COPV 2.12 m tank, single set point PPU (95%)
- **Thermal**: Boom attached, reactor radiators, deployable electronics/PPU radiators, MLI and Heaters
- **Mechanical**: Hexagonal Bus, Jack-knife extendable reactor boom
- **Communications, C&DH**: Ka-Band- up to 500 kbps Data rate from Saturn, 2.1 m Antenna, X-band backup comm, UHF comm with lander, 8 Tb non-volatile storage
- **AD&C**: 4 Star Trackers, 2 IMUs, 6 reaction wheels, Hydrazine propulsion RCS









MEL Summary: Case 1_Enceladus Sample Return CD-2025-225	NEP Vehicle	Orbilander	Sample Capsule	TOTAL
Main Subsystems	Basic Mass (kg)	Basic Mass (kg)	Basic Mass (kg)	Total Basic Mass(kg)
Science	171.8	1909.0	49.4	2130.2
Attitude Determination and Control	82.8	0.0	0.0	82.8
Command & Data Handling	84.2	0.0	0.0	84.2
Communications and Tracking	48.9	10.1	0.0	59.0
Electrical Power Subsystem	4170.5	0.0	0.0	4170.5
Thermal Control (Non-Propellant)	1064.3	0.0	0.0	1064.3
Propulsion (Chemical Hardware)	115.7	0.0	0.0	115.7
Propellant (Chemical)	475.1	3920.0	0.0	4395.1
Propulsion (EP Hardware)	1059.2	0.0	0.0	1059.2
Propellant (EP)	9124.4	0.0	0.0	9124.4
Structures and Mechanisms	1400.0	0.0	0.0	1400.0
Element Total	***17796.9***	***5839.1***	***49.4***	***23685.4***
Element Dry Mass (no prop,consum)	8197.4	1919.1	49.4	10165.9
Element Propellant	9599.5	3920.0	0.0	13519.5
Element Mass Growth Allowance (Aggregate)	1587.0	294.4	8.4	1889.8
MGA Percentage	19%	15%	17%	19%
Predicted Mass (Basic + MGA)	9784.4	2213.5	57.8	12055.7
System Level Mass Margin	1229.6	543.1	7.4	1780.1
System Level Growth Percentage	15%	28%	15%	18%
Element Dry Mass (Basic+MGA+Margin)	11014.0	2756.6	65.2	13835.8
Element Inert Mass (Basic+MGA+Margin)	11673.2	2771.6	65.2	14509.9
Total Wet Mass (Allowable Mass)	***20613.5***	***6676.6***	***65.2***	***27355.3***


NASA
COMPASS