ADVANCED
CONCEPTS

Applications of Nuclear Thermal Propulsion Systems for Deep Space Science Missions

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Overview

- Background
- Current Study Progress
- Future Work

Background

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Background

- Nuclear Thermal Propulsion (NTP): A propulsion system that uses the thermal energy from a nuclear fission reactor to heat propellant, which is then expanded out of a nozzle

- NTP Engines were ground tested in the 1960s and 1970s as potential engine candidates for Apollo missions

- U.S. Congress passed appropriations bill in February 2019
- Included language:
  - "[…] not less than $100,000,000 for the development of nuclear thermal propulsion, of which not less than $70,000,000 shall be for the design of a flight demonstration by 2024 for which a multi-year plan is required by both the House and the Senate within 180 days of enactment of this agreement."

- As part of plan for NTP development, NASA MSFC's Advanced Concepts Office directed to explore design reference missions (DRMs) that evaluate the mission-enabling capabilities of NTP for science missions

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NTP Vehicle Trade Space

Reactor Temperature

Low
(1876 K)

Medium
(2216 K)

High
(2586 K)

Propellant Type

Hydrogen
Highest performance

Ammonia
No cryo requirements, good packing density

Hydrogen CFM

Active
Provides mission planning flexibility

Passive
Avoids inert mass of active cooling system

Vehicle Staging

NTP + Chemical Stage
Optimal staging for max ΔV

NTP Single Stage
Subsystems shared with payload, NTP performance for all burns

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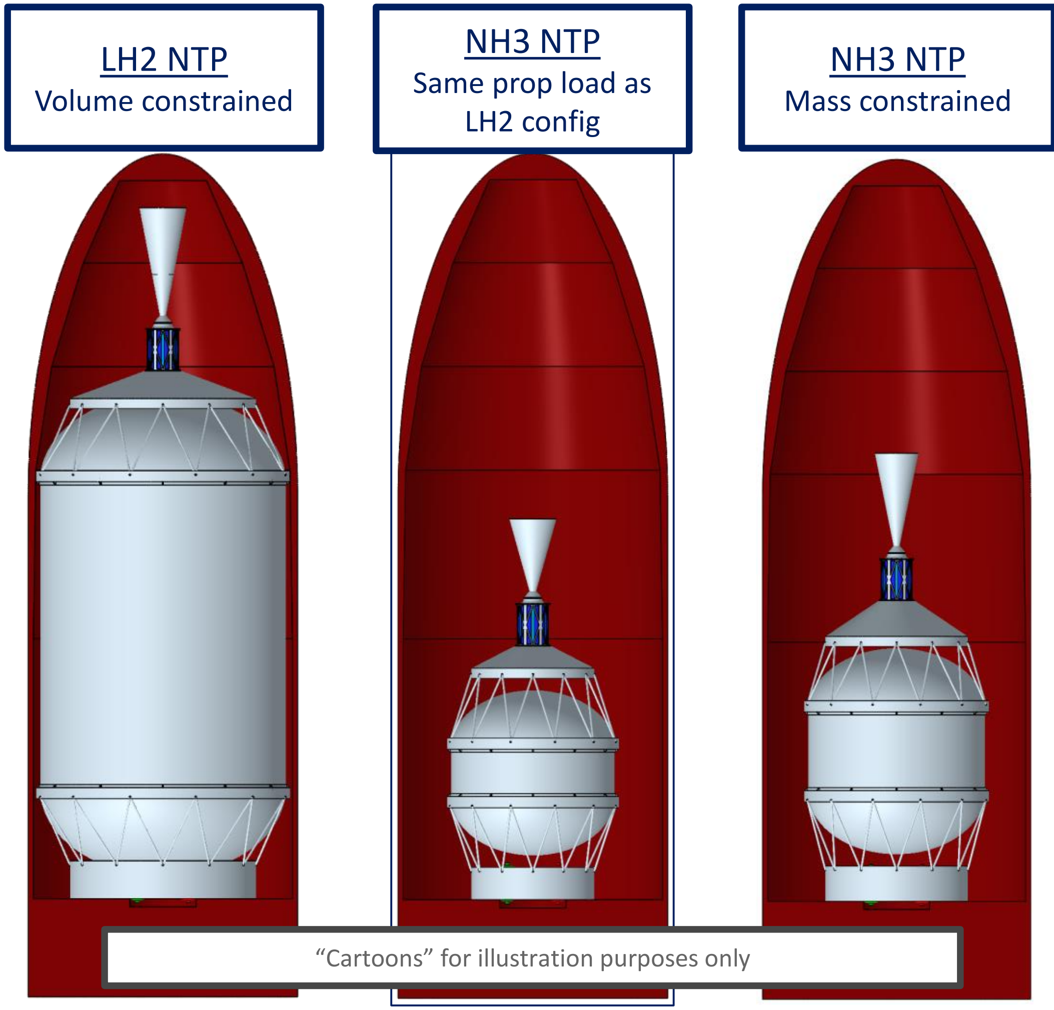
NTP Propellant Trade

- The low molecular weight of hydrogen allows the highest specific impulse for NTP
  - Low density leads to volume-constrained vehicles
- An ammonia-fueled NTP has about half the specific impulse as hydrogen at the same reactor temperatures
  - Higher density means the vehicles are typically mass constrained
  - Storable without an active cryogenic fluid management (CFM) system



LH2 NTP
Volume constrained

NH3 NTP
Same prop load as LH2 config

NH3 NTP
Mass constrained

“Cartoons” for illustration purposes only

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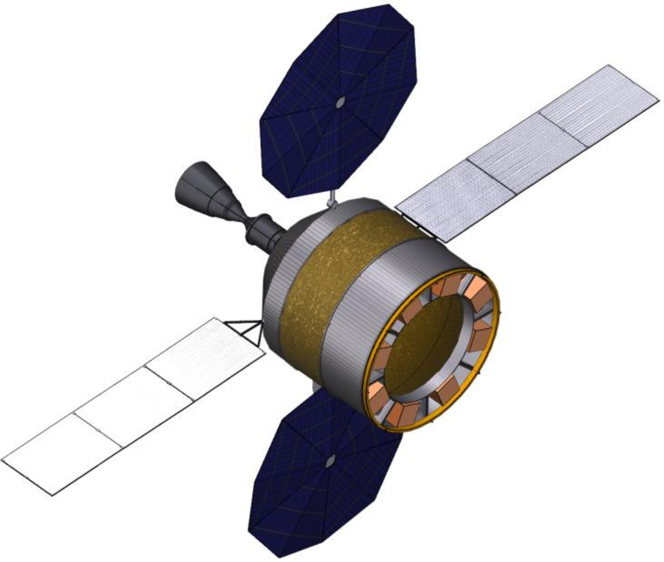
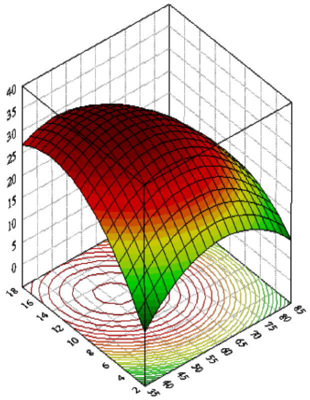
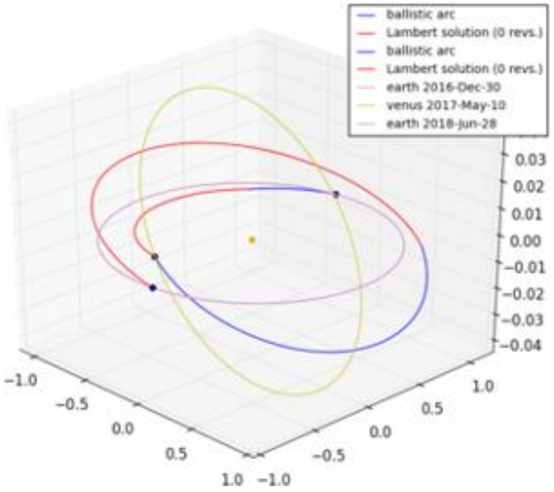
Mission/vehicle Methodology



- Vehicle Trade Space
  - Vehicle Sizing Models
  - Vehicle Sizing Surrogate Models
- Mission Trade Space
  - Trajectory Modeling
  - Preliminary Mission Optimization
- Integrated Optimization
- Reference Mission Refinement



“Surrogate” Model



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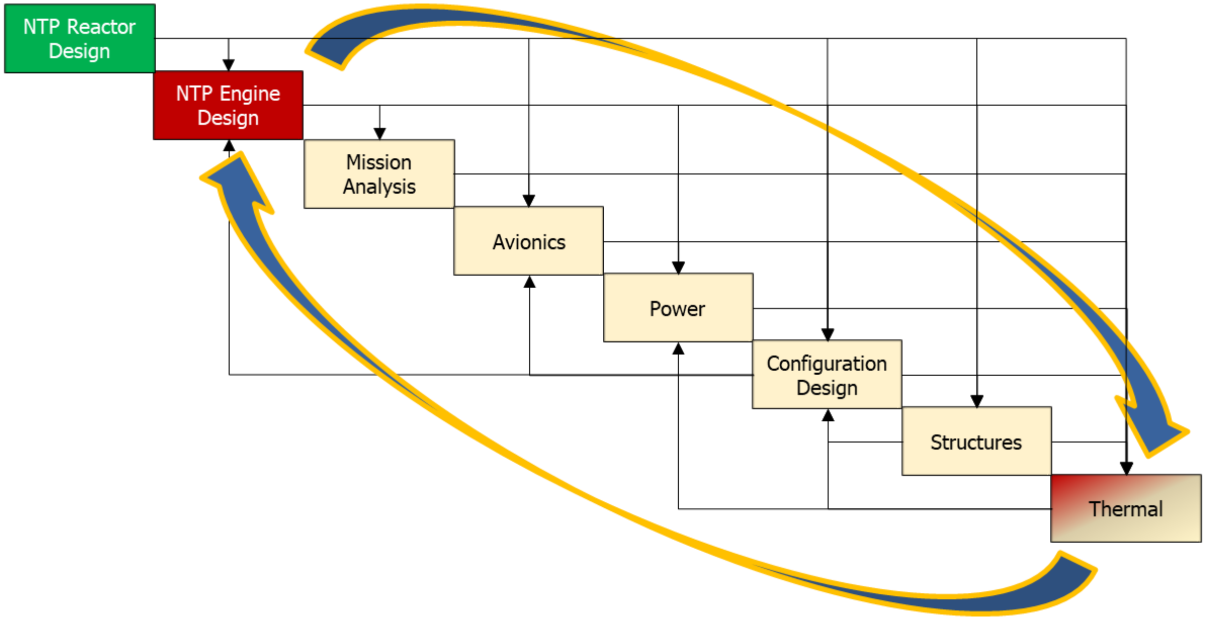
Vehicle Modeling

- Dynamic Rocket Equation Tool (DYREQT) used for modeling the NTP vehicle
- DYREQT is written in Python upon the Open Multi-Disciplinary Analysis and Optimization (OpenMDAO) framework
- Trade space is populated with specific assumptions for each mission as appropriate
- Surrogate model generated from DYREQT outputs
- New Glenn and SLS Block 2 (8.4m fairing) considered



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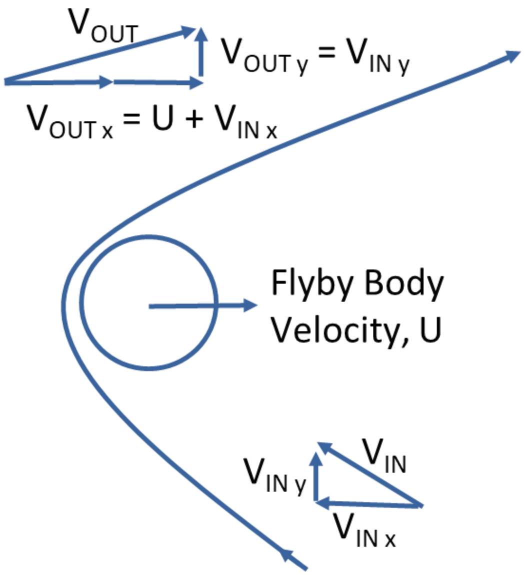
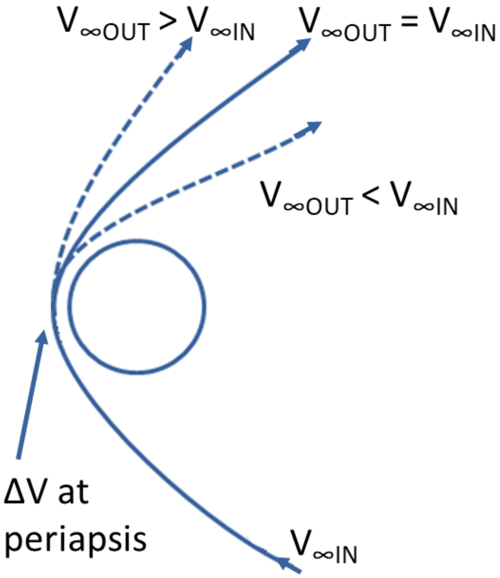
Trajectory Modeling

- Because of high energy requirements for the selected DRMs, direct trajectories from Earth are impractical
  - Necessitates use of gravity assist trajectories for energy changes, velocity alignment, and/or inclination changes

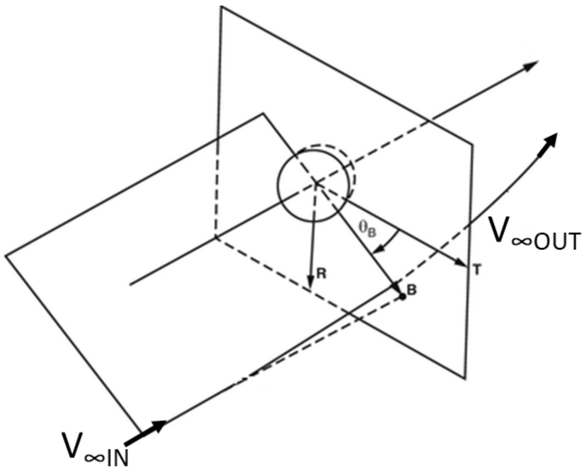
Flyby Body Ref. Frame



Heliocentric Ref. Frame



Powered Flyby Body Ref. Frame



Flyby Body Ref. Frame
with B Plane

Current Study Progress

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Study Progress

- Several DRMs examined as part of NTP science mission portfolio
  - Uranus Orbiter Mission
    - Delivers orbiter payload to Uranian space
    - Can consider similar orbit configuration as Triton mission, featuring moons like Mimas or other moons of interest
  - Jupiter Orbiter Mission
    - Similar to Uranus orbiter mission; may consider payloads/landers to Galilean moons or others of interest
  - Triton orbiter/lander mission
    - Involves entering Neptunian space and deploying an orbiter/lander payload on Triton
    - Derived from baseline reference that had used Delta IVH and SEP system
    - Includes storable chemical propulsion 2nd stage in tradespace
    - Insert into high-elliptical orbit aligned with Triton; Inclination/periapsis alignment with Triton at apoapsis
  - Solar Polar Orbiter Mission
    - Involves deploying a heliophysics payload in a polar orbit over the Sun
    - Involves multiple gravity assists from Jupiter and Venus to assist in solar orbit circularization and generating sufficient energy to insert into solar polar orbit
  - Interstellar Probe Mission
    - Sends a science payload into deep space (>100 AU) to measure particle properties of solar winds and interstellar medium, heliosphere bow shock and other particle/magnetic field interactions
    - Derived using previous in-house studies on interstellar medium missions featuring NTP vehicles
    - Requires high energy for solar system escape, likely via Oberth maneuver

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Jupiter Orbiter Results

	Fast Transfer SLS Mission	Max Payload CLV Mission
Launch Vehicle	SLS B2	New Glenn
Earth-Jupiter Transfer Type	Fast-transfer, direct	Earth Gravity Assist
Earth-Jupiter Transfer Time	**1.2 years**	4.9 years
NTP Payload Capability	**4,000 kg into Jovian orbit**	**10,850 kg into Jovian orbit**
Conventional Payload Capability	1,120 kg into Jovian orbit	4,450 kg into Jovian orbit
NTP Payload Benefit	**3.6x conventional capability**	**2.4x conventional capability**

- NTP vehicle could deliver a payload approximately ***twice the size of the Juno mission***, into Jovian orbit in a fast-transit
- Comparable solid propulsion configuration featuring Star 48BV stages would only deliver approximately 1,120 kg, vs. 4,000 kg for the NTP vehicle

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Uranus Orbiter Results

	Fast Transfer SLS Mission	Max Payload CLV Mission
Launch Vehicle	SLS B2	New Glenn
Earth-Uranus Transfer Type	Fast-transfer, direct	Venus-Earth-Earth-Jupiter Gravity Assists
Earth-Uranus Transfer Time	**7.6 years**	12.0 years
NTP Payload Capability	**4,350 kg into Uranus orbit**	**14,900 kg into Uranus orbit**
Conventional Payload Capability	1,260 kg into Uranus orbit	6,800 kg into Uranus orbit
NTP Payload Benefit	**3.5x conventional capability**	**2.2x conventional capability**

- Similar payload performance for fast-transit option as Jupiter NTP mission, but with longer mission time (***still shorter than baseline in Decadal Survey by 4.4 years***)

- Comparable solid propulsion option with Star 48BV engines results in 1,260 kg vs. 4,350 kg for NTP fast-transit option

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Triton Results

Propellant/ Launch Vehicle	1^{st} Stage ΔV [km/s]	Capture Stg ΔV [km/s]	1^{st} Stage Prop [kg]	1^{st} Stage Burn Out Mass [kg]	Capture Stg Prop [kg]	Capture Stg Burn Out Mass [kg]	Aero-capture/ brake	Payload to Triton Orbit [kg]	Triton Payload÷ Baseline	Triton Payload w/o Orbiter [kg]
Baseline Delta IV Heavy	7.01	2.11	2,610 Xe	1,600	1,233	NA	Yes	1,115	Baseline	NA
NH_3 SLS 2B	5.03	2.28	40,620	5,730	6,560	1,950	No	3,530	**3.17x**	4,190
LH_2 New Glenn	5.63	2.53	16,950	11,330	4,220	1,410	No	1,350	**1.21x**	1,980
LH_2 SLS 2B	5.14	1.68	28,090	17,090	7,650	2,180	No	8,000	**7.17x**	8,620

- Payload without Neptune orbiter shown for potential alternative architecture
- Using a comparable commercial launch vehicle, NTP can deliver more payload than the baseline without the use of an aeroshell

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Solar Polar Orbiter Results

- Mission profile requires spacecraft to handle large heat loads, and places a premium on observation time
  - Both impact spacecraft performance and delta-V budget for mission

- Minimum energy solutions had mission times that were deemed infeasible
  - These solutions did not include the final circularization energy required, which would drive the mission times further out

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Interstellar Probe Results

Vehicle	Flyby Sequence	Escape V [AU/y]	Years to 100AU	Departure Date	Escape Man. Date	CFM Req.	Case Notes
LH_2 / SLS 2B	E,V,V,E,J,Sun	14.8	16.4	9/2/2038	5/27/2048	N	Max Escape V
LH_2 / SLS 2B	**E,J,Sun**	**13.9**	**10.1**	**11/27/2039**	**11/20/2042**	**N**	**Soonest to ISM**
NH3 / SLS 2B	E,M,E,J,Sun	14.1	15.5	2/16/2039	7/30/2047	N	NH_3 Max V
LH_2 / NG	E,V,V,E,Sun	13.3	16.3	2/4/2031	1/4/2040	Y	Commercial Max V
LH_2 / SLS 2B	E,Jupiter	9.1	11.7	3/3/2031	2/2/2032	N	No Solar Shield
Chem. Baseline	E,Jupiter	8.6	est. 12.3	9/2/2038	5/27/2048	N	No Solar Shield
Chem. Baseline	E,J,Sun	12.6	---	~7/2034	Unknown	N	
STP Baseline	E,J,Sun	19.1	est. 14.5	2/16/2036	5/25/2045	Y	Max non-NTP V

- While a STP system can deliver the highest escape velocity, an NTP system can deliver the shortest time to 100AU

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Future Work

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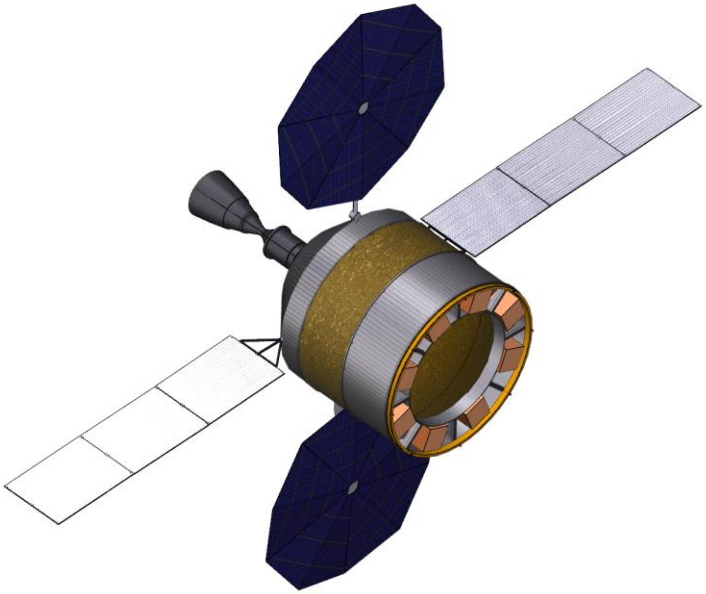
Future Work

- Updates to existing selection of launch vehicles
  - Performance and availability/cadence updates based on new vendor data
- Expansion of existing LV tradespace
  - Incorporating additional future LVs capable of handling NTP payload
- NTP vehicle performance updates
  - Updates to vehicle subsystems and subsystem performances
    - Reactor updates, alternate thruster considerations
    - Power systems and structural systems updates
    - Some subsystems updates are LV-dependent, thus impacted by LV tradespace changes
- Mission selection updates
  - Analyses of other deep-space science missions of interest as those are identified
    - Potential future missions of interest: Trojan asteroid orbiter, planetary defense/impactor, long-duration survey missions, and more
- Further study refinements
  - Updates to mission design models and development of tools to optimize spacecraft systems; incorporate subsystem changes such as alternate NTP engine configurations



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