APPLICATIONS OF NUCLEAR THERMAL PROPULSION SYSTEMS FOR DEEP SPACE SCIENCE MISSIONS

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ABSTRACT

Nuclear thermal propulsion (NTP) systems occupy a unique area in the space propulsion technology landscape due to their ability to combine moderate-to-high thrust systems normally seen in chemical propulsion systems with specific impulses that are closer to those observed in some electric propulsion systems. Consequently, NTP systems have the potential to greatly expand access to deep space and can enable a variety of missions that achieve the science goals outlined in NASA's decadal surveys. This paper leverages previous analysis performed to show the applicability of NTP systems for notional science missions, expanding the analyzed portfolio to encompass additional science mission profiles and demonstrating how the use of NTP affects various mission parameters, such as trip time and delivered mass. This paper also outlines efforts to improve the fidelity of the existing NTP design concepts and vehicles that are utilized by leveraging previous work on nuclear propulsion systems for human-Mars missions. The fidelity of the analysis in this work is improved over previous studies, permitting commensurate improvements in the analyses of previous mission concept studies – the Triton lander, the solar polar orbiter, and the interstellar medium probe missions.

INTRODUCTION

Nuclear thermal propulsion (NTP) systems feature the use of a fission reactor, in which heat from the reactor is used to heat a propellant that is then expanded through a nozzle, providing thrust. NTP engines have the potential to provide thrusts comparable to conventional chemical combustion engines, but with up to twice the chemical combustion specific impulse. NTP has been considered for use since the Apollo era, with a number of reactor ground tests performed during the 1970s. Since then, NTP engines have been considered for a variety of missions, ranging from human missions to Mars to robotic science missions into deep space [1-3]. The high specific impulse and moderate-to-high thrust potential of the NTP engine can potentially enable or enhance payload capabilities for existing mission opportunities, as well as enabling new mission opportunities.

BACKGROUND

In February of 2019, the United States Congress directed NASA to develop plans for conducting an NTP engine flight demonstration by 2024. Specifically, the appropriations bill passed at the time requested that, "[…] 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." [4] To establish the traceability of the flight demonstrator (FD) design requested as part of this work to an operational mission application, the Advanced Concepts Office at NASA's Marshall Space Flight Center was directed to explore a range of NASA science design reference missions (DRMs) that would be enhanced or enabled by an NTP propulsion system with the operational characteristics of the flight demonstration engine.

OBJECTIVES

The purpose of this paper is to provide an overview of the mission analysis performed to date on selected DRM profiles featuring an NTP transport vehicle. This is a continuation of the analysis reported in Refs. [5][6]. Additionally, this paper provides a description of upcoming work that will refine and update the existing NTP vehicle models and expand the DRM tradespace.

METHODOLOGY

The analysis requires the evaluation of two separate models – a vehicle model and a mission model. The vehicle trade space and the mission trade space were both assessed in parallel, resulting in sizing models for the NTP vehicle and preliminary trajectory models for the DRMs under consideration. The vehicle sizing models were then used to generate surrogate models that could be used in an integrated optimization problem. The trajectory models were first optimized and refined on their own, then integrated with the vehicle surrogate models for further optimization and refinement. Figure 1 shows the process flow of that resulted in an integrated final reference mission optimization of both the vehicle design and mission.

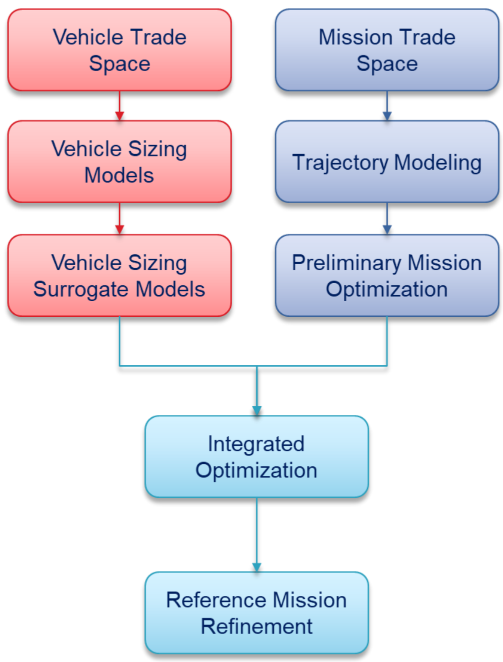

Figure 1. Process flow of vehicle and mission design.

VEHICLE DESIGN TRADES

The NTP vehicle tradespace was defined by specific vehicle considerations and constrained by the launch vehicles available for use. Recently, NASA's Space Technology Mission Directorate (STMD) has invested significantly in work to prove the utility of high-assay, low-enriched uranium (HALEU) nuclear reactor fuel for NTP Engines. The HALEU reactor fuel is limited to 19.75% uranium enrichment [7], which has advantages with respect to nuclear nonproliferation considerations. Additionally, a series of studies were performed to evaluate potential NTP flight demonstrator concepts that could be deployed within the decade [8]. Much of this work was leveraged in the NTP vehicle design presented in this paper. Several common vehicle design assumptions were made for the various vehicle subsystems [5][6], but the vehicle design also highlighted several major trades for consideration.

The major vehicle design trades can be summarized as follows:

1) **NTP Reactor Core Temperature:** The reactor temperature has a direct impact on the resulting specific impulse of the NTP engine. However, different configurations can yield different temperature values. To simplify the tradespace, three reactor configurations were evaluated – a “low” temperature of 1,876 K, a “medium” temperature of 2,216 K, and a “high” temperature of 2,586 K. These temperatures represent tradeoffs between the vehicle performance, and design/technological maturity. All configurations assumed a 12,500-lbf thrust level.
2) **NTP Propellant:** Two propellants were evaluated for this work; liquid/cryogenic hydrogen (LH_2), and liquid ammonia (NH_3). For the reactor core temperatures considered, liquid hydrogen’s specific impulse values are 750, 825 and 900 seconds, that correspond to the “low,” “medium,” and “high” reactor core temperatures respectively. For ammonia, the specific impulses values are 367, 404 and 440 seconds respectively. While liquid hydrogen has a higher specific impulse in general, it has a lower density and likely requires active cryofluid management for long-duration missions. Both factors can impact the dry mass allocations for an NTP propulsion system, which in turn affects the overall deliverable payload mass and mission performance.
3) **Launch Vehicle:** For this work, the SLS Block 2 and the New Glenn vehicles were considered. These two were selected based on the launch performance data that was available at the time of the work. Additionally, they represent tradeoffs between SLS’s larger capacity and the commercial vehicle’s mission flexibility and reduced cost.
4) **Cryogenic Fluid Management (CFM):** Depending on the propellant and mission evaluated, the NTP vehicle may require either a largely passive CFM system or an active system. While both options incorporate passive elements such as insulation and radiator panels, the active CFM system incorporates active cryocooler elements that require mass and power allocations. If ammonia is evaluated as the propellant, a “passive” system is sufficient. For hydrogen, some missions may be achievable with a passive system, but only an active CFM system can enable the use of liquid hydrogen for longer-duration science missions.
5) **Stage Composition:** Two configurations were considered for the vehicle design; a single-stage NTP vehicle, or a two-stage vehicle featuring an NTP stage and a chemical propulsion stage. For the chemical propulsion stage, a solid rocket motor (SRM) was used; STAR 48BV and CASTOR 120 SRM’s were evaluated for this work. Using a single NTP stage leveraged the more efficient NTP engine for all mission-critical burns, but having a multistage option could potentially maximize the ΔV budget available through more optimal staging considerations.

VEHICLE DESIGN APPROACH

To size the vehicle and optimize it for the given missions, a modeling/optimization toolkit known as the Dynamic Rocket Equation Tool (DYREQT) was used [5][6]. DYREQT is a multidisciplinary analysis and optimization (MDAO) tool written in Python that enables the user to synthesize and evaluate various space vehicle/mission architectures [9]. DYREQT uses the OpenMDAO Python package to handle inputs and outputs between the various vehicle sub-elements that are being modeled, as well as the mission elements.

MISSION DESIGN TRADES

Several missions were evaluated in the DRM tradespace, with many of the missions relevant to findings from the 2013-2022 decadal survey [10], the Ice Giants pre-decadal report [11] and the findings from work performed on a notional Interstellar Medium mission [12]. The baseline/reference cases that were used in this study as a point of comparison are elaborated upon in further detail in Ref. [5].

The missions considered in the DRM portfolio were:

1) **Triton Orbiter/Lander Mission:** Featuring an orbiter/lander payload, the vehicle would enter Neptunian space and insert into a high-elliptical orbit aligned with Triton, such that the orbit apoapsis would bring the vehicle into proximity of Triton's orbit.
2) **Uranus Orbiter Mission:** This mission would deliver an orbiter into Uranian space, with the possibility of insertion into an orbit that brings the vehicle within range of Uranian moons of interest, such as Mimas.
3) **Jupiter Orbiter Mission:** This mission is similar in payload profile to the Uranus orbiter mission, except with a focus on the Jovian planetary space and moons of interest, such as the Galilean moons.
4) **Solar Polar Orbiter Mission:** This mission involves deploying a heliophysics payload in a polar orbit over the sun.
5) **Interstellar probe Mission:** This mission features a science payload that is deployed into deep space, in excess of 100 AU, from the solar system, to measure properties of solar winds, the interstellar medium and other particle/magnetic field interactions.

MISSION DESIGN APPROACH

Because of the high energy requirements for these missions, it is problematic to attempt direct transfers from Earth. As a result, the trajectory models generally incorporated a variety of gravity assists and flybys to help reduce the energy requirements imposed on the NTP vehicle. Patched conic approximations were used in order to simplify the models evaluated, and to allow for the processing of large numbers of trajectories for optimization [5]. The NASA JPL SPICE toolkit was used to provide heliocentric coordinate and velocity information [13], and the pykep toolbox's Lambert solver was used to help evaluate the starting and ending velocities for a minimum energy trajectory [14].

RESULTS AND DISCUSSION

TRITON ORBITER/LANDER MISSION

The summary results of the Triton Orbiter/Lander Mission are shown below in Table 1.

Table 1. Triton Orbiter/Lander Mission results.

Propellant/ Launch Vehicle	***1st Stage ΔV [km/s]***	***Capture Stg ΔV [km/s]***	***1st Stage Prop [kg]***	***1st 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

The solutions for the Triton mission summarized in table 1. They are based upon a trip time of approximately 12 years, to match the electric/chemical propulsion baseline case's trip time. The solutions involved a two-stage vehicle, with a powered flyby at Jupiter using the NTP stage that would be jettisoned prior to the Neptune arrival. Alternate payload configurations that removed the lander requirement were also considered, with resulting payloads in excess of 8.6 mT possible at Neptune arrival. Increasing the payload mass resulted in longer trip times by up to eight years for a payload mass of 10 mT. An additional enhancing aspect of the NTP vehicle solutions is that they negated the need for an aerocapture in the Neptune system, which removed the mass penalty associated with aerocapture requirements and could either result in an increased payload or improved engine performance in the mission.

URANUS ORBITER MISSION

The summary of results for the Uranus Orbiter Mission are shown in table 2.

Table 2. Uranus Orbiter Mission 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

The mission times reported from the NTP solutions were shorter than the baseline Decadal Survey reference mission by up to 4.4 years [10]. By extending the trip time and incorporating additional gravity assists at Earth, Venus and Jupiter, it was possible to place 14.9 mT into Uranus orbit using an NTP vehicle, as opposed to 6.8 mT using conventional capabilities. The disparity in performance between conventional and NTP solutions is even more apparent in the "fast-transfer" option, with the NTP solution providing over 3.5 times the payload capability as the conventional case using Star 48BV engines.

JUPITER ORBITER RESULTS

The summary of results for the Jupiter Orbiter Mission are shown in table 3.

__Table 3.__ Jupiter Orbit Mission 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

The Jupiter fast-transfer NTP solutions feature a similar payload performance as the Uranus fast-transfer NTP solution, albeit with a much shorter trip time. Notable here is the ability of the NTP vehicle to deliver a payload into Jovian orbit with roughly twice the mass of the Juno mission orbiter, in a trip time of 1.2 years in the fast-transit mode. This represents roughly 3.6 times the payload capability of a comparable chemical propulsion transfer vehicle. With an Earth gravity assist using the New Glenn launch vehicle, the trip time is increased to 4.9 years, but the payload capability is more than doubled compared to the conventional solution.

SOLAR POLAR ORBITER RESULTS

The solar polar orbiter mission proved to be particularly problematic for the NTP vehicle, given the constraints and assumptions made [5]. The main factors complicating the solar polar orbiter mission could be summarized as such:

1) **Solar environment requirements:** A significant portion of the vehicle/payload mass would be devoted to the thermal shielding that would be needed to handle the increased solar radiation environment due to the close proximity to the Sun.
2) **Mission profile energy requirements:** To achieve a solar polar orbit, a large amount of ΔV needs to be allocated for the changes in orbit needed to reach a close solar approach, and an additional amount of ΔV needs to be allocated to transfer into a highly inclined orbit required to directly observe the polar regions of the Sun. Orbits that had longer dwell time in the optimal regions for data gathering required higher energy trajectories. Additionally, the high inclination of the target orbit greatly limited access to gravity assists from other planets.

As a result of these limitations, the NTP solutions obtained featured unacceptably long mission times compared to the baseline reference case [5]. Thus, further analysis was not performed for this mission.

INTERSTELLAR PROBE RESULTS

The results for the interstellar probe mission are shown in table 4.

Table 4. Interstellar Probe mission 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

The baseline cases for the interstellar medium mission included a solar thermal propulsion (STP) configuration, which uses solar thermal energy concentrators to facilitate heat expansion of a propellant through a nozzle. The resulting performance is comparable in specific impulse to an LH_2-propellant NTP vehicle, but with a much lower thrust. In the case of the interstellar mission, the STP baseline compared with other propulsion options had the highest escape velocity at 100 AU, but the NTP vehicle solutions were capable of reaching 100 AU at shorter trip times. Notable in this mission evaluation is that the ammonia-based NTP vehicle in an SLS fairing was able to reach 100 AU before the hydrogen-based NTP vehicle launched in a commercial vehicle. The heavy lift capability of SLS was leveraged to great effect, allowing the denser and heavier ammonia-based NTP configuration to overcome the reduced specific impulse and achieve the mission destination in a shorter trip time.

CONCLUSIONS AND FUTURE WORK

The analyses presented in this paper show that NTP vehicles are capable of enhancing missions to the outer planets and into deep space. The combination of high specific impulse and relatively high thrust provided by an NTP engine allowed for greater flexibility in tradeoffs between trip times, mission payloads, and launch vehicle orbit injections, resulting in a more robust science mission architecture. Future work focuses on several areas pertaining to vehicle design, mission selection, and further study refinement.

VEHICLE DESIGN UPDATES

Recent updates and refinements to the NTP engine and relevant subsystems must be incorporated into the DYREQT sub-elements used in the vehicle design. This includes updates to the reactor system, CFM elements, power, and structural systems. Additional thruster configurations are also to be incorporated into the vehicle design space, increasing the range of performance for the NTP vehicle.

Launch vehicle performance data also must be updated as newer data or additional options become available. This involves updating the launch performance data for the SLS Block 2 and the New Glenn commercial vehicle, as well as incorporating additional commercial launch vehicles with comparable performance. Updating the launch vehicle tradespace will also impact the launch vehicle payload limits imposed upon the mission.

MISSION SELECTION

Refining existing mission trajectories can help potentially identify additional viable NTP solutions. Additionally, updates to the NTP vehicle design and launch vehicle tradespace will necessitate updates to mission trajectories to reflect the changes in NTP vehicle performance. Additional missions of interest may be incorporated into the science mission portfolio, such as missions to the Trojan asteroids, planetary defense, long-duration survey missions, and many others.

STUDY REFINEMENTS

In addition to the refinements mentioned regarding vehicle design and mission selection, refinements to the DYREQT model as well as the pykep toolkit used for trajectory optimization will also be considered. This can involve improving the physical models used to size the DYREQT sub-elements for the NTP vehicle, as well as considering alternate trajectory modeling approaches that improve the trajectory fidelity.

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