Enabling Deep Space Science Missions with Nuclear Thermal Propulsion

A White Paper in Response to the Planetary Science and Astrobiology Decadal Survey 2023–2032 Call

Kurt A. Polzin
NASA-George C. Marshall Space Flight Center
kurt.a.polzin@nasa.gov, 256.544.5513

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Co-Authors
C. Russell Joyner, Aerojet Rocketdyne
Timothy Kokan, Aerojet Rocketdyne
Stephen Edwards, NASA-MSFC
Adam Irvine, Onyx Aerospace/MSFC
Mitchell Rodriguez, Jacobs/MSFC
Michael Houts, NASA-MSFC

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Abstract. Nuclear thermal propulsion (NTP) enables entirely new classes of deep-space science missions to yield scientific returns that, in most cases, are simply not possible with traditional architectures. NTP systems can yield dramatically reduced interplanetary travel times, deliver roughly 2-3 times (or more) the mass that can be delivered by conventional chemical propulsion systems, or provide a combination of these advantages to further enhance scientific return. Present NASA and DoD-sponsored plans for NTP systems will mature the technology using prototype and flight demonstration engines to prove the designs. These prototype engines will have performance in the correct thrust range so as to permit use as a low-risk propulsion stage in support of high-payoff deep space science missions. Additionally, the use of low-enriched Uranium (LEU) fuels over highly-enriched Uranium (HEU) fuels reduce the costs of engine development, qualification, acceptance and launch, and lowers the risks associated with proliferation management.

Purpose. The purpose of this white paper is to share with the Decadal committee the performance and scientific-return benefits of NTP for deep space science missions and to motivate additional conceptual studies to further examine the usefulness of NTP for science missions. In response to the Planetary Science and Astrobiology Decadal Survey 2023-2032 call, this white paper provides study results for deep space missions to the outer planets and into the interstellar medium using NTP. The system and mission advantages that can be realized using NTP are highlighted, and a description of current and planned investments in NTP by NASA and other government agencies that can be leveraged for deep space science is provided.

Background. NTP systems will enable faster interplanetary transits and/or increased payload delivery, providing the capability to execute deep space science missions – such as large orbiter probes visiting outer gas giants and their moons – within a reasonable timeframe. Amazing planetary science has been accomplished through the years using chemical propulsion systems. *New Horizons* is perhaps the most recent example, but this mission – which included a passive Jupiter gravity assist maneuver – required nearly ten years from launch to Pluto fly-by. Future missions, requiring larger energies and more ΔV to fulfill science objectives, will need more advanced propulsion systems. There are significant challenges to using solar sails and electric thrusters for deep space missions. Solar sails are optimally used in proximity to the Sun (within ~1.5 AU). Solar electric propulsion (SEP) systems have demonstrated great utility, performing notably on the *Dawn* mission to Vesta and Ceres. However, electric propulsion-propelled missions to gas giants and beyond will require the use of nuclear electric propulsion (NEP) systems.

Nuclear thermal propulsion (NTP) presents a distinct and compelling alternative in the advanced propulsion landscape to enable the achievement of entirely new deep-space science missions. NTP provides improved propulsion efficiencies compared to traditional chemical propulsion, while also providing substantial thrust. Therefore, unlike electric propulsion, NTP systems provide high acceleration, enabling greatly reduced trip-times compared to higher-I_{SP} alternatives.

A further advantage of NTP relative to NEP concepts is that the process for adding energy to the propellant stream is much more simple and straightforward. An NTP reactor replaces the combustion process of a chemical rocket, heating the working fluid (usually liquid hydrogen) to high temperature and pressure and then venting it through a rocket engine nozzle for thrust. The use of hydrogen or other low-molecular-mass propellant yields a combination of relatively high specific impulse (≥900s) and high thrust (~1-100klbf). By contrast, an NEP system involves a multi-step process where heat must first be efficiently converted to electricity and then that electricity must subsequently be conditioned to the proper current and voltage before finally being applied to electrically accelerate the propellant stream. Each of these steps incurs some energy loss and requires a portfolio of technologies, including low specific mass power conversion and heat rejection.

Technological developments are also required to enable the use of NTP, however, there are several ongoing and planned efforts to develop these technologies and to field an operational NTP system at a size and thrust-level that would be beneficial for deep space science missions. As this white paper will demonstrate, an NTP stage in the 1-15klbf thrust range can be enabling or significantly enhancing for delivering science payloads to deep-space targets.

A Viable Approach for Science. NTP engine development solely for the use of deep-space science missions is likely to be cost-prohibitive, due to high non-recurring costs and a long development time. However, an appropriately phased system development plan that leverages a smaller NTP engine and mature, existing liquid rocket component hardware provides a path to lower cost and a shorter technology development schedule. There are parallel NASA and DoD-sponsored efforts currently planned or underway that follow elements of this development plan. Both agencies are planning to develop demonstration engines in the correct thrust range that could be leveraged to provide enabling or enhancing NTP capabilities in support of deep space science. These programs aim to mature nuclear fuel design and development processes in parallel with maximizing the use of current liquid rocket engine turbopumps, valves, and chamber-nozzle designs. This approach enables the assembly of a pathfinder integrated engine system and nuclear propulsion stage in the ≤15klbf thrust class. This activity shall dramatically lower the development and testing costs relative to much larger NTP engines and can proceed more quickly to a system-level demonstration to advance the technology readiness level. These already-ongoing and planned efforts will result in an NTP system design at a technology readiness level (TRL) of ~6 that can be subsequently demonstrated in space and used for deep space science missions.

A major investment area for NASA's Space Technology Mission Directorate (STMD) is in proving the utility of High-Assay Low Enriched Uranium (HALEU or LEU) (19.75% U235 isotope in the uranium) as an alternative to weapons grade Highly Enriched Uranium (HEU) (93% U235 isotope in the uranium) for in-space propulsion and power system fuel.[1] Studies of LEU-based systems have produced reactor and NTP engine designs in the 2-15klbf thrust range with an I_{sp} of 900s or greater, which could be used in prototype designs for an NTP flight demonstration mission. Once these prototypes have been demonstrated in flight, it will be a low development risk to refine them into production-ready stages that could be used for deep space science missions.[2]

The use of LEU greatly reduces the proliferation risks associated with nuclear fuels fabrication and engine development, engine qualification and acceptance, and launch. The use of LEU also significantly reduces both the non-recurring development costs and the recurring costs of producing nuclear fuels required to field an NTP system. The STMD program, with work occurring at multiple NASA Centers and Dept. of Energy (DOE) locations, is focused on the design, development, and maturation of these LEU fuels and the control systems, turbomachinery, and cryogenic fluid management systems needed for nuclear propulsion systems. High temperature nuclear fuel testing at NASA-MSFC has shown promise in a gaseous hydrogen environment up to 2,800-deg Kelvin and the results of irradiated coupon testing at DOE's Idaho National Labs indicate that the fuel matrix strength and integrity are maintained in that environment. NASA STMD space nuclear efforts are aimed at providing a significant advancement in NTP technology readiness, with a planned prototype NTP system ready for testing by early 2027.

The Department of Defense also has a renewed interest in nuclear propulsion capabilities for application in high-Earth orbits and Cislunar space environments. The Defense Advanced Research Projects Agency (DARPA) has recently issued a request for proposals for a Demonstration Rocket for Agile Cislunar Operations (DRACO),[3] which is designed to operate below 10klbf thrust and at an I_{sp} up to 900s. The program plan aims for a demonstration in the late 2025/early 2026 timeframe.

NTP Mission Concepts and Benefits for Deep Space Science Missions. We describe several deep-space science missions where transformational science-objectives could be realized through the use of an NTP in-space stage. These include missions relevant to planetary science goals outlined in the previous 2013-2022 decadal survey[4] and the Ice Giants pre-decadal report[5] – specifically a Neptune/Triton orbiter, a Jupiter orbiter, and a Uranus orbiter – and the high science value Interstellar Probe mission to study the interstellar medium[6]. Primary benefits using NTP for these missions include greater payload masses to a destination and/or shorter trip times.

Neptune/Triton-Mission: Delivers at least 21% More Payload than Baseline w/o Aerobraking

Neptune and its moon Triton are of scientific interest for several reasons. Modeling of Triton's highly inclined retrograde orbit around Neptune shows that it is likely a captured member of a Kuiper Belt binary system.[7] Despite having a temperature of only 37K, Triton has an atmosphere, organic compounds on the surface, and evidence of an active geology.[8] Radiogenic heating and tidal dissipation in a subsurface ocean are thought to generate the heat driving Triton's activity.[9]

One study found that a spacecraft launched in late 2029 on a Delta IV Heavy (Del4H) and using electric propulsion, chemical propulsion, and an aeroshell for aerocapture and aerobraking, could enter a transfer orbit around Neptune in 2041 and deliver a payload of 1,115kg to a 200km circular orbit around Triton. A 792kg Neptune orbiter separates about the same time as the aeroshell to enter a 4,000 x 488,000 km orbit around Neptune. A combination of solid and storable liquid propulsion systems are used for orbital operations around Neptune, and the Triton payload is a descent stage and a hopping lander that vaporizes captured surface ice to reposition.[10]

The Advanced Concepts Office (ACO) at NASA-Marshall Space Flight Center studied NTP-powered missions to Triton, considering many different planetary flyby, launch vehicle, and propellant combinations. The objective was to find the maximum payload mass delivered to the same 200km circular orbit around Triton with a baseline-matching 12 year trip time that departed in the same timeframe, but did not employ aerocapture/aerobraking. Payload to Triton with and without delivery of the Neptune orbiter described in Ref. 10 was calculated. A two stage vehicle was modeled with a single engine NTP first stage. Both liquid hydrogen (900s I_{sp}) and ammonia (440s I_{sp}) were considered as propellants with hydrogen having the advantage of higher specific impulse and ammonia having a much higher density. The second stage was a storable chemical propellant stage with an assumed I_{sp} of 320s and an RTG electrical power system. Propellant load and the split between the stages was determined by the optimizer and limited by the launch vehicle payload volume of an SLS Block 2 (SLS 2B) with an 8.4m long shroud or a New Glenn (NG).

Table 1: Neptune/Triton NTP-powered mission study results for multiple launch vehicle and propellant options

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]**
LH_2 / SLS 2B	5.14	1.68	28,090	17,090	7,650	2,180	**No**	**8,000**	**7.17x**	**8,620**
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 / NG	5.63	2.53	16,950	11,330	4,220	1,410	**No**	**1,350**	**1.21x**	**1,980**
Baseline / Del4H[10]	7.01	2.11	2,610 Xe	1,600	1,233	NA	**Yes**	**1,115**	**1.0x**	**NA**

While there were hundreds of solutions for this mission, we present three in Table 1 that arrive in a Neptune orbit in ~12 years and provide a payload mass that exceeds the option in Ref. [10]. The three solutions all had one powered flyby of Jupiter using the NTP 1st stage, which was jettisoned prior to arrival at Neptune. The capture ΔV includes insertion around Neptune into a transfer orbit, an inclination change at apoapsis, and insertion into Triton orbit at the aligned transfer orbit periapsis. The NTP delivered payload could enable more capable or multiple landers and/or orbiters. While these solutions maximize payload, the optimizer could also reduce total mission time while holding the payload constant if shorter mission times are desirable.

Interstellar Probe: Reaching the ISM up to 4.4 Years Sooner than a Solar Thermal System

The interstellar probe mission involves a science payload deployed into the region of the Heliopause, starting at ~100 AU, where the Interstellar Medium (ISM) dominates the environment. The travel distances make it difficult to quickly reach the ISM – *Voyager 1* took 29 years to travel to 100 AU and *New Horizons* should take 32 years. The size and shape of the heliosphere, nature of the transition from the local solar environment to the ISM, and the general physical properties of the ISM are not well known. Improved knowledge and direct measurements of this region would provide insight into the formation of stars and planets.[6] Achieving a high heliocentric escape velocity is difficult to do directly, but it requires much less energy if the escape maneuver occurs close to a large gravitational body where it has a high velocity.

The following studies, used as a baseline for comparison, assume the interstellar probe has a mass comparable to the New Horizons spacecraft. The first configuration used an SLS Block 2 with a Centaur-derived third stage and STAR 48BV 4th and final kick stages, with the spacecraft able to achieve an excess velocity of 8.6AU/year using a Jupiter flyby. The second used the same configuration with a CASTOR 30XL final stage and a solar shield on a solar flyby to achieve ~12.6AU/year.[11] Finally, a third configuration using hydrogen in a solar thermal propulsion system on a solar flyby and a final solar electric propulsion system was able to achieve 19.1AU/year.[6] The ACO calculated the total time to 100AU for the first and third configurations to be 12.3 years and 14.5 years respectively. There was not enough information provided for the solar approach trajectory to calculate this time for the solar flyby mission using a solid stage.

A MSFC ACO Interstellar probe study considered an NTP-powered spacecraft using Jupiter and solar flybys with optional solid propellant kick stages. A solar flyby requires the addition of a solar shield to the vehicle that is scaled depending on the periapsis radius, while the final stage is sized based on the work in Ref. [11]. Table 2 shows a summary of selected mission results for different mission and NTP options. The NTP 1st stage is used for propulsive maneuvers prior to the final flyby. If no propulsion is required between the Earth departure and final flyby maneuvers, a passive cryogenic fluid management (CFM) system is used to reduce 1st stage burn out mass.

Table 2: Interstellar Probe NTP-powered mission selected results for multiple launch vehicle and propellant options

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	Comm. 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**

Of particular interest is the second option given in the table (LH_2, SLS launch, solar flyby), which uses the same vehicle configuration and launch vehicle as the first but has a significantly lower mission duration to 100AU for a slightly-reduced final escape velocity. Depending on mission objectives, this may be a desirable trade. The results show that an NTP-powered solar flyby mission to the ISM can reach 100AU faster and have a higher final escape velocity relative to comparable chemical propulsion missions in the literature. While a solar thermal propulsion system delivers the maximum escape velocity for an interstellar mission, such a system has limited utility for missions within the solar system. Finally, it takes over 40 years from the time of launch for the solar thermal powered spacecraft to reach a heliocentric distance equal to the NTP option in the second row of Table 2, with that occurring at 600 AU from the sun.

Jupiter: Enabling Fast Delivery of up to 2.4-3.6x More Payload than Chemical Baseline

NTP can deliver substantially greater payloads for a Jupiter orbiter mission compared to a conventional alternative (such as a Star 48BV-based kick stage) for both fast transfer and max payload trajectory options. Work by Joyner *et al.*,[3] summarized in Table 3, shows that an NTP stage launched on a SLS Block 2 with a single 15klbf / 900s NTP engine, similar to the size and performance envisioned in the NASA STMD development program, could deliver a 4,000 kg spacecraft (significantly larger than *Juno*) into orbit around Jupiter in 1.2 years on a direct fast transfer trajectory using a storable chemical insertion. A similar 1.2 year transfer using a Star 48BV departure stage with a storable chemical insertion would deliver a spacecraft less than 1/3 the size (1,120 kg). An NTP stage sized to launch on a commercial launch vehicle, such as New Glenn, can also deliver significant additional payload into orbit around Jupiter. Utilizing a 4.9 year transfer similar to the Juno mission, with a single Earth gravity assist, the same 15 klbf / 900 sec NTP can deliver 10,850 kg into orbit around Jupiter using a storable chemical insertion. By comparison, a Star 48BV departure stage with a storable chemical insertion and 4.9 year transfer would deliver approximately 40% of the NTP payload mass into Jovian orbit (4,450 kg).

Table 3: Transfer time and mass delivery values and benefits for an NTP-powered Jupiter mission

	Fast Transfer SLS Mission	Max Payload CLV Mission
Launch Vehicle	SLS 2B	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 to Jovian Orbit	**4,000 kg**	**10,850 kg**
Conventional Payload Capability to Jovian Orbit	1,120 kg	4,450 kg
NTP Payload Benefit vs Conventional Capability	**3.6x**	**2.4x**

Uranus: Delivering 2.4-3.5x More Payload for Flexible Science Capabilities to Outer Planets

Similar to the Jupiter mission, NTP provides significantly greater payload capability for a Uranus orbiter mission for both fast transfer and max payload trajectories when compared to a conventional chemical alternative, as summarized in Table 4. Launching on an SLS Block 2, an NTP stage with 15klbf / 900s could deliver a total payload mass of 4,350 kg – twice the size as that described in Ref. [5] – to Uranus orbit in 7.6 years, 4.4 years faster than the baseline 12-year transfer time. A similar 7.6 year fast transfer using a Star 48BV departure stage with a storable chemical insertion would deliver a spacecraft less than 1/3 the size (1,260 kg). Alternatively, if the baseline 12-year mission is assumed and a New Glenn launch vehicle is used, a stage utilizing the same 15 klbf / 900 sec NTP can deliver 14,900 kg into orbit around Uranus using a storable chemical insertion. A Star 48BV departure stage with a storable chemical insertion combination would deliver a 6,800 kg payload mass into the same orbit, less than half the NTP capability.

Table 4: Transfer time and mass delivery values and benefits for an NTP-powered Uranus mission

	Fast Transfer SLS Mission	Max Payload CLV Mission
Launch Vehicle	SLS 2B	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 to Uranus Orbit	**4,350 kg**	**14,900 kg**
Conventional Payload Capability to Uranus Orbit	1,260 kg	6,800 kg
NTP Payload Benefit vs Conventional Capability	**3.5x**	**2.2x**

Potential for Additional NTP Benefits and Enhancements. The use of an NTP stage for deep space science missions is shown to have quantifiable benefits relative to other more conventional propulsion systems. However, there are additional potential benefits to having an NTP system that have not been well-quantified to date and that merit investigation in future studies to determine the impacts these features might have on deep space science missions.

One of these potential benefits is the production of electrical power (~5 kW_e) from the thermal output of the NTP reactor.[12] Having multiple kW of electrical power available *in-situ* would be enabling for a wide range of more capable science instruments, thermal management, increased data-transmission power/bit-rate, and would additionally reduce or eliminate the need for a RTG power source on deep-space missions.

The benefits of having propellant available for end-of-trip NTP operation are thought to be significant, but require detailed study to fully quantify and address. Long-term cryogenic propellant storage is an ongoing area of research and development for all cryogenically-fueled propulsion systems, including NTP. If propellant boil-off losses can be significantly reduced or entirely eliminated, then the remaining propellant would enable the use of the NTP system for the end of trip braking and insertion maneuvers. Most studies use cryocoolers on cryogenic systems to reduce boil off, but these are not yet mature technologies. A potential alternative solution is to execute the NTP Earth departure burn soon after launch to minimize initial boil-off and significantly lower the pressure of the tank. The propellant remaining after the burn would continue to boil off, causing the tank pressure to increase. Depending on the volume of the tank and the amount of propellant remaining after the burn, this pressure increase might be sufficiently low to be containable within the tank for a long period of time. In addition, as the stage travels further from the sun, the external temperature decreases, further slowing the propellant boil-off rate. If enough propellant remained, it would be available for an NTP-powered insertion burn. If the cryogenic propellant issues cannot be readily solved to permit these type of end of trip maneuvers, then yet another alternative could be to use LH_2 on the departure burn and use storable NH_3 propellant for NTP-powered maneuvers at the destination.

Conclusions

- NTP systems using LEU fuel can support large payload masses and/or fast transit times, enabling more ambitious orbiter/probe or orbiter/lander science missions to the outer planets and reaching the interstellar medium relatively rapidly compared to baseline missions studies using chemical, electric, or solar thermal propulsion in combination with aerobraking,
- The use of LEU fuel as opposed to HEU fuel reduces the cost and programmatic risks associated with fuel production while lowering the associated risks of nuclear proliferation.
- Current and planned future development of NTP systems for NASA and the DoD will build and test prototype and demonstration engines in space. These engines will possess performance characteristics that are well-suited for deep space science missions (≥900s I_{sp} and 2-15klbf

thrust), will leverage existing liquid and cryogenic propulsion technologies, and could be used on NASA science missions for relatively low (non-recurring and recurring) cost.

Recommendations

- Include NTP in the Decadal survey as a propulsive option for deep space science missions to the outer planets and beyond.
- Articulate support for the current work of NASA and the DoD in developing NTP systems, including planned flight demonstration missions that aim to have performance levels that will also be enabling for deep space science missions.
- Articulate support for the performance of additional studies that compare NTP-powered deep space science missions to those propelled by alternate means, including conventional chemical propulsion and nuclear electric propulsion, and evaluate the TRL and system-level maturity, risk, and cost associated with each propulsive option.

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