Nuclear Thermal Propulsion for High Delta-V Science Missions

Ethan Chaleff[1], Craig Foulds[1], Adam Schilffarth[1], Michael Eades[1], [1]Ultra Safe Nuclear (Seattle, WA) Point of Contact: Ethan Chaleff, e.chaleff@usnc-tech.com, 425-341-3072

1. INTRODUCTION

Nuclear thermal propulsion (NTP) is an emerging near-term propulsion technology that will greatly improve the capability of planned science missions and unlock currently unavailable mission architectures. Multiple government programs and private investments are underway to finally bring NTP onto the launch pad, with a demonstration occurring as soon as 2026, funded through STMD. USNC is a leader in the development of NTP, and we are actively working with our public and private partners to enable propulsion solutions for upcoming science and commercial missions currently not possible with available propulsion technology. By creating a clear demand signal for NTP systems, SMD can ensure NTP is funded over this finish line. In turn, this will enable heavier payloads, faster transfers, and more flexible launch windows for SMD science missions being planned for the late 2020s and early 2030s.

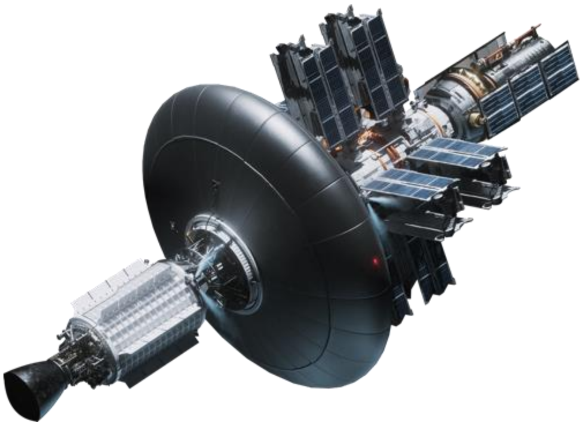

Figure 1. Artist Rendering of NTP Vehicle with Multiple Science Payloads

NASA's recent NTP efforts have emphasized development of NTP as the propulsion subsystem for a late 2030's human mission to Mars. An Outer Planets- and Small Bodies-focused approach still supports those longer-term Mars aspirations, but at a lower cost, risk, and schedule. Importantly, NTP provides real mission benefits (such as 200% payload increase) to these missions without relying on the higher risk NTP performance envelopes (in terms of thrust and Isp) needed to justify NTP in a Mars mission application.

1.1. KEY BENEFITS

The key identified benefits that NTP can bring to science missions includes:

- Faster transit times to distant destinations.
- Larger science payloads and spacecraft.
- Greater flexibility in launch windows by avoiding narrow-window, gravity-assist trajectories.
- Use of new, low-cost commercial launchers (Falcon Heavy, New Glenn, Starship) that were previously only possible with SLS.
- Combining multiple missions into a single rideshare.
- If NH_3 NTP is pursued, high (450s+) Isp maneuvers following long in space loiter without CFM.

2. WHAT CAN NTP DO FOR DEEP SPACE MISSIONS?

Deep space orbital destination science missions can benefit greatly from NTP as part of the propulsion subsystem. NTP has a higher specific impulse than comparable chemical propulsion and can produce orders of magnitude more thrust than electric propulsion. This has been described quite well in previous efforts, such as white paper responses to the Planetary Science and Astrobiology Decadal Survey (2023-2032 Call).

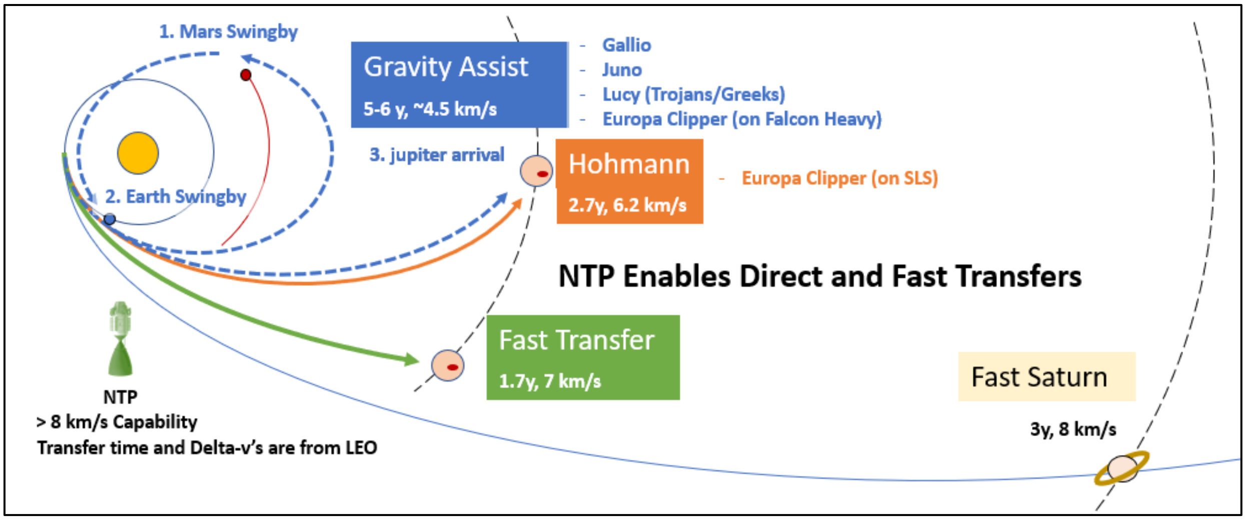

Figure 2. NTP enables direct and fast transfers of high-mass payloads to outer solar system destinations without gravity assists alignment. Certain use cases allow new capabilities such as long-loiter and high storability.

NTP enables science missions that use delta-v as an unconstrained resource, employing delta-v of 8 km/s from LEO at high thrust, with 10 km/s as a stretch goal, summarized in Figure 2. Reference mission concept abstracts that NTP can help enable include the list below, but also allows unique mission architectures, examples of which are explored below that list.

Outer Planets Assessment Group (OPAG)

- Jupiter System Observatory at Sun-Jupiter Lagrangian Point One
- New Frontiers Titan Orbiter
- Interstellar Object Interceptor Missions: Opportunities and Challenges
- Uranus Orbiter and Probe (UOP)
- Enceladus Orbilander
- Saturn Probe
- Triton Ocean World Surveyor
- Prometheus: A New Frontiers mission concept to Jupiter's moon Io

Small Bodies Assessment Group (SBAG)

- Centaur orbiter and lander (CORAL)
- Ceres Sample Return
- Comet surface sample return (CSSR)
- ISO Interceptor (Interstellar Object Interceptor Missions)
- Halley 2061 Missions
- Technology gaps for rapid response missions to near-Earth objects, interstellar objects, and long-period comets

Mercury Exploration Assessment Group (MExAG)

- Mercury Lander Mission Concept Study.

NTP represents enabling propulsion technology not currently captured in existing mission concept. As such, two mission concepts are explored briefly below.

2.1. MISSION CONCEPT I: MULTI-MOON SATURN FLAGSHIP

As an example of how NTP can enable Flagship Science missions, below we describe a mission concept combining 3 separate OPAG missions into one launch, which we call the "Multi-Moon Saturn Flagship". This mission would combine the "Titan Orbiter", "Saturn Probe", and "Enceladus Orbilander," into a single NTP-enabled mission launched to LEO via

Starship or SLS. We assumed a science payload of approximately 15t which we believe accommodates the objectives of all three of these OPAG missions, especially when considering potentially shared vehicle systems like communications and power. This results in a 150 t IMLEO combined NTP vehicle which could provide over 7.5 km/s at high thrust. This is enough to depart LEO for a direct Hohmann transfer to Saturn (~7 km/s) and enough to propulsively capture into Saturn orbit without waiting for gravity assist alignment, arriving at Saturn in under 3 years. Greater margin on propulsion system performance would expand the launch window or further decrease transit time. This is the type of SMD missions that NTP enables— high mass delivery quickly to deep space orbital destinations unbounded by the constraints of multi-planet alignments.

2.2. MISSION CONCEPT II: LOITERING SMALL BODY MISSION OF OPPORTUNITY

This mission concept is similar to ISO, but with the important distinction that rapid response could be abled with a long-term loiter by an interceptor until a mission of opportunity presents itself. One of the challenges of any high-performance in-space propulsion concept is propellant management for long periods. An NTP mission leveraging NH_3 as propellant provides unique opportunities to deploy a loitering, high delta-v vehicle for small body missions of opportunity, such as orbital flybys or interceptions. Ammonia as an NTP propellant does not offer the same specific impulse as hydrogen NTP systems (with a target Isp of approximately 450s compared to 900s for hydrogen) but does come with other critical mission enabling benefits. Notably, it exhibits higher Isp than best-in-class/ proposed storable propellant systems with a dense, well understood mono-propellant. With a small science payload, the mission can respond to a newly discovered interstellar object, Earth mini-moon, or other asteroid or comet with enough delta-v to feasibly reach heliocentric escape velocity from LEO (>8.5 km/s) and consequently all locations within the ecliptic of the solar system directly. This high delta-v loiter capability is unique to NH_3 NTP architectures. This delta-v can be used creatively for a wide variety of SBAG objects of interest, especially when including a smaller (~5t-class) conventional propulsion stage deployed from the parent NTP vehicle as a terminal interceptor.

2.3. FURTHER MISSION CONCEPTS

Our goal in describing the above concepts is to demonstrate how NTP can be uniquely enabling to SMD missions compared to existing propulsion technologies—other missions most certainly exist. USNC is eager to engage with SMD mission planners to help understand how NTP could enable missions currently outside the planned performance envelope of existing propulsion solutions.

3. CONCEPTUAL VEHICLE DESCRIPTION WITH NTP

3.1. ARCHITECTURE

NTP vehicles are conceived to be high delta-V, in-fairing, upper stage vehicles resembling conventional upper stages similar to Centaur (or Fregat), but with longer mission life and significantly greater delta-V (exceeding 8 km/s for high thrust options). The major sub-components for an NTP subsystem would be the reactor itself, the tank and propellant management systems, and the structural frame. The vehicle would then comprise the propulsion subsystem, vehicle systems, and the science payloads it carries. Depending on the specific mission architecture, the science payload itself would be an independent spacecraft deployed from an NTP transport stage, or a “ride-along” style science payloads that stay with the parent vehicle for the duration of the mission.

3.2. LAUNCH VEHICLES

NTP vehicles utilize economies of scale at a fundamental design-level and continue to improve in performance as launch vehicle capacity to LEO increases. Based on USNC's internal analysis, there is a minimum IMLEO threshold in which NTP performance begins to exceed conventional propulsion methods. This is heuristically defined as where the mass of the reactor ceases to be a significant component of the fairing volume and mass to orbit. For the specification of NTP subsystems being developed by USNC, Falcon Heavy represents the first commercial launch vehicle with IMLEO capacity exceeding this design threshold, and emerging vehicles are expected to follow suit. Falcon Heavy, New Glenn, Vulcan, and Starship, in addition to SLS are all candidates for useful NTP vehicles carrying deep space science missions.

3.3. PROPELLANT

USNC has developed NTP concepts for two different propellant architectures and is currently improving internal sizing tools to support a variety of mission cases. NH_3 vehicles have half the propellant performance of LH2, but they can make up for it at a vehicle-level in a way that is cost competitive for the same payload mass or delta-v. Missions with maximum performance requirements will require LH2, while NH_3 NTP vehicles can be built in the near-term and offer certain mission-application-specific advantages, mostly related to the propellant density and long-term storability.

4. NTP PROVIDES A NEAR-TERM PATH TO COST EFFECTIVE PERFORMANCE

Both NASA and DARPA have active programs to demonstrate NTP in the near term. After decades of intermittent progress, in recent years, NTP has seen technology and infrastructure advances that bring the time horizon for deployment of an NTP system closer than at any time since the closure of the NERVA program. The realization of multiple heavy-lift vehicles is also an important environmental enabler of NTP-supporting missions. The most important recent technical advances have all centered around materials science and associated testing capabilities for LEU-capable NTP fuels.

Figure 3. The NTREES at NASA MSFC facility enables low-cost, non-nuclear testing of NTP fuel elements in a flight-like thermal/chemical environment.

From a technology maturity perspective, the only significant gap remains the performance of the fuel for systems of interest; fortunately, significant advancements in LEU-capable fuels are actively being made. These fuels deliver fission product retention and low-proliferation risks, reducing the cost and burden on fuel-testing, engine-testing and eventual launch operations. Recent successes for NTP fuel demonstration have increased the confidence in achievable fuel performance envelopes, though significant work remains.

Hand-in-hand with technology maturity is the ability to test that technology; here too, significant advancements have been made in recent years. Upgrades to existing facilities (e.g. CFEET, NTREES) and near-term non-nuclear testing capabilities (such as USNC's upcoming Hot Hydrogen Mechanical Test Facility) are rapidly accelerating the nation's capability to perform non-nuclear testing of relevant NTP fuels, enabling faster iteration at lower cost and accelerating the design cycle. Newly available testing capabilities at TREAT (including the near-term work for the BUSTER test cell) will enable hot, flowing hydrogen transient testing and allow for the most prototypic NTP testing capabilities since NERVA. NASA's recent Space Nuclear Propulsion Office supported reactor and engine design studies have advanced the maturity of the non-fuel elements of engine and vehicle subsystems, while recent tipping points on Cryogenic Fluid Management (CFM) all show promise if storable LH_2 missions are pursued. Importantly, fast outer-planet transit science missions can significantly decrease the challenge of CFM compared to human Mars missions, either by avoiding requirements for ZBO systems if used only as an upper stage or by using storable propellant vehicle architectures (e.g. NH_3).

4.1.COST FOR DELIVERY OF AN NTP SYSTEM

As described above, NTP can provide a clear performance benefit to science missions; the ultimate question is whether the performance justifies the cost expenditure. Significant work on the part of STMD's SNP program and its industry and lab partners have continued to define cost- and schedule-acceptable pathways for developing and deploying an NTP engine within a modern regulatory framework. Specifically, recent work at INL to support advanced reactor development (NRIC) coupled with revisiting past program assumptions could enable NTP engine demonstration at hundreds of millions of dollars less than previously estimated. Further cost savings can be realized by targeting engine performance specifications which are bounded by existing infrastructure constraints; these compromises are acceptable for the science-supporting missions referenced in this White Paper. Estimates for program and engine costs for NTP as part of science missions will of course vary widely and have key sensitivities to mission parameters and schedule drivers. That said, within a class of reasonable options, from its perspective as a potential vendor of reactor/engine subsystems to a reasonable class of science missions, USNC estimates that the overall government investment in NTP for a first mission use-case is on the order of \$0.75-\$1.0B. Once development is complete, we estimate that the cost to provide an operational NTP propulsion subsystem to be on the order of \$150M.

The timeline for delivery of an NTP system will as well be intimately coupled to available funding and mission drivers. The key driver SMD missions can make is to help ensure that NTP vehicle and propulsion subsystem specifications can be connected to specific mission drivers. This will allow key trades to be made and closed, accelerating deployment. A timeline of the late-2020's appears feasible for delivery of an operational propulsion subsystem for vehicle integration for planned OPAG and SBAG missions.

5. CONCLUSION

Our goal in describing the above concepts is to demonstrate how NTP can be uniquely enabling to SMD missions compared to existing propulsion technologies. By creating a clear demand signal for NTP systems, SMD can ensure NTP is funded over this finish line. In turn, this will enable heavier payloads, faster transfers, and more flexible launch windows for SMD science missions being planned for the late 2020s and early 2030s.