Versatile Nuclear Thermal Propulsion (NTP)

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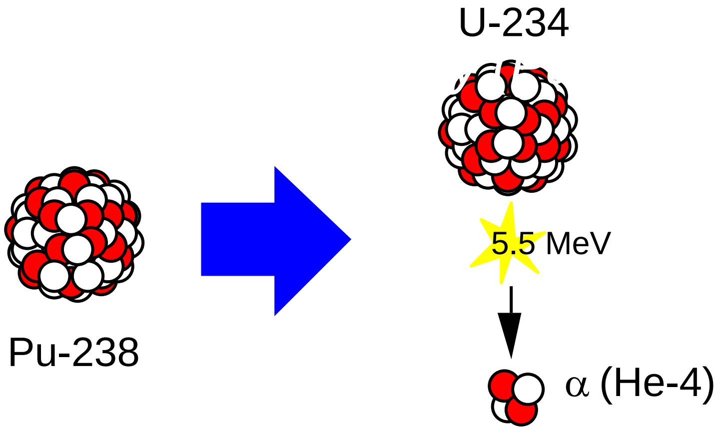
Nuclear Thermal Propulsion (NTP)

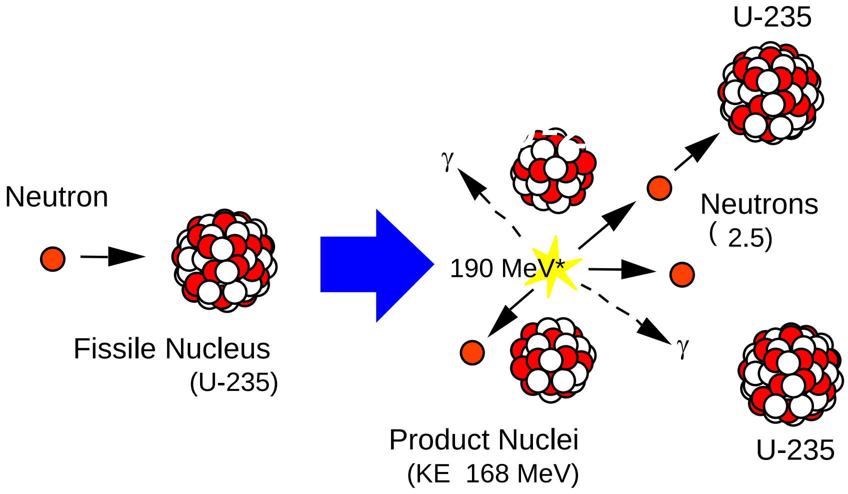
- For human Mars missions, NTP can reduce crew time away from earth from >900 days to <600 days while still allowing ample time for surface exploration.
  - Reduce crew exposure to space radiation, microgravity, other hazards.
- NTP can enable abort modes not available with other architectures.
  - NTP provides option to return to earth anytime within 3 months of earth departure burn, and option to return to earth immediately upon arrival at Mars.
- Stage/habitat optimized for use with NTP could further reduce crew exposure to cosmic rays and provide shielding against any conceivable solar flare.

Potential Nuclear Thermal Propulsion (NTP) Benefits

- NTP can reduce cadence and total number of SLS launches.
- NTP has potential for reducing cost, increasing flexibility, and enabling faster response times in cis-lunar space.
- NTP-derived space fission power systems could be optimal at unit sizes >100 kWe.
- First generation NTP is a stepping stone to highly advanced nuclear propulsion systems that could further improve crew safety and enable extremely ambitious missions.

Basics of Nuclear Systems





Heat Energy = 0.023 MeV/nucleon (0.558 W/g Pu-238)

Natural decay rate (87.7-year half-life)

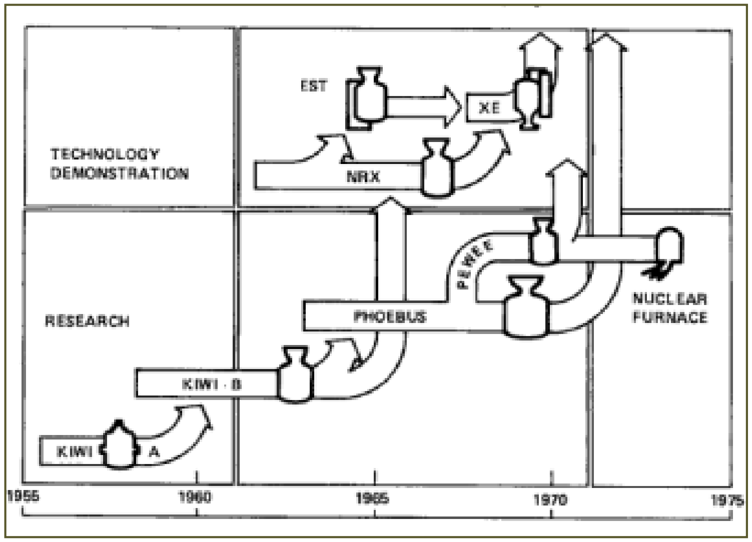
Heat Energy = 0.851 MeV/nucleon

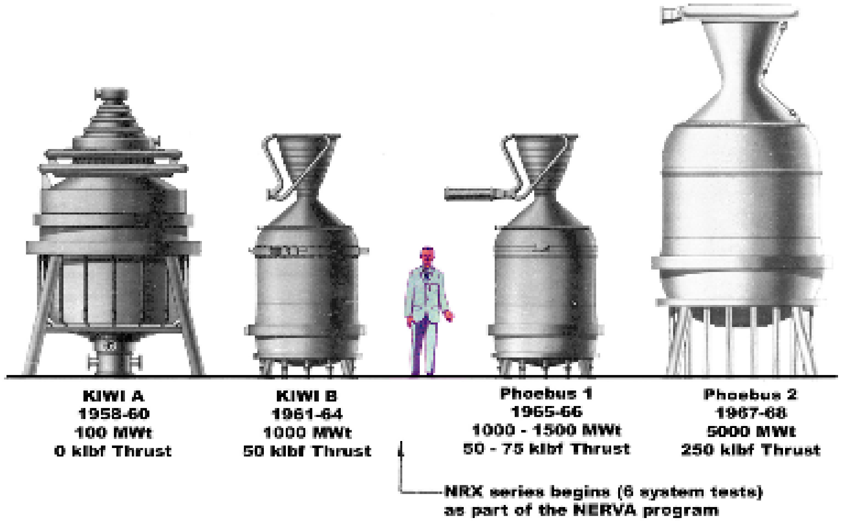
Controllable reaction rate (variable power levels)

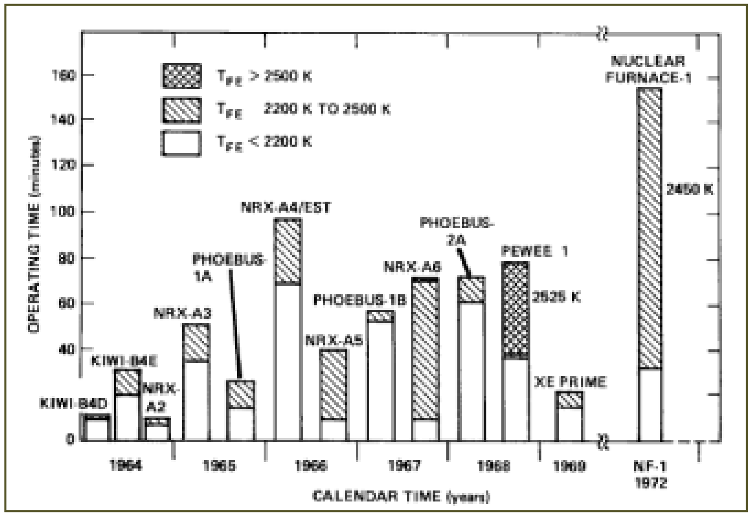
- Long history of use on Apollo and space science missions
  - 44 RTGs and hundreds of RHUs launched by U.S. since the 1960s
- Heat produced from natural alpha (α) particle decay of Plutonium (Pu-238)
- Used for both thermal management and electricity production

- Used terrestrially for over 70 years
  - Fissioning 1 kg of uranium yields as much energy as burning 2,700,000 kg of coal
- One US space reactor (SNAP-10A) flown (1965)
  - Former U.S.S.R. flew 33 space reactors
- Heat produced from neutron-induced splitting of a nucleus (e.g. U-235)
  - At steady-state, 1 of the 2 to 3 neutrons released in the reaction causes a subsequent fission in a “chain reaction” process
- Heat converted to electricity, or used directly to heat a propellant

20 NTP Engines Designed, Built, and Tested During the Rover/NERVA Program (1955-1973)

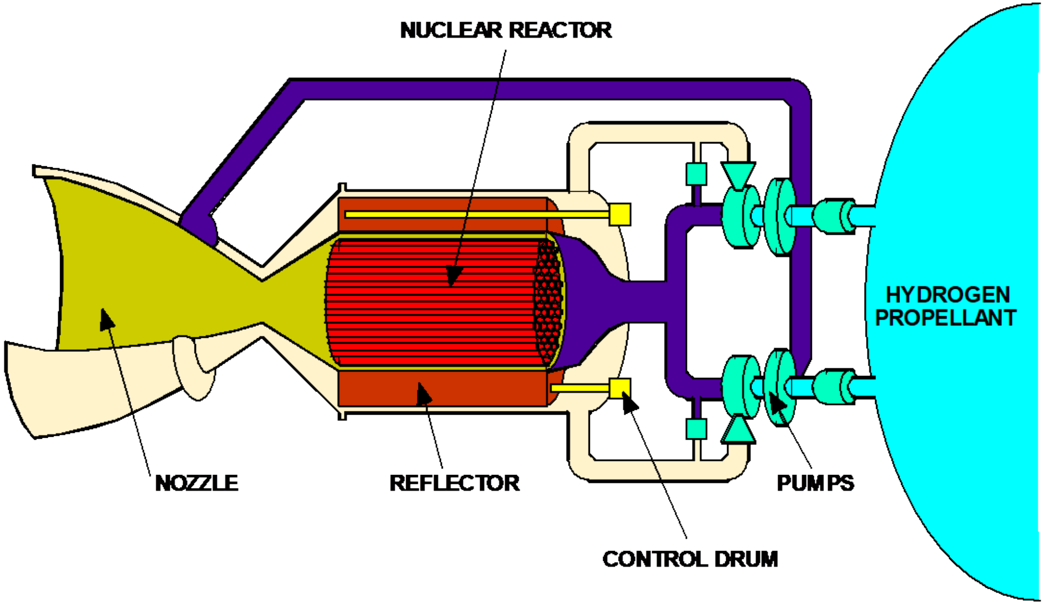






How Might Initial NTP Systems Work?

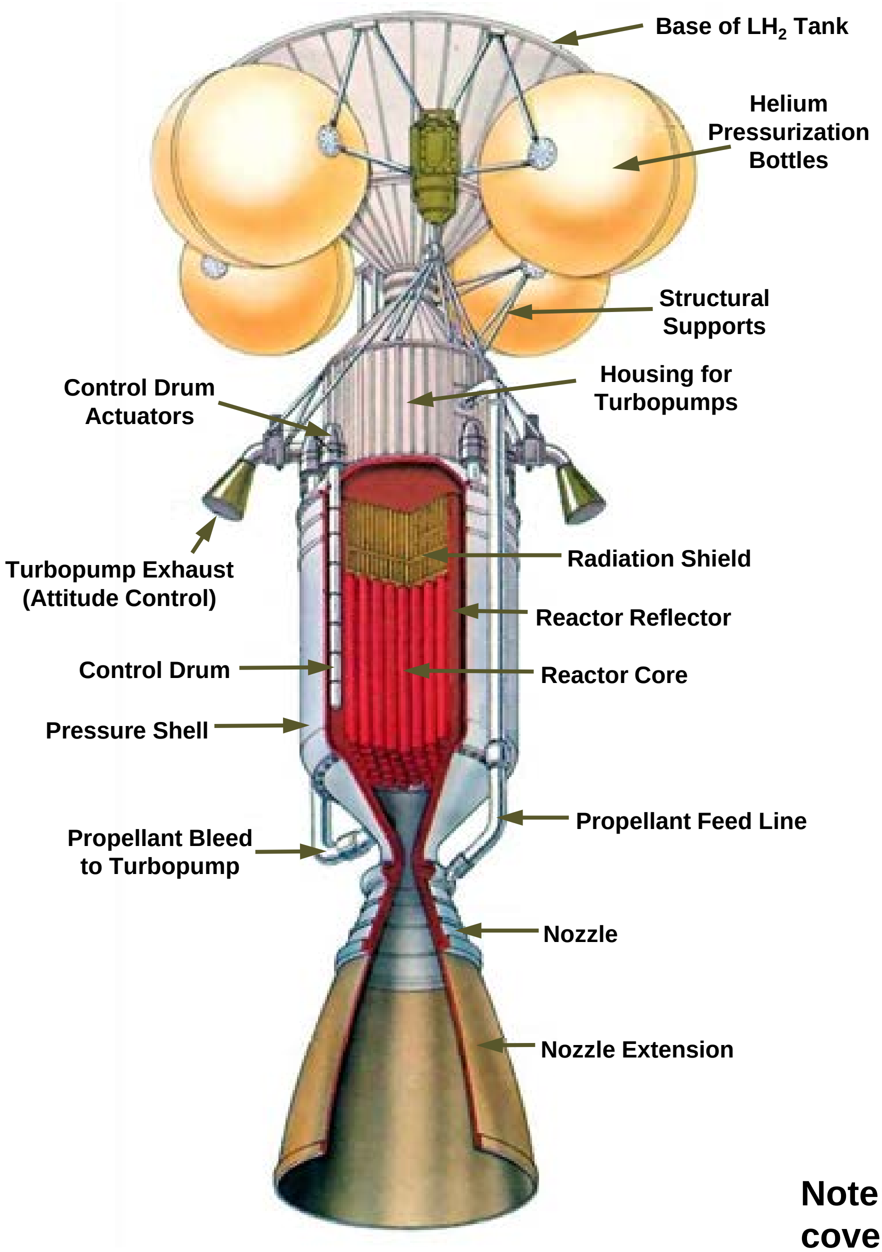
- Propellant heated directly by a nuclear reactor and thermally expanded/accelerated through a nozzle
- Low molecular weight propellant – typically Hydrogen
- Thrust directly related to thermal power of reactor. Specific Impulse directly related to exhaust temperature: 830 - 1000 sec (2300 - 3100K)
- Specific Impulse improvement over chemical rockets due to lower molecular weight of propellant (exhaust stream of O2/H2 engine actually runs hotter than NTP)



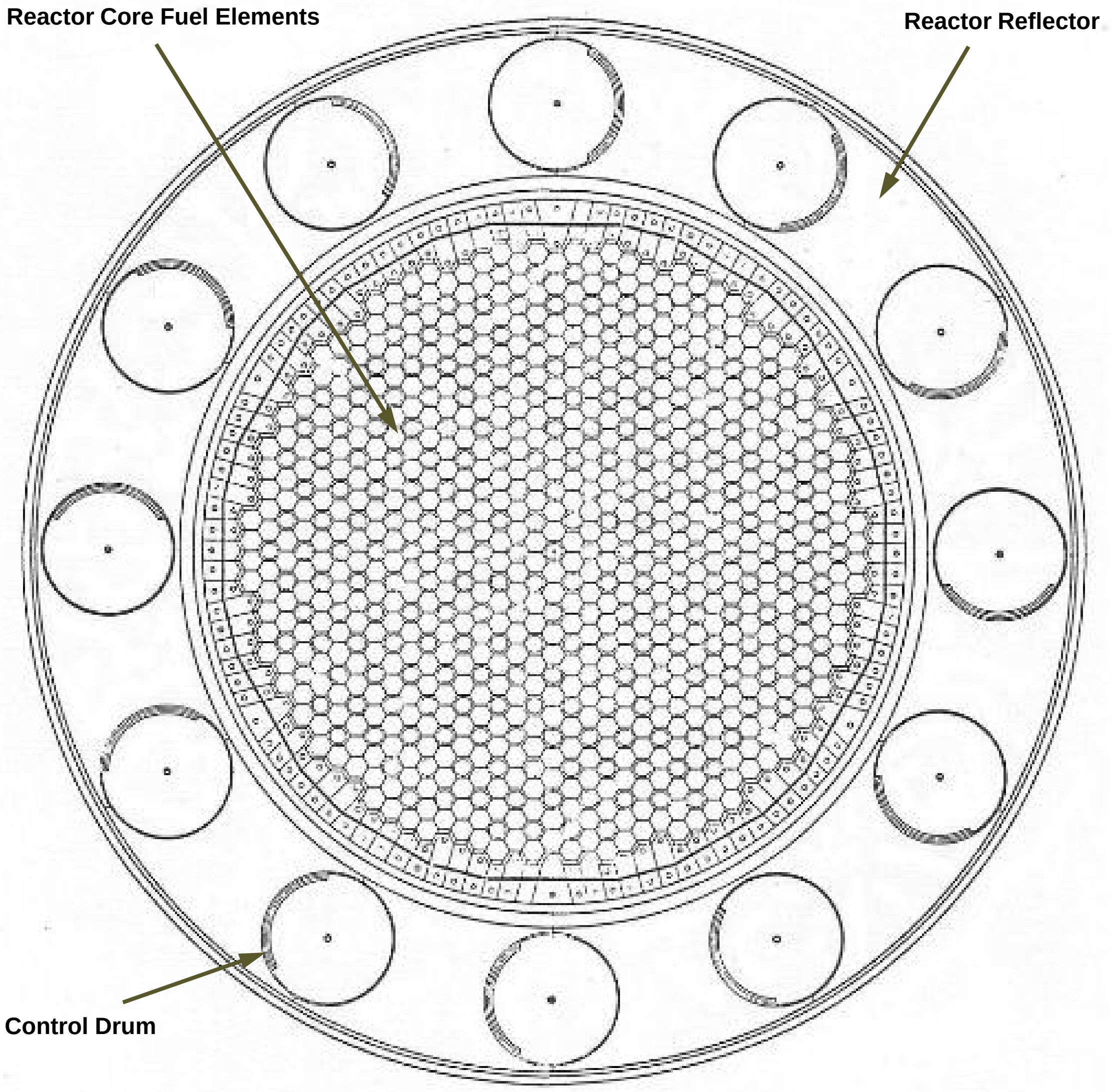
Major Elements of a Nuclear Thermal Rocket

NERVA Nuclear Thermal Rocket Prototype

How Might Initial NTP Systems Work?



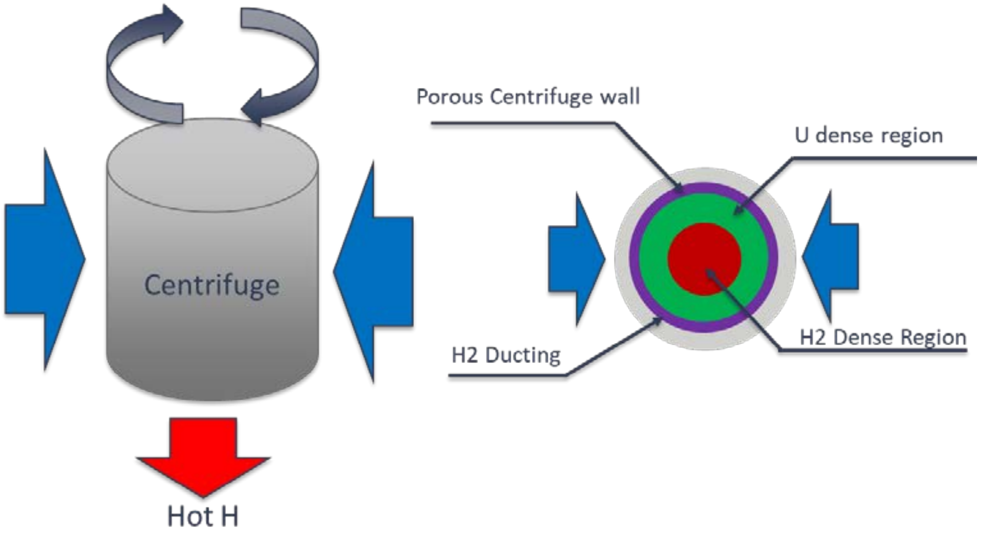
Cross Section



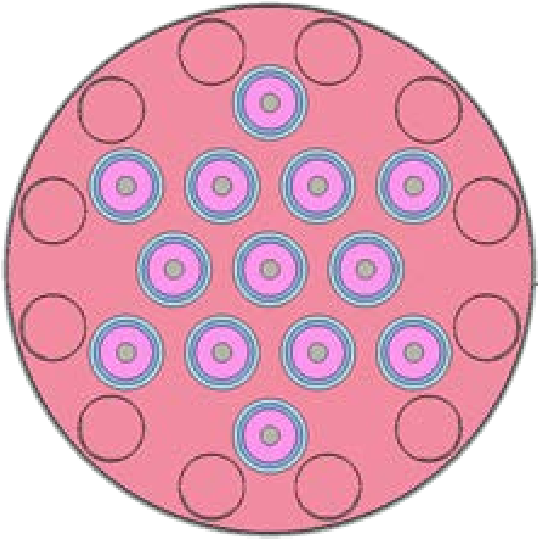
Note: Control drums rotate to control reactivity. Portion of circumference covered with neutron absorber and remainder is reflector.

Potential Second Generation NTP Systems

One option for a potential second generation NTP system is the Centrifugal Gas Core Reactor (CGCR)



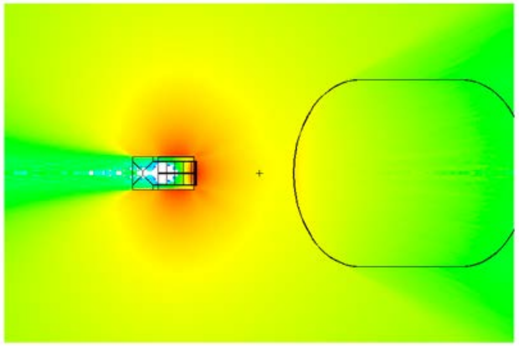
Rotating Fuel Element for CGCR



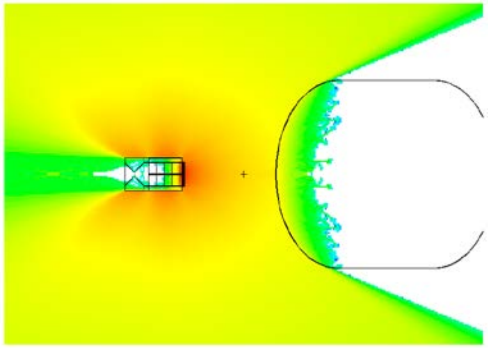
Notional CGCR with 13 Rotating Fuel Elements

Optimize Shielding Approach for Multiple Purposes

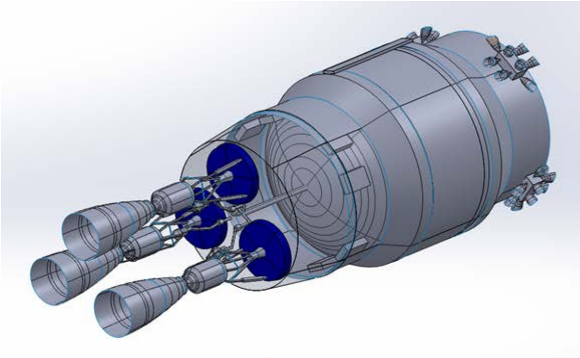
- Baseline approach: External shield for neutron and gamma shielding
  - Potentially ~1 mT / engine
  - Mitigates potential of nucleate boiling within propellant tank
- Consider: No external shield
  - Energy absorbed by propellant is used to help autogenously pressurize tank
    - » Constant pressure requires 290 W of latent heat of vaporization / 1 MW reactor power
  - Challenge is to effectively harness energy so that it goes directly into heat of vaporization of propellant
    - » May not require any modifications to standard tank design
- Use boost pump to maintain desired turbopump inlet conditions



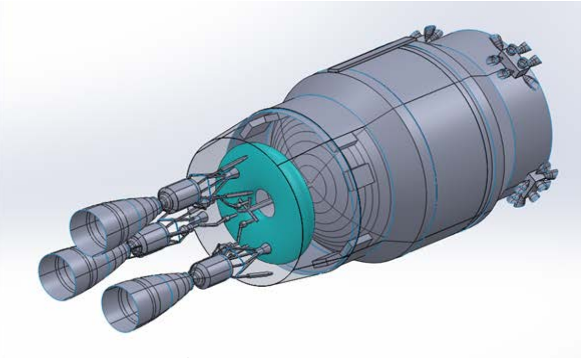
Example of Radiation Flux without External Shield



Example of Radiation Flux with External Shield



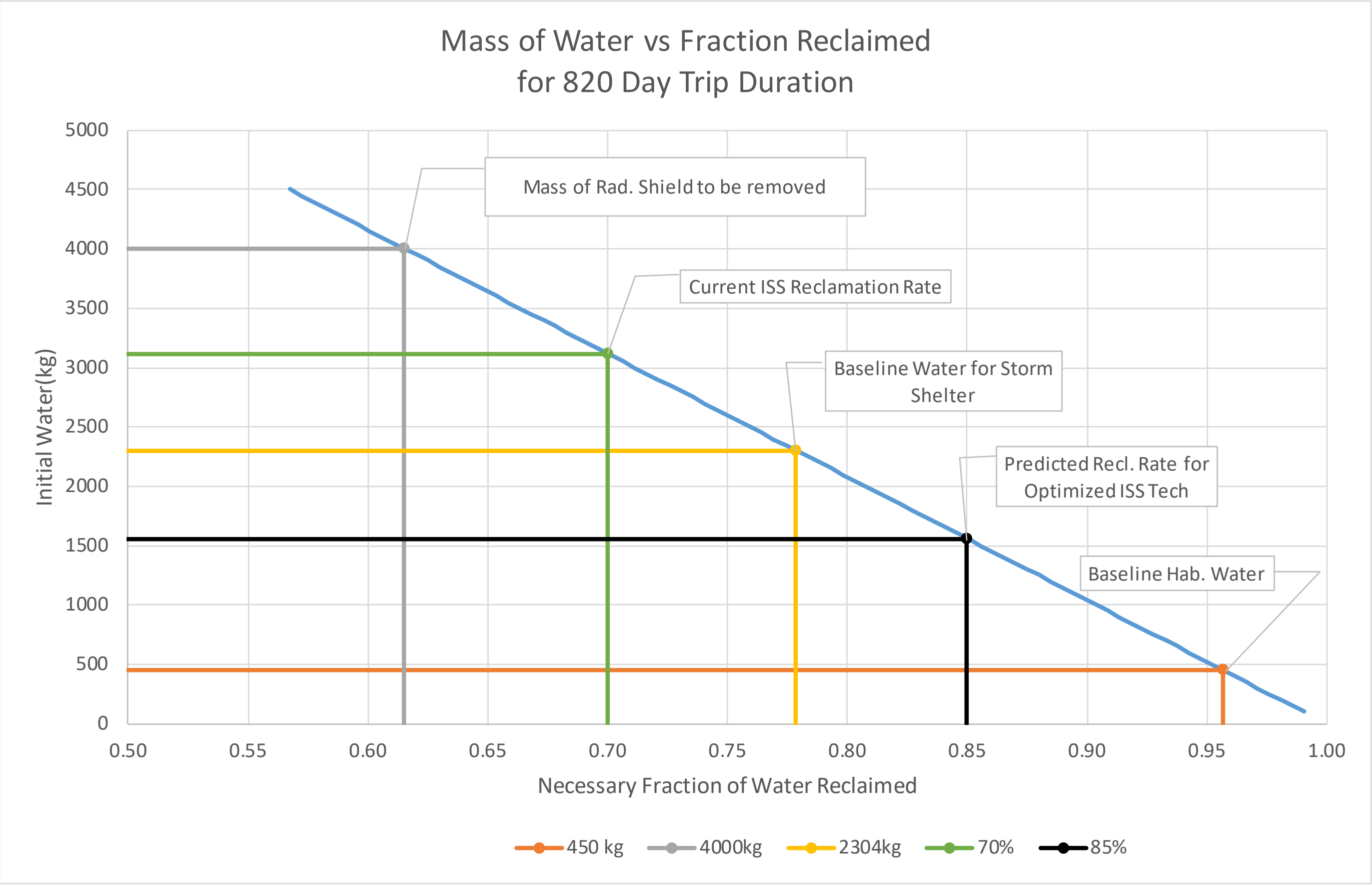
Engine Configurations with External Shields



Engine Configuration with Secondary Pressurization Tank

Transitioning Shielding Mass from Inert Weight to ECLSS Water

- Mass reduction in the habitat strains water reclamation requirements
  - Pushes technology requirements of ECLSS system
- External shield mass allocation may be transitioned to useable water for the ECLSS system
  - Serves as a radiation “storm” shelter
  - Reduces water reclamation requirement
- Water reclamation requirement may be reduced from >0.95 to <0.65



References:

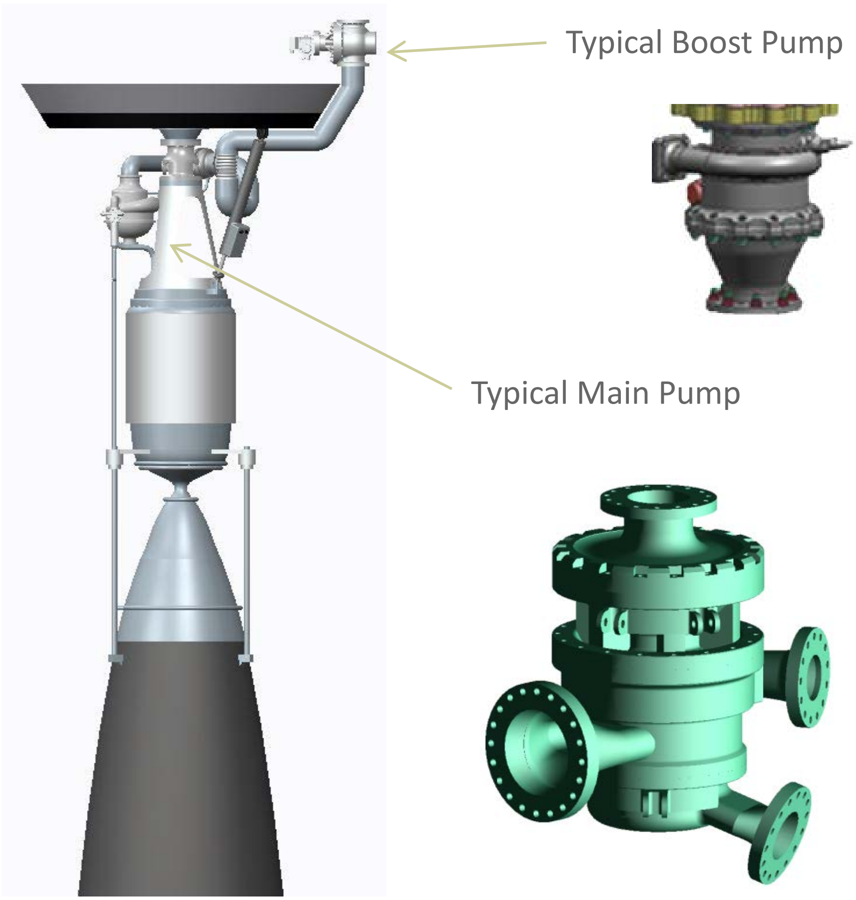
- Simon, Molly et al. “NASA’s Advanced Exploration Systems Mars Transit Habitat Refinement Point of Departure Design.” 38th 2017 IEEE Aerospace Conference; 4-11 Mar. 2017; Big Sky, MT; United States

- Curley, Su et al. “Deep Space Habitat ECLSS Design Concept.” 42nd International Conference on Environmental Systems; 15-19 Jul. 2010; San Diego, CA; United States

Changing the neutron and gamma shielding approach to a “storm” shelter has the added benefit of reducing water reclamation requirements in the crew habitat.

Boost Pumps Condition the Propellant

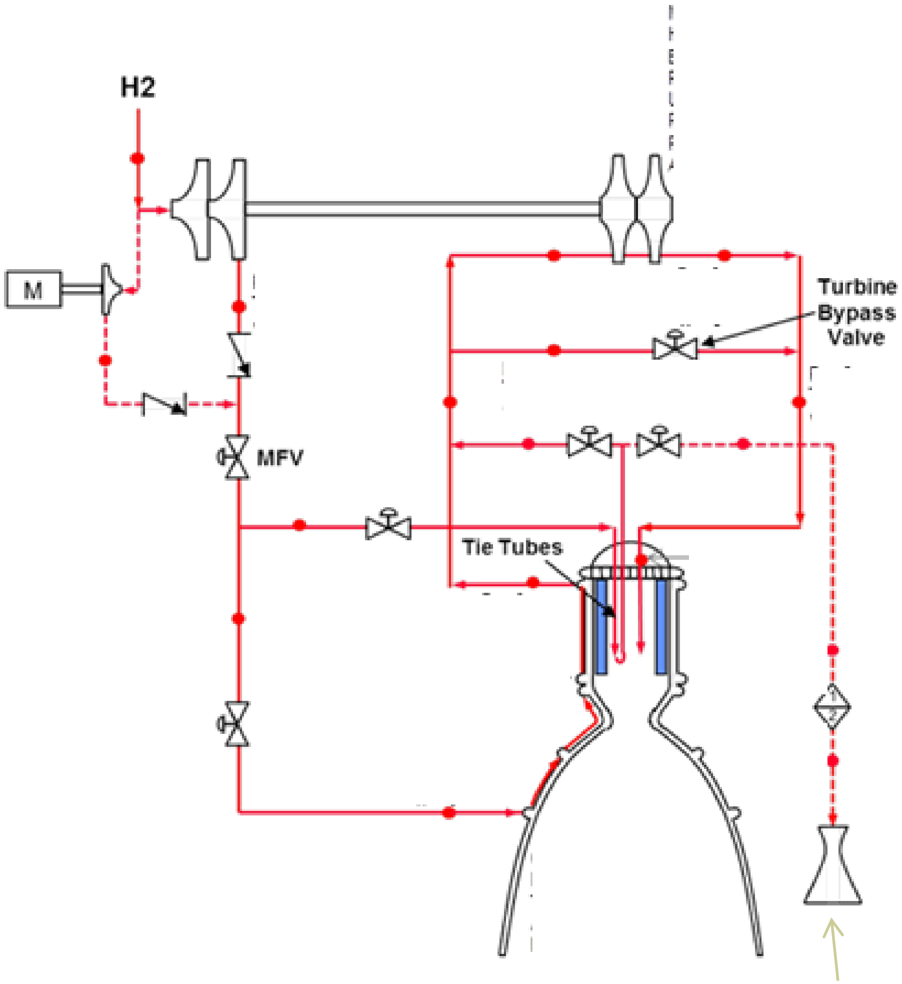
- Autogenous pressurization may not be able to maintain steady state pressure of the tank
  - Analysis indicates a drop of ~12 psia during longest burn
  - Boost pump brings propellant back up to turbopump inlet conditions
  - Allows some saturated vapor to exit from the main propellant tank (risk mitigation to nucleate boiling)
- Investigating electric or hydraulic options
  - May have relatively small impact to system mass
  - May add additional approach to engine control



Introduction of a boost pump prior to main turbo pump allows for a wider range of propellant outlet conditions from the propellant tank.

Reactor Energy for Hot H_2 Orbital Maneuvering

- Leveraged for Mars and Earth Sphere of Influence
  - E.g. NRHO to LDRO, Mars plane changes
- Hydrogen flow path through existing tie tubes
  - Integrates with core without changing fuel element or tie tubes
  - Additional valves on tie tube circuit
- Performance exceeds storable bi-propellant
  - Isp = ~500s
  - Benefit of removing mass and overhead of bi-propellant systems
- Investigating approaches to leverage hot H_2 for RCS, e.g. attitude control
- Including heat exchanger provides potential for power generation.

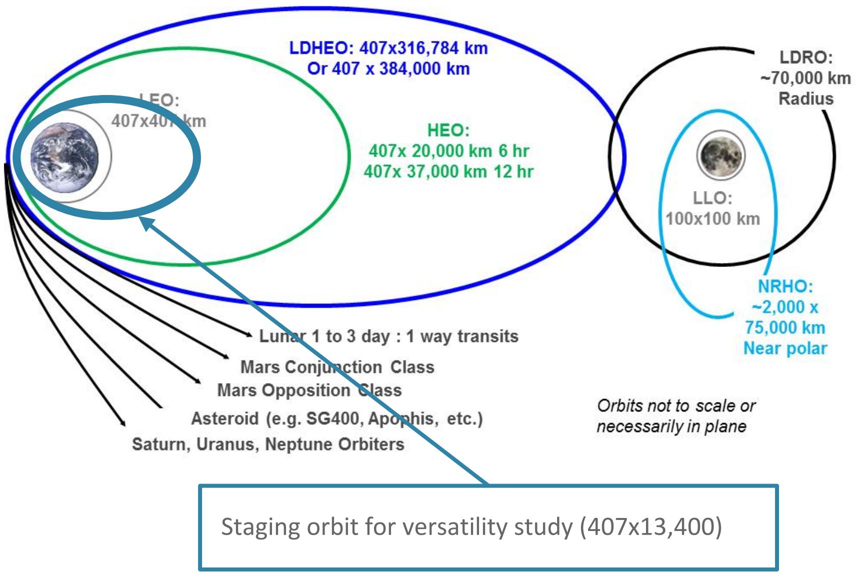


Hot Hydrogen OMS Thruster (x2)

The low molecular weight of hydrogen combined with the superfluous power of NTP creates an opportunity for low-impulse orbital maneuvering.

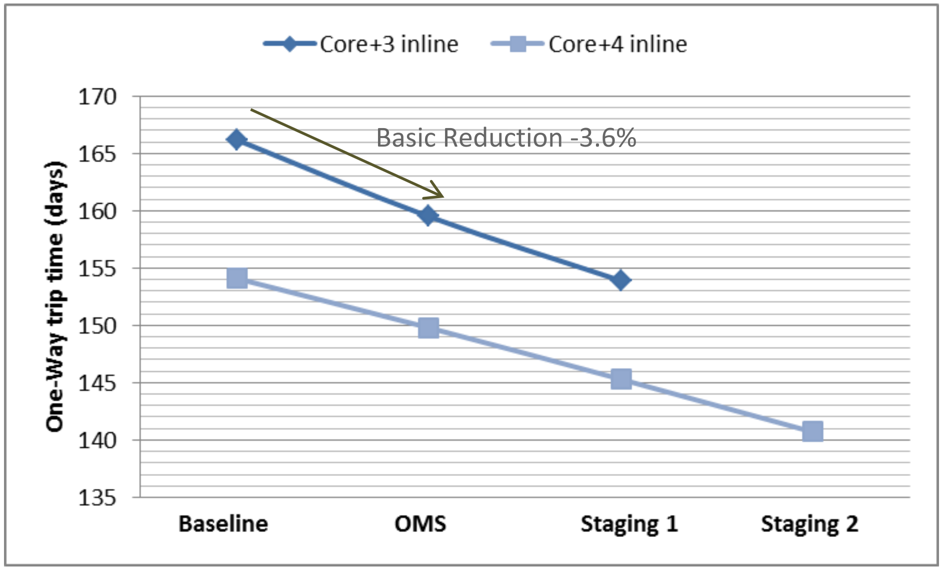
Evaluating New Mission Architectures

- Reduce staging orbit from LDHEO / LDRO to 407x13,400 km
  - Provides 68.5 mT vehicles with 8.4m SLS fairing
- Consider staging of in-line tanks at Mars
- Reduction in trip time reduces radiation exposure
- Evaluation of orbital debris and thermal environmental impacts pending

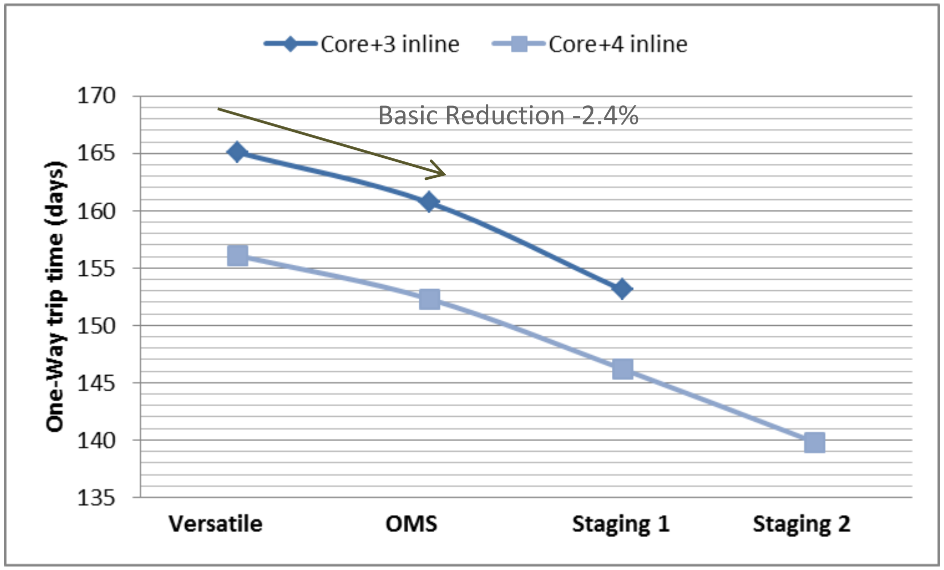


Orbits not to scale or necessarily in plane

Staging orbit for versatility study (407x13,400)



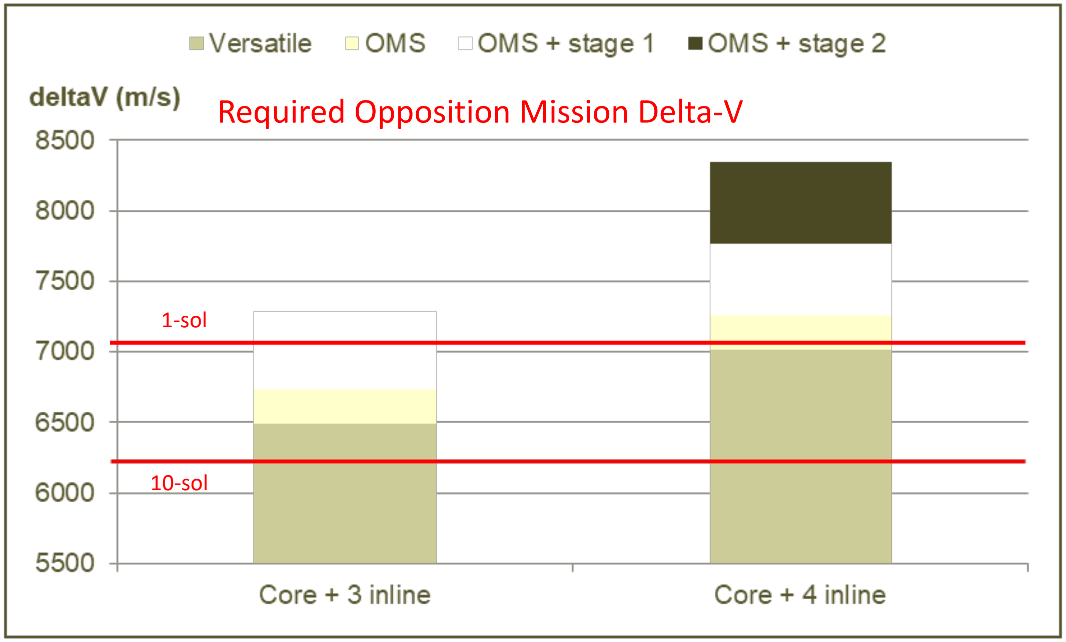
Baseline PoD 45 mT Stage Vehicle

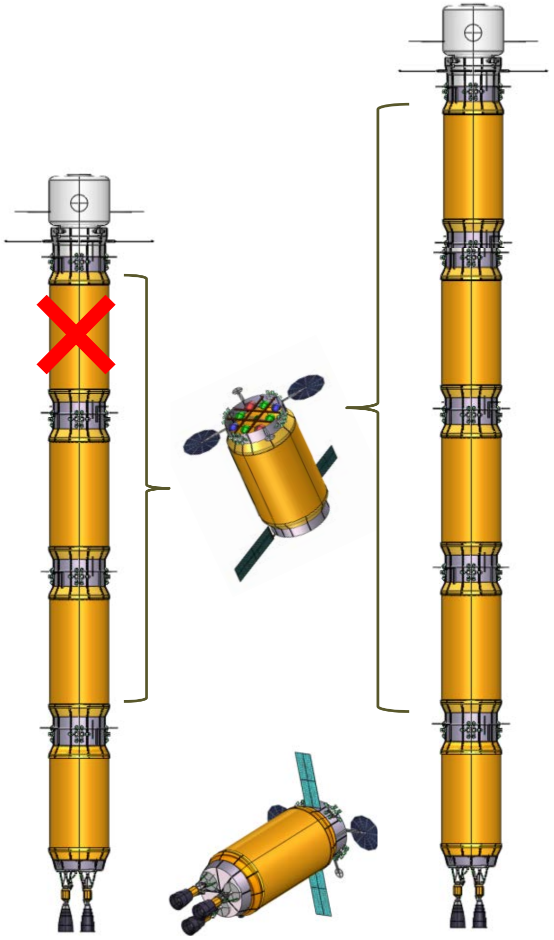


Versatile 68.5 mT Stage Vehicle

Opposition Class Mission Architectures

- Reduced systems (higher prop) mass fraction and performance enables greater delta-V
- Some opposition class missions are achievable
  - Core + 3 or 4 inline stages (68.5 mT wet mass) or
  - Staging, e.g., leaving, stages at Mars provides additional capability





68.5 mT Versatile Stage Elements

Versatile NTP may enable "short" stay opposition class mission architectures.

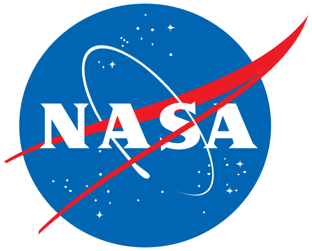
Observations

- Space fission power and propulsion systems are game changing technologies for space exploration.
- First generation NTP systems could provide significant benefits to sustained human Mars exploration and other missions.

  Potential for Earth-Mars transit times of 120 days; <600 day total Mars round trip mission times; reduced crew health effects from cosmic radiation and exposure to microgravity; robust Mars architectures including abort capability.

  Faster response times, improved capability, and reduced cost for cis-lunar operations. NTP derivatives could enable very high power systems on lunar surface (ISRU) and in space.

- Advanced space fission power and propulsion systems could enable extremely ambitious space exploration and development.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