Design Options for a Versatile Nuclear Thermal Propulsion (NTP) Stage

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A study was initiated to investigate propulsion stage and mission architecture options potentially enabled by fission energy. One initial concept is a versatile Nuclear Thermal Propulsion (NTP) system with a maximum specific impulse of 900 s and a maximum thrust (per engine) of 15 klbf. The system assumes a monopropellant stage (hydrogen), and is designed to also provide 300 lbf of thrust (potentially split between multiple thrusters) at an Isp > 500 s. Boost pumps are used to assist with engine decay heat removal and low thrust engine burns, and to compensate for partial tank depressurization during full thrust engine burns. Potential stage assembly orbits that take full advantage of launch vehicle payload mass and volume capabilities are being assessed. The potential for using NTP engines to also generate a small to moderate amount of electrical power is also being evaluated.

I. Nomenclature

CFEET	=	Compact Fuel Element Environmental Test
ECLSS	=	Environmental Control and Life Support System
FCM	=	Fully Ceramic Microencapsulated
Isp	=	Specific Impulse
NASA	=	National Aeronautics and Space Administration

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NTP = Nuclear Thermal Propulsion
NTREES = Nuclear Thermal Rocket Element Environmental Simulator
SLS = Space Launch System

II. Introduction

Space fission power and propulsion systems have tremendous versatility. This versatility stems primarily from the extremely high energy density of fission, along with ongoing advancements in design, materials, manufacturing processes, and other technologies.

The strawman Nuclear Thermal Propulsion (NTP) stage discussed in this paper is designed to be launched by a rocket, such as the Space Launch System (SLS) capable of delivering 70 metric tonnes into a 407 km x 10,000 km orbit. Each NTP propulsion stage element is limited to a maximum mass of 70 metric tonnes and a volume that will fit in an 8.4m diameter x 27.4 m payload faring. Once the NTP stage is assembled it is then attached to the payload, or if needed the stage can propel itself to the location of the payload.

Several potential NTP stage simplifications are being investigated. The stage will include either one or three 15 klbf (~350 MW) engines, depending on the mission. The engines are designed to be capable of also running at low thrust (~300 lbf) while still providing a high (>500 s) Isp. Neutron and gamma heating from the NTP engines is used to partially re-pressurize propellant tanks during engine burns, and the potential for additionally using boost pumps (electric or other) may completely eliminate the need for a traditional tank re-pressurization system. Boost pumps could also be used for reactor decay heat removal and low thrust engine operation. An additional goal is for the NTP stage to be entirely monopropellant, with all thrust provided using energy from the reactor, and using hydrogen for propellant. Reactor geometries and materials that could provide additional simplifications and benefits are also under consideration.

The high Isp (~900 s) of NTP results in the optimal NTP stage assembly orbit being different from other propulsion options. In general, it is beneficial to use the NTP stage to provide as much of the mission velocity increment (delta-V) as possible. Various potential NTP stage assembly orbits are being assessed, taking into account not only overall mission performance but also differences in thermal, radiation, and orbital debris environments that could affect assembly orbit selection.

Radiation shielding for robotic missions is provided by the combination of distance, hydrogen propellant, walls/structure, and spot shielding. Additional radiation protection may be desired for human missions, especially for scenarios where the engines are running at full thrust with very little hydrogen remaining in the propellant tanks. The NTP stage design assumes that this shielding would be provided by placing additional water in the walls of the habitat's radiation "storm shelter." Locating the radiation shielding in the habitat not only helps maximize the energy available for passive propellant tank re-pressurization (via neutron and gamma heating), but also provides extra water that could be of use to the Environmental Control and Life Support (ECLS) system. The extra water would also improve the performance of the radiation shelter during a coronal mass ejection event, and could be used to reduce astronaut radiation dose from the high energy proton component of galactic cosmic rays.

The cermet fuel being developed for the NTP reactor is suitable for use with either H_2 or NH_3 propellant, and was originally proposed to help enable high power, high performance space fission power systems. A derivative of the NTP reactor could be well suited for powering a high performance direct gas Brayton cycle, potentially useful for In-Situ Resource Utilization (ISRU) or other applications on the surface of the moon or Mars. Alternative fuels (such as ZrC-based fully ceramic microencapsulated (FCM) fuels) are also being considered.

For certain missions it may also be beneficial for a small to moderate amount of electrical power to be extracted from the reactor when the NTP engine is not being used to provide full thrust. Modest amounts of thermal power could be provided from a separate cooling loop passing through the reactor tie tubes or moderator block. Various options for converting the thermal power to electrical power are being examined to provide a wide range of capability.

A variety of applications are being evaluated for the versatile NTP stage. A single-engine stage could be useful for numerous cis-lunar and advanced deep space mission. A three-engine stage could be useful for conjunction or opposition-class human Mars missions with up to 8 crew members. The stage would provide robust abort capabilities and options for rapid transit or round-trip times.

The ability to affordably test NTP components and engines is important to the eventual utilization of NTP. Options are being evaluated for meeting various testing needs.

III. Overview of Versatile NTP Stage for Human Mars Missions

A versatile NTP stage configured to support human Mars mission could include a single "core tank" stage, and two, three, or four "in-line tank" stages, depending on the mission. Typically a vehicle with two or three in-line tank stages would be used to support conjunction class human Mars missions, and a vehicle with three or four in-line tank stages would be used to support opposition class missions. All stages fit within the proposed SLS 8.4m diameter x 27.4 m payload faring.

In addition to providing high thrust (~15 klbf per engine) at ~900 s Isp, hydrogen flow through the engine is also designed to allow for lower thrust (~300 lbf per engine) at modest Isp (>500 s). Additional study is being performed to determine if the vehicle can be made fully monopropellant (e.g. hydrogen only), with the exception of any traditional propulsion capability needed for assembly of the propulsion stages.

IV. Reference Stage Assembly Orbit

One option under consideration uses in-line and core stages that fully utilize the SLS payload volume and have a maximum mass of 68.5 mT, allowing for an SLS drop-off orbit of 407 x 13,400 km. One architecture option could be to assemble the NTP vehicle in that orbit and then for the vehicle to rendezvous with the Mars habitat at the location where the habitat is assembled and outfitted. Habitats with a mass up to 68.5 mT could also be launched directly from earth to the NTP vehicle assembly orbit. Figure 2 illustrates how the 68.5 mT stage elements fit into the proposed SLS 8.4m diameter x 27.4 m payload faring. A schematic of a vehicle configured for an opposition class human Mars mission is shown in Figure 1.

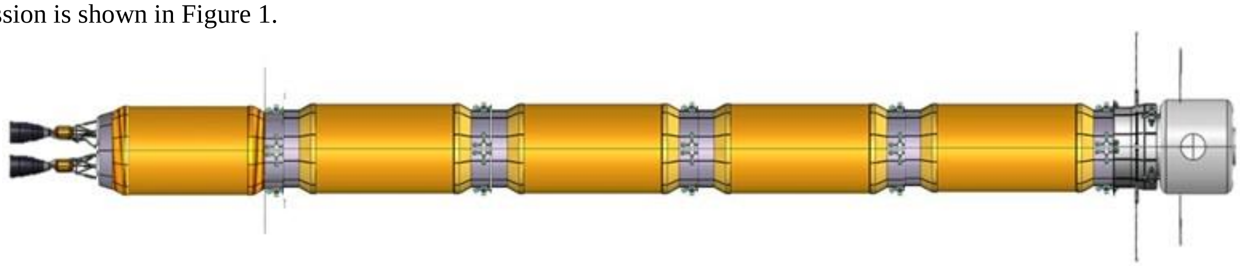

Fig. 1 Potential vehicle configuration for opposition class human Mars mission.

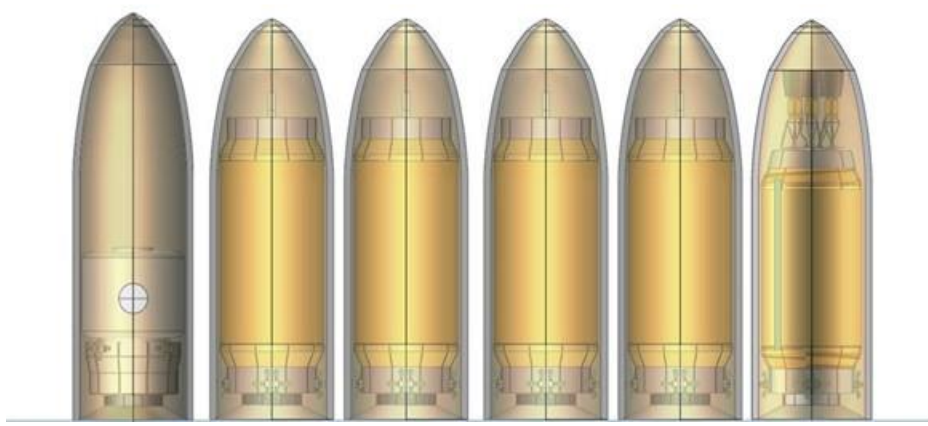

Fig. 2 Packaging of the lower drop-off orbit NTP stages in the SLS 8.4 meter fairing.

V. Shielding Strategy

Shielding options are being investigated that simultaneously provide enhanced crew radiation protection (compared to non-NTP architectures), allow for passive tank re-pressurization, and reduce hydrogen cryo-cooling requirements. In these options spot shielding is used to protect sensitive components near the NTP engines, but neutron and gamma heating in the hydrogen tanks is optimized to provide passive tank re-pressurization as hydrogen is pumped from the tanks during an engine burn. To maintain tank pressure, approximately 290 W can be deposited into the propellant tank (via neutron and gamma heating) for every 1 MW of reactor power. Initial calculations indicate that it may be difficult to maintain tank pressure using only neutron and gamma heating, although the use of a boost pump may make the reduction in pressure acceptable and the boost pump drive gas could augment the heating from the reactor for pressurization. Designing to allow for a reduction in propellant tank pressure during a burn also effectively builds in thermal inertia, potentially reducing overall cryo-cooling requirements.

While the hydrogen propellant will provide radiation shielding for the trans-Mars habitat, some radiation will reach the habitat during the final engine burn when very little hydrogen remains in the tanks. To shield residual radiation, additional water for the habitat's Environmental Control and Life Support Systems (ECLSS) in the form of a radiation "storm" shelter is considered. For simplicity, a 4000 kg mass savings on the external shield is assumed to be provided for a more robust storm shelter that could provide shielding during engine firings and solar particle events. Beyond providing more robust radiation shielding, this re-allocated mass from inert shielding to water provides relief on the reclamation requirement for a Mars mission, possibly reducing technology development risk in the ECLSS system.

Baseline values for amount of water consumed per day per crew member are described by Anderson[1]. Utilizing these baselines and the conservative estimates that the only water available is in the clean water tank, as well as that any non-reclaimed water from urine or waste is lost, it is possible to calculate an amount of water loss per day based on the water revitalization percentage. By finding the amount of water loss per day it is easy to calculate the amount of days the water will last.

There are various studies and research that have evaluated required water and reclamation rates for Mars missions. Figure 3 maps various initial water levels in the Habitat with reclamation requirements for a 820 day trip (this assumes worst case that a Mars Landing is aborted and crew are required to be within the Habitat for all 820 days).

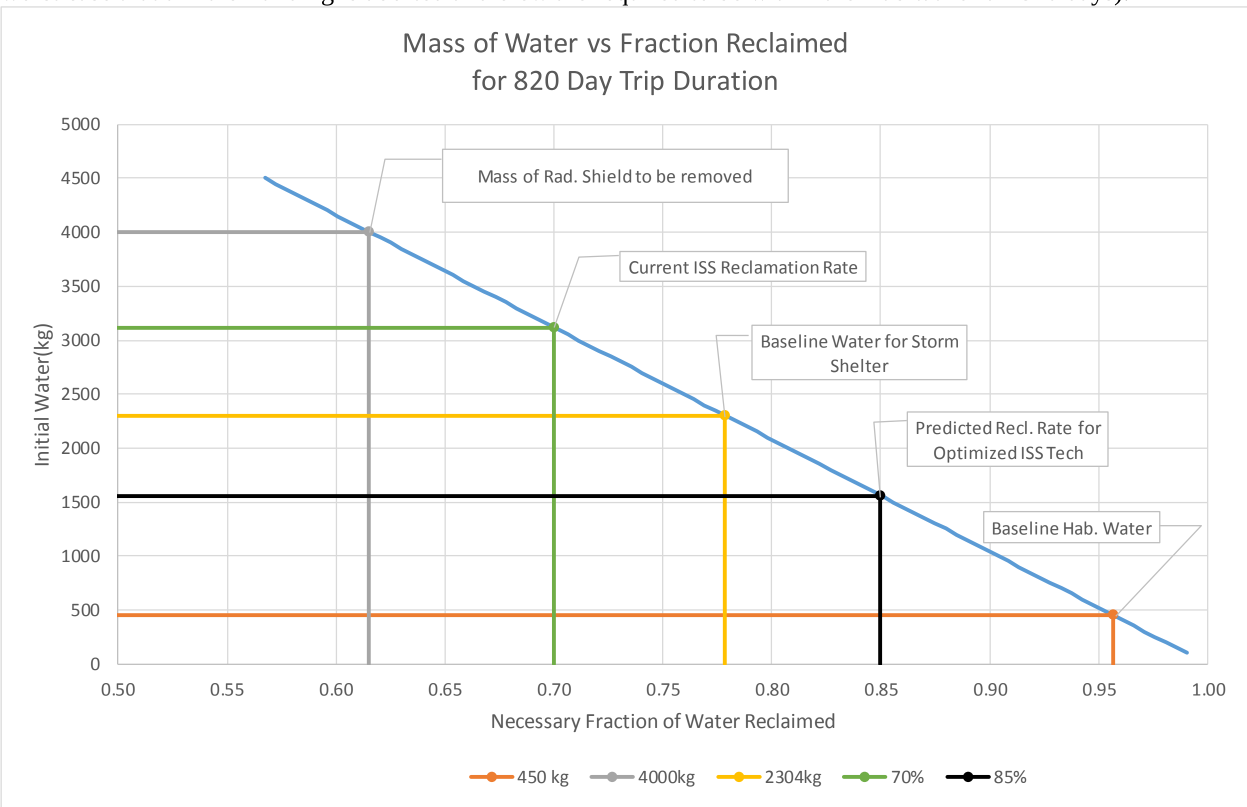

Fig. 3 Water mass vs. reclamation fraction of water.
Re-allocating NTP shielding mass to water mass of a "storm" shelter greatly reduces water reclamation requirements of a trans-Mars habitat.

This analysis plots various points for reference. The conservative assumption of mass re-allocation from a radiation shield to a storm shelter reduces reclamation requirements to 62%. One Mars transit habit design leverages technology

[1] Anderson M et al. "Life Support Baseline Values and Assumptions Document." Report Number: NASA/TP-2015-218570/REV1, JSC-E-DAA-TN51698. NASA Johnson Space Center; Houston, TX, United States

from the ISS water revitalization system[1]. This system has limits of 70% recovery of water from urine (green line), however it may achieve up to 85% or higher using technologies that remove calcium or sulfuric acid from the urine, or through use of pretreatment chemicals[3] (black line). The habitat described by Simon utilizes 450kg of water for all consumable needs (orange line). This was for a 4 crew member mission of 388 days, yet was scaled for these analyses. This paper also describes a storm shelter utilizing a 2304 kg wall of water (yellow line).

VI. Boost Pump

Several versatile NTP capabilities are enhanced or enabled by the use of a hydrogen boost pump. First, the pump can be used to maintain a constant saturated liquid hydrogen at the turbopump inlet, even if propellant tank pressure is allowed to decrease during an engine burn. Allowing propellant tank pressure to decrease during a burn potentially eliminates or reduces the complexity for a dedicated tank re-pressurization system, assuming adequate pressure can be maintained using passive neutron and gamma heating of the propellant. Allowing tank pressure to decrease during engine burns may also reduce integrated cryo-cooling requirements – heat leaking into the propellant tanks between engine burns is either removed by the cryo-coolers or used to slowly bring tank pressure back up to nominal. The boost pump can also be used to provide hydrogen flow needed for low thrust burns (~300 lbf per engine), and to facilitate decay heat removal while minimizing thermal cycles on the fuel and other engine components. Boost pumps using recirculated hydrogen from the pump, hydrogen gas tapped off the moderator or turbine discharge circuits and electric power are being examined for reducing the complexity of the pressurization system and the main turbopump.

VII. NTP Reactor and Engine Design

The reference versatile NTP engine design produces 15 klbf of thrust, uses a $ZrH_{1.8}$ moderator, and uses UN fuel clad with either Mo or Mo/W, depending on the location within the engine. Additional fuels under consideration include a zirconium carbide based fully ceramic microencapsulated (FCM) fuel which may have several potential advantages over the reference fuel. In addition to ZrHx moderated systems, BeO moderated systems are also being evaluated. All systems use low-enriched uranium, i.e. uranium containing <20% U-235.

Beryllium oxide (BeO) appears to be a candidate for a solid core nuclear reactor engine moderator. Beyond its neutron scattering ability, low density, and thermal conductivity, there is a chance for more contribution to the neutron economy via (n, 2n) reaction in the beryllium. BeO can also operate at a temperature twice that of zirconium hydride (ZrHx); this temperature capability allows for a less complex support element design for the fuel modules. In ZrHx moderated fuel elements, there is a need for tie tubes inside and outside of the ZrHx. The tie tubes keep the ZrHx cool, but involves a more complicated manufacturing process as each element must contain not only an insulator and ZrHx, but two tubes inside and outside of the ZrHx. With each element measuring roughly 2.5 cm across, intricate concentric tubing can be complicated and leave more room for error. BeO's high melting point may allow for the elimination of tie tubes. Although BeO's moderating capability is less than that of ZrHx, the volume made available through omitting tie tubes could make up for most of this difference. Irradiated BeO can experience volume expansion as well as micro-cracking. However, micro-cracking is more significant at temperatures under 800K, and the reactor will be operating at higher temperatures. Methods for preventing micro-cracking include utilizing reduced grain sizes, as well as using cold pressed, sintered BeO. The use of cladding will aid in the prevention of volumetric swelling. Integrated neutron fluence within the NTP engine is typically low compared to terrestrial power reactors, which would also help mitigate radiation effects on the BeO.

VIII. Other Considerations

The decay heat of the rocket core in post-thrust operation must be rejected or dissipated by some means. Traditionally, the propellant is used to produce marginal thrust in the first 30 seconds after reactor shutdown. After the first 30 seconds the propellant is pulsed through the reactor periodically to dissipate decay heat. This pulsed propellant is used ineffectively and produces thrust at non-optimal times.

If one was to introduce a power cycle into the NTP engine for electricity generation, some of this heat dissipated through the propellant rejection could instead be used productively, as opposed to losing the heat and mass without benefit. Additionally, shortly after engine shutdown the electric power system could potentially be driven to allow a

[2] 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

much higher heat rejection temperature and thus rejection of a much higher fraction of the shutdown decay heat. Within a few hours of shutdown decay heat would typically have decreased to the level where electric power production could resume.

The benefit of incorporating a power cycle with the NTP engine is two-fold. The first benefit is that it provides a way of cooling the reactor core immediately following engine shutdown, when decay heat is too high to be removed entirely by passive means. Secondly, it provides power to the payload without the need for large solar arrays. Solar energy is dependent on the solar flux available at a given distance from the sun, which makes it a very inconsistent source of energy. Incorporating a power cycle not only provides a constant amount of energy, but allows the stage to be used on deep space missions in addition to potentially saving mass and complexity for missions to Mars or in cis-lunar space. There are several potentially viable options for converting energy from the NTP engine into electricity. For the versatile NTP study, a closed-loop Brayton cycle has been chosen as the reference. The initial focus is to incorporate a 1 kWe Brayton cycle to be used for deep-space science missions. Hot hydrogen would be brought from the outlet of the tie tubes into a heat exchanger to heat up a He-Xe mixture to run through a Brayton cycle. The main areas of interest in this power cycle is how to minimize radiator area while at the same time designing a heat exchanger to provide a maximum turbine inlet temperature. Efficiency of the cycle is of some importance, but of more importance is reducing the mass required per kilowatt of energy produced. This same approach could be used on a larger scale as well to produce power for human Mars missions.

IX. Test Facilities

The successful development of NTP will require both nuclear and non-nuclear testing. Non-nuclear testing of fuels and components is currently being performed using NASA's Compact Fuel Element Environmental Tester (CFEET) and NASA's Nuclear Thermal Rocket Element Environmental Simulator (NTREES). Idaho National Laboratory (INL) has successfully restarted its Transient Reactor Test (TREAT) facility, and preliminary assessments are being performed to determine the suitability of TREAT for testing NTP fuels and other components. Although TREAT is not designed for long duration testing, it appears capable of testing NTP fuels at prototypic startup temperature ramp rates and at peak temperatures in a hydrogen environment.

It may also be possible to use university reactors to perform realistic nuclear testing of ex-core NTP components. There are currently 25 operating university research reactors in the United States, the majority of these are TRIGA and pool reactors. The University of Missouri: Columbia (UMC) and Massachusetts Institute of Technology (MIT) reactors are capable of the highest thermal power levels, at 10MW and 6MW, respectively. The Rhode Island Nuclear Science Center (RINSC) and University of California: Davis (UCD) operate at 2MW. North Carolina State, Oregon State, Pennsylvania State, Texas A&M, University of Massachusetts, University of Texas: Austin, University of Wisconsin and Washington State all operate at about 1MW, with the remaining university reactors all operating below 500kW. MIT, UCD, RINSC, Oregon State, North Carolina state, Pennsylvania State, and Texas A&M all possess irradiation research capabilities with varying dry sample size options of potential interest to the development of NTP.

X. Sample Mission

One sample mission currently being evaluated is an opposition class Mars mission requiring 4 SLS-class launches for the crewed propulsion system, assuming at least one of the inline tanks can be dropped once empty. Each stage element would have a maximum mass of 68.5 mT, and the vehicle would depart from a 407x13442 km High-Earth Orbit (HEO) and return to Lunar Distant High Earth Orbit (LDHEO). Each stage element would have a mass of 68.5 mT, and the crew would be delivered to a 1-sol Mars orbit. Figure 4 shows the impact on the versatile NTP MTV when trading integrated NTP main propulsion and orbiting maneuvering system (OMS) and staging at Mars for an opposition class mission. The stage and propellant loads were held constant for the 68.5 mT SLS drops off at HEO. Delta-V capability increases as various mission burns are permitted to be performed with the ~500 sec NTP OMS and stages are un-docked and left at Mars. Total Mars opposition mission time remained the same around ~600 days total trip time. Trades on the 68.5 mT versatile NTP MTV for the opposition mission example shows the flexibility of the versatile NTP approach when stages or with the integration of a NTP MPS and NTP OMS that is part of the primary engine system. A core+ 3in-line MTV can achieve the Mars opposition mission when arriving at a 10 Sol (10 Mars solar day orbit) or if 1 in-line is staged the MTV can arrive directly into the 1 Sol orbit with delta-V margin. If the versatile NTP MTV is configured with 4 in-line stages, the vehicle can perform the Mars opposition mission with a

NTP MPS and storable OMS system or when using the integrated NTP MPS and OMS, no in-line stages need to be dropped and entire vehicle can return to earth into the LDHEO for possible later reuse.

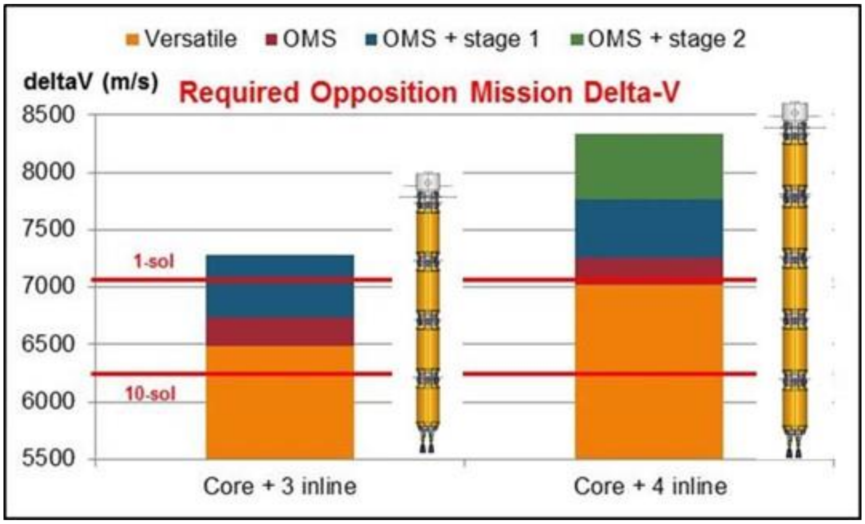

Fig. 4 The impact on the versatile NTP MTV when trading integrated NTP main propulsion and orbiting maneuvering system (OMS) and staging at Mars for an opposition class mission.

XI. Future Work

Considerable additional work remains for all topics discussed in this paper. The specific design of the boost pump needs to be developed to ensure that constant hydrogen pressure can be maintained at the turbopump inlet as propellant tank pressure decreases during the engine burn. The boost pumps being examined for the versatile NTP engine system can be designed to facilitate decay heat removal and operation in low thrust (~300 lbf) mode. Detailed calculations are needed to confirm that potential nucleate boiling in the liquid hydrogen along the aft propellant tank wall (due to neutron and gamma heating in the wall) does not result in unacceptable amounts of gas entrainment into the boost pump, and that if it does the effect can be mitigated by tank or boost pump design. Hydrogen management and distribution, including the potential for using hydrogen for all vehicle propulsion requirements needs to be further designed. For human missions, radiation shelter design needs to be optimized to provide full radiation protection during engine burns and large coronal mass ejection events, and to reduce crew dose from the high energy proton component of galactic cosmic radiation during normal operations. Methods for using clean water from the radiation shelter to augment and provide some redundancy for the ECLSS system should be devised. Additional work also remains on engine design, including potential methods for extracting low to medium (e.g., 1 kWe to 20 kWe) amounts of electrical power from the versatile NTP core.

XII. Conclusion

The use of NTP typically shows architectural benefits, even for architectures optimized to *not* use NTP. However, if properly utilized NTP can provide even more significant benefits to human exploration and other advanced space missions. For human missions specific potential benefits include shorter transit times, shorter round-trip times, abort modes, ideal cadence of SLS launches, reduced crew radiation exposure, reduced ECLSS performance requirements, and others. For advanced science missions potential benefits include shorter mission times, increased payload at the destination, and increased power at the destination.

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[2] 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