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Versatile Nuclear Thermal Propulsion (NTP)

Michael G. Houts[a*], Claude R. Joyner[b], John Abrams[c], Jonathan Witter[d], Paolo Venneri[e]

[a] *NASA Marshall Space Flight Center, MSFC, AL 35812,* michael.houts@nasa.gov
[b] *Aerojet Rocketdyne, 17900 Bee Line Hwy, Jupiter, FL 33478* claude.joyner.ii@rocket.com
[c] *Analytical Mechanics Associates, Inc., 2460 W 26th Ave Ste 440-c, Denver, CO 80211* j.abrams@ama-inc.com
[d] *BWX Technologies, Inc., 109 Ramsey Place, Lynchburg, VA, 24504* jkwitter@bwxt.com
[e] *USNC-Space, Seattle, WA, 98199* p.venneri@usnc-space.com
* Corresponding Author

Abstract

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 for orbital maneuvering and station keeping. 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. A first generation versatile NTP stage could enable 8 of 9 upcoming opportunities for short (less than 24 month) round trip human missions to Mars. A second generation versatile NTP is under consideration that could potentially provide a maximum specific impulse of 1800 s at 15 klbf, and enable ambitious missions throughout the solar system. The second generation NTP system under consideration would also allow a choice of volatiles to be used as propellant. This would potentially allow in-situ resources such as water, ammonia, methane, or other compounds to be used directly as propellant by the second generation engine.

Keywords: Nuclear Propulsion Fission Power Moon Mars

Acronyms/Abbreviations

Advanced Gas Reactor (AGR), Compact Fuel Element Environmental Test (CFEET), Department of Defense (DoD), Environmental Control and Life Support System (ECLSS), Fully Ceramic Microencapsulated (FCM), Specific Impulse (Isp), Low Enriched Uranium (LEU), National Aeronautics and Space Administration (NASA), Nuclear Thermal Propulsion (NTP), Orbital Maneuvering System (OMS), Space Launch System (SLS), Trilayer Isotropic (TRISO).

1. Introduction

Space fission propulsion and power 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 68.5 metric tonnes into a 407 km x 13,400 km orbit. Each NTP propulsion stage element is limited to a maximum mass of 68.5 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.

Much of the stage volume and mass is liquid hydrogen propellant, and an additional option is to offload a portion of the hydrogen propellant and launch the stage into an even more energetic orbit, then "top off" the stage with liquid hydrogen. This may become the preferred option once commercial propellant tankers are available.

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. Independent hydrogen flow loops through the NTP engines enable a fission-powered orbital maneuvering system (OMS) with a total thrust up to 300 lbf and a high specific impulse (>500 s) for the OMS thrusters. 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.

One nuclear fuel option for the versatile NTP would build on the Advanced Gas Reactor (AGR) Trilayer Isotropic (TRISO) fuel that is fully developed and tested for terrestrial High Temperature Gas Reactors of sizes from special purpose micro-reactors, to small modular reactors, to larger power reactors [1]. This fuel (and associated graphite compact) is the baseline nuclear fuel for other government-led programs and would ensure a shared technology basis. The use of TRISO-derived fuel particles for NTP could be enabled by optimizing layer thicknesses within the TRISO particle and using a high temperature carbide (such as ZrC) for an outer coating, as was done for the Space Nuclear Thermal Propulsion (SNTP) particle bed reactor. Further enhancement of the fuel could be accomplished by implementing non-graphite matrix materials that are able to operate in the high-temperature hydrogen environment of an NTP core. Production of the TRISO-derived particles for NTP could be performed using the same facilities, equipment, and processes used for the production of standard TRISOs for other government and commercial applications.

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.

2. Overview of Versatile NTP Stage

The versatile NTP stage would include a single "core tank" stage, and two or more "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 (>900 day round-trip), and a vehicle with three or more in-line tank stages would be used to support opposition class missions (<700 day round-trip). For the most difficult opposition class missions, it may be necessary to pre-deploy full propellant tanks at Mars, or to "drop" empty tanks prior to returning to earth. All stages fit within the proposed SLS 8.4m diameter x 27.4 m payload faring.

A schematic of the main NTP hydrogen propellant flow is shown in Figure 1.

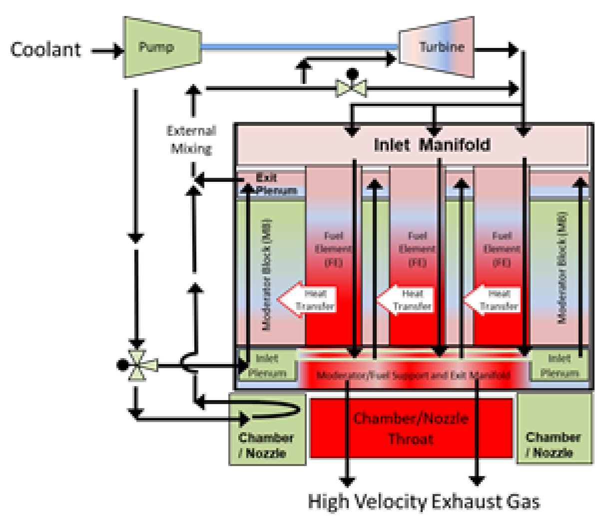

Figure 1. Hydrogen flow path for the Versatile NTP

In addition to providing high thrust (~15 klbf per engine) at ~900 s Isp, a separate hydrogen flow loop through the engine is designed to allow for an OMS system with up to 300 lbf (total) per NTP engine and high Isp (>500 s) with no complex valves or piping. 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.

3. Reference Stage Assembly Orbit

One Versatile NTP assembly 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 option for using the Versatile NTP to support human Mars missions 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. A schematic of a vehicle configured for an opposition class human Mars mission is shown in Figure 2. Figure 3 illustrates how the 68.5 mT stage elements fit into the proposed SLS 8.4m diameter x 27.4 m payload faring.

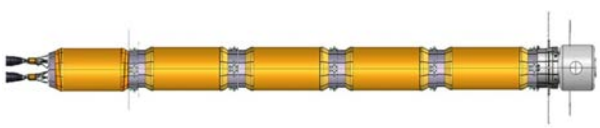

Figure 2. Potential vehicle configuration for opposition class human Mars missions.

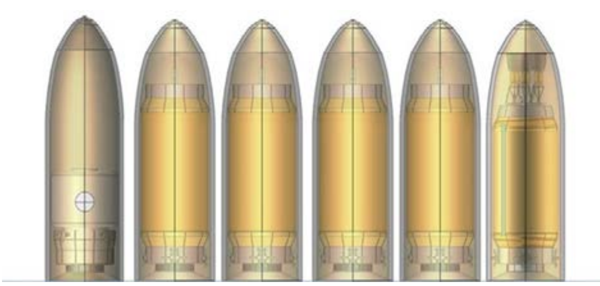

Figure 3. Packaging of the lower drop-off orbit NTP stages in the SLS 8.4 m faring.

4. 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 must be deposited into the propellant tank (via neutron and gamma heating) for every 1 MW of reactor power. An engine operating at 350 MWt would thus require that ~100 kWt be deposited into the propellant tank to maintain tank pressure as liquid hydrogen is pumped from the tank through the engine. 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 thermal inertia into the tank, 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, an additional water supply for the habitat's Environmental Control and Life Support System (ECLSS) in the form of a radiation "storm" shelter is considered. For simplicity, 4000 kg of water (mass saved by reducing the need for external engine shields) is used to provide a more robust radiation storm shelter for crew shielding during engine firings and solar particle events. Beyond providing excellent radiation shielding (compared to non-NTP options), this re-allocated mass from inert shielding to water provides relief on the reclamation requirement for a Mars mission, possibly reducing ECLSS system technology development risk.

Baseline values for the amount of water consumed per day per crew member are described by Anderson [2]. 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 4 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).

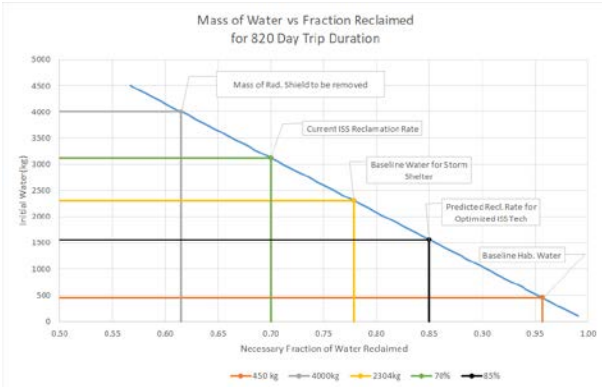

Figure 4. Water mass vs. reclamation fraction of water.

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 from the ISS water revitalization system. 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). Re-allocating NTP shielding mass to water mass of a "storm" shelter greatly reduces water reclamation requirements of a trans-Mars habitat.

5. 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 pressure 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 of 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.

6. First Generation NTP Reactor and Engine Design

The reference versatile NTP engine design produces 15 klbf of thrust, uses a moderator block comprised of either ZrHx, Be or BeO (or a combination of the three), and uses TRISO-derived fuel compacts with fuel kernels, coating thicknesses, coating materials, and matrix materials optimized for NTP applications. The approach is intended to allow utilization of current TRISO production line capabilities, with some augmentation required to allow production of the NTP fuel particles. All systems under consideration use low-enriched uranium, (uranium containing <20% U-235) and are designed to take advantage of certain features of LEU, such as negative reactivity feedback from Doppler broadening and low parasitic neutron absorption of the carbide based fuels relative to the refractory metal CERMETS.

Beryllium oxide (BeO) appears to be a good 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. 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. The use of ZrHx as a moderator block (as done by the former Soviet Union) appears to have advantages and disadvantages when compared to a BeO moderator block.

7. Potential Second Generation NTP Reactor Design

One potential second generation NTP reactor is the Centrifugal Gas Core Reactor (CGCR). The CGCR uses centrifugal force to contain liquid and gaseous fuel, as opposed to other gas core concepts that rely primarily on thermal hydraulic confinement. Although the CGCR is lower performing compared to other proposed gas core concepts (~1800 s Isp vs >3000 s Isp) [4], its design and development may be simpler and it could potentially provide an intermediate step to extremely high performance fission propulsion systems.

A conceptual schematic of the CGCR fuel element is shown in Figure 5, and a conceptual schematic of the CGCR core configuration is shown in Figure 6.

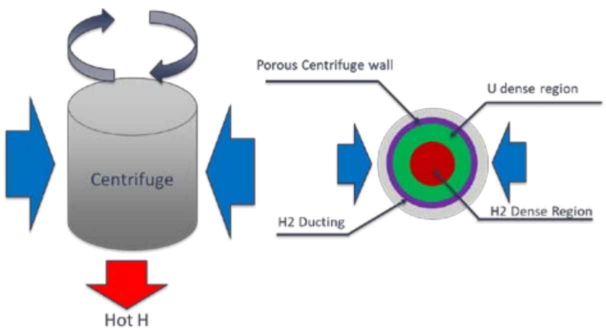

Figure 5. CGCR conceptual fuel element

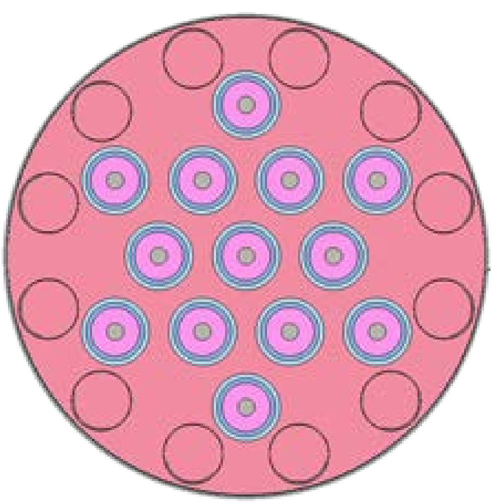

Figure 6. CGCR conceptual core configuration

The CGCR uses rotating cylinders as fuel elements. Fission energy heats the metallic fissile fuel, which is solid near the cylinder wall and liquid or vapor closer to the center of the cylinder. Hydrogen coolant is fed radially through a porous liner between the structural (pressure containing) wall of the cylinder and the fueled region. Centrifugal force separates the hydrogen (or other) propellant from the fuel, and the hydrogen preferentially exits axially from the center of the rotating cylinder and through a nozzle. The radial propellant inflow configuration allows peak reactor material temperatures (including the cylinder walls) to be maintained at <800 K, while the temperature of the gaseous fuel and propellant within the rotating cylinders can exceed 5000 K. Reactor mass is estimated to be <2000 kg if beryllium can be used as the structural material for the cylinder walls.

Significant design and engineering challenges remain for the CGCR. Fuel will tend to condense on the relatively cool (~800 K) hydrogen inlet frit, blocking propellant flow and causing the fuel to liquefy or vaporize (from fission heating) and be pushed towards the center of the cylinder by inward flowing hydrogen. The frit will need to be designed to withstand highly dynamic operating conditions for at least an hour, and possibly several hours for re-usable applications.

Fuel cylinder dimensions and rotational speed need to be optimized to ensure adequate separation of the fuel and propellant, with a potential design goal of <0.01% fuel entrainment in the propellant as it exits the nozzle. Fuel cylinder dimensions and spacing will also need to be optimized to minimize engine mass, and the optimal moderator design for use in the interstitial spaces between the cylinders will need to be determined. Reliable methods for initiating and maintaining cylinder rotation will need to be devised.

Techniques for routing the extremely hot propellant through the nozzle can build on experience with liquid rocket engines. However, the temperature of the CGCR propellant may exceed 5000 K, whereas the most efficient chemical rocket engines typically operate at peak combustion chamber temperatures of ~3600 K. In addition, the CGCR "chamber" will be rotating, whereas in chemical engines the combustion chamber is stationary.

Startup and shutdown techniques will need to be devised that minimize fuel loss while maintaining extremely high overall mission efficiency. Potential reactivity effects from fuel movement within the rotating cylinders will need to be assessed and (if necessary) mitigated. Reliable methods for adding small amounts of fuel during operation may be needed.

Numerous other design and engineering challenges will also need to be overcome. However, if successful the CGCR shows promise for achieving ~1800 s Isp when using hydrogen as propellant, and achieving ~900 s Isp using propellants such as ammonia, methane, or water.

8. Conclusions

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 crew exposure to other space hazards, reduced ECLSS performance requirements, and others. In cis-lunar space, missions include re-usable tugs and rapid, efficient orbit transfers. For advanced science missions potential benefits include shorter mission times, increased payload at the destination, and increased power at the destination. NTP-derived systems may also be well suited for providing electric power at unit sizes >100 kWe.

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