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LEU NTP FLIGHT DEMONSTRATION VEHICLE AND APPLICATIONS TO OPERATIONAL MISSIONS

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Nuclear thermal propulsion (NTP) has been extensively researched as a potential main propulsion option for human Mars missions. NTP's combination of high thrust and high fuel efficiency makes it an ideal main propulsion candidate for these types of missions, providing architectural benefits including smaller transportation system masses, reduced trip times, increased abort capabilities, and the potential for transportation infrastructure reuse.

Since 2016, AR has been working with NASA and members of industry as part of the NASA Space Technology Mission Directorate Game Changing Development Nuclear Thermal Propulsion Project. The overall goal of this project is to determine the feasibility and affordability of a low enriched uranium (LEU)-based NTP engine with solid cost and schedule confidence.

Having shown feasibility and affordability, program planning has been underway for follow-on activities to continue to mature the LEU NTP engine technology. These activities include program planning for reactor fuels testing, reactor component design, engine component technology development, test facility design and demonstration, and a demonstration engine available for ground test and potentially flight test. These follow-on activities would set the stage for full scale development of a human rated NTP flight engine for use in human exploration missions.

This paper presents details of a potential LEU NTP prototype flight test and corresponding first flight vehicle along with potential applications of an evolved vehicle for subsequent operational missions.

NOMENCLATURE

AR = Aerojet Rocketdyne
CFM = Cryogenic Fluid Management
CLV = Commercial Launch Vehicle
DoD = Department of Defense
E-M = Earth-Moon
L1 = First Lagrange Point
GCD = Game Changing Development
Isp = Specific Impulse
LEO = Low Earth Orbit
LEU = Low Enriched Uranium
LH2 = Liquid Hydrogen
MEO = Medium Earth Orbit
MLI = Multilayer Insulation
MMOD= Micro-meteoroid Orbital Debris
MSFC = Marshall Space Flight Center
NASA = National Aeronautics and Space Administration
NTP = Nuclear Thermal Propulsion
RAAN = Right Ascension of the Ascending Node
RCS = Reaction Control System
SLS = Space Launch System
SOFI = Spray-on Foam Insulation
STMD = Space Technology Mission Directorate
TDRS = Tracking and Data Relay Satellite
ULA = United Launch Alliance

I. INTRODUCTION

Since 2016, AR has been working with NASA, the Department of Energy, and members of industry as part of the NASA Space Technology Mission Directorate (STMD) Game Changing Development (GCD) Nuclear Thermal Propulsion (NTP) Project. The overall goal of this project is to determine the feasibility and affordability of a low enriched uranium (LEU)-based NTP engine with solid cost and schedule confidence.

Having shown feasibility and affordability, program planning has been underway for follow-on activities to continue to mature the LEU NTP engine technology. These activities include program planning for:

1. Initial NTP engine system technology development including reactor fuels testing, reactor component design, engine component technology development, test facility design and demonstration;
2. Prototype NTP engine development including potential testing either on the ground or in flight;
3. Human rated NTP flight engine full scale development for the full scale flight engine for human exploration mission.

As seen in Figure 1 below, the prototype NTP engine development and testing provides a path, along with the initial NTP engine system technology development activities, to a human rated NTP flight engine system.

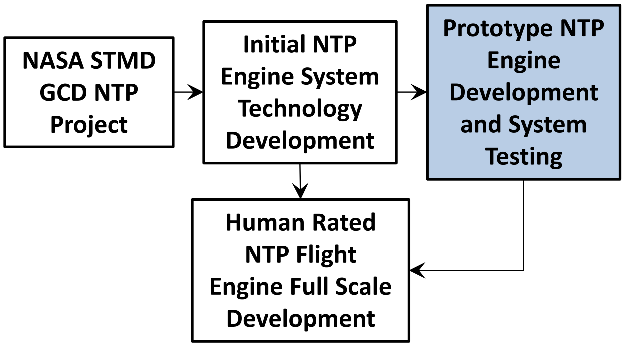

Fig. 1. Prototype NTP engine development and system testing, either on the ground or in flight, provides a path from STMD GCD NTP feasibility assessment to NTP flight engine full scale development

AR is currently performing preliminary definitions of potential prototype NTP engine flight test options that can reduce technical risk for the larger human rated NTP flight engine full scale development. The following sections will discuss these flight test options along with potential options for evolved vehicles based on the flight test vehicle to perform operational missions.

II. PROTOTYPE ENGINE FLIGHT TEST OPTIONS

In 2019, AR started examining various approaches for prototype NTP engine flight test vehicles that would have lineage to a NTP-based human Mars architecture.

An initial screening of flight test mission concepts examined missions that provide information on NTP operational verification, demonstration of integrated cryogenic systems versus non-cryogenic systems, NTP integration with a cryogenic stage similar to the Mars vehicle, packaging capability for launch on a commercial launch vehicle (CLV), and many other attributes.

Based on these initial screening activities, the best NTP and stage flight test approach appears to be one that achieves the following goals:

1. Have drop-off orbit that provides safety - independent of prototype NTP engine operation;
2. Demonstrate operation of a NTP engine (reactor) in space: Perform multiple burn sequences (start-up, main stage, shutdown, cooldown) with burn times to demonstrate NTP capability;
3. Demonstrate processes for a safe launch and operation of a nuclear reactor into space via commercial launch similar to Department of Defense launches;
4. Demonstrate passive cryogenic fluid management (CFM) for an extended period of time applicable to Lunar and Mars missions and apply data to design of robust passive/active CFM technologies;
5. Demonstrate launch of a cryogenic stage in the payload fairing of a launch vehicle (Figure 2).

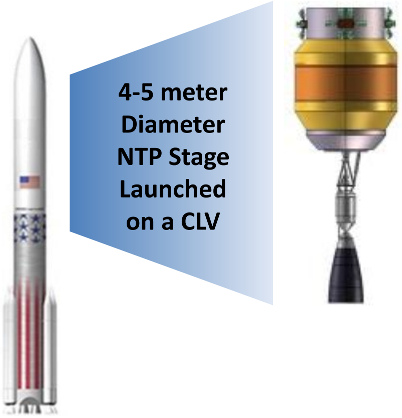

Fig. 2. A prototype NTP flight test vehicle can be sized to fit on existing or near-term future CLVs

Many potential flight test mission options can satisfy these goals, including low Earth orbit (LEO) plane changes (either changes in inclination or right ascension of the ascending node (RAAN)), LEO-to-medium Earth orbit (MEO) altitude changes, and LEO-to-Earth-Moon (E-M) L1 transfers.

The LEO plane change demonstration mission (Figure 3) was selected for further study because it has several operational advantages:

1. Flexibility in the final orbit allowing for shorter or longer than nominal NTP burn times;
2. Continuous nuclear-safe orbit throughout the mission;
3. Altitude is kept below the global continuous coverage provided by the Tracking and Data Relay Satellite (TDRS) system.

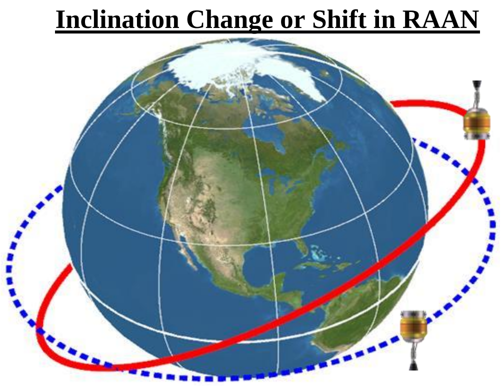

Fig. 3. LEO plane change flight test mission

III. LEO PLANE CHANGE MISSION PARAMETRIC TRADES

Parametric trades of different prototype flight vehicle sizes and different prototype NTP engine thrust levels are provided in Section III.

A primary flight test mission goal is to demonstrate NTP operability over several main engine burns. In order to achieve this goal, the LEO plane change mission is envisioned to consist of two burns, each with a minimum burn time of six minutes (30 second startup, minimum of 5 minute main stage, 30 second shutdown). This results in the need for a stage large enough to permit up to 10 minutes of NTP main stage burn time.

A nuclear safe LEO starting orbit of 2,000 km x 2,000 km x 25° is selected. This orbit is advantageous for several reasons, including:

1. Low orbital debris spatial density;
2. Negligible atmospheric drag;
3. Continuous tracking and data relay coverage provided by TDRS.

Figure 4 provides a sensitivity of burn time to stage gross mass for two different prototype NTP engine thrust levels (12.5 klbf and 15.0 klbf) with different launch vehicle class capabilities called out. A prototype NTP engine flight test vehicle with a 12.5 klbf NTP engine and a 20 mT vehicle gross mass is highlighted with the blue star as it provides sufficient total NTP main stage burn time and can be launched on the Delta IV Heavy or a future medium CLV such as Vulcan or Omega.

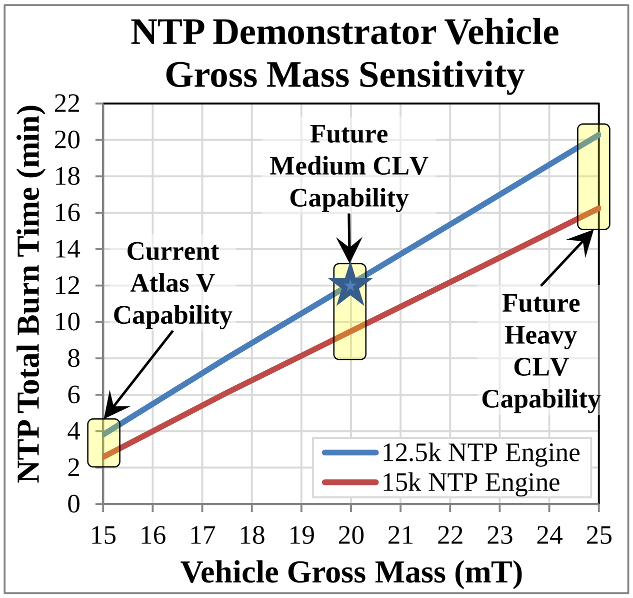

Fig. 4. Several launch vehicle options are capable of launching a prototype NTP engine flight test vehicle sized to achieve the prototype engine total burn time goal of >10 min

Figure 5 shows the orbital changes envisioned for the prototype NTP engine flight test mission. The mission details are for an example 12.5 klbf prototype NTP engine thrust and an initial test flight vehicle gross mass of 20 mT. This engine and vehicle size combination allows for over 12 minutes of main stage burn time.

Burn #1 is envisioned to operate at a lower reactor temperature, providing additional reactor temperature margin for the first use of the reactor in space, resulting in an initial Isp of 800 seconds. Burn #2 is then envisioned to operate at the 2700 K nominal reactor operating temperature, resulting in an Isp of 900 seconds.

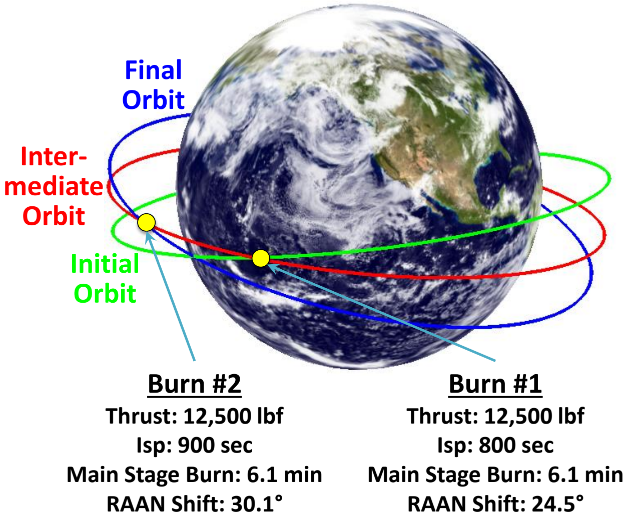

Fig. 5. Two-burn prototype NTP engine flight test mission achieves key demonstration goals (multiple burn sequences, >10 minutes of NTP main stage burn time) while staying within a nuclear safe orbit

Figure 6 provides the envisioned concept of operations for the example 12.5 klbf / 20 mT prototype NTP flight test vehicle mission shown in Figure 5. The near-24-hour mission consists of an initial checkout of approximately 6 hrs, a first 6-minute main stage burn, a 6-hr coast / cooldown, a second 6-minute main stage burn, a second 6-hr coast / cooldown, and a final approximate 6-hr for mission closeout and stage safing and monitoring.

12.5k NTP Engine / 20 mT Gross Mass Vehicle			
	$T_{Initial}$ (hr)	**ΔT (hr)**	**T_{Final} (hr)**
Launch to 2,000 km circ @ 25 deg	0.0	0.5	0.5
Spacecraft Checkout (3 orbits)	0.5	6.0	6.5
First Burn (Startup / Main Stage / Shutdown)	6.5	0.1	6.6
Coast / Engine Cooldown (3 orbits)	6.6	6	12.6
Second Burn (Startup / Main Stage / Shutdown)	12.6	0.1	12.7
Engine Cooldown / Checkout (3 orbits)	12.7	6	18.7
Mission Closeout / Monitoring	18.7	6	24.7

Fig. 6. Near-24-hour prototype NTP engine flight test vehicle mission duration is sufficient to achieve mission goals

Figure 7 shows the example 12.5 klbf / 20 mT prototype NTP flight test vehicle within the United Launch Alliance (ULA) Vulcan launch vehicle 5.4m diameter payload fairing. The NTP test vehicle can be sufficiently sized with enough liquid hydrogen (LH2) to permit at least 10 minutes of NTP main stage burn time while still fitting within the dynamic envelope of the Vulcan payload fairing.

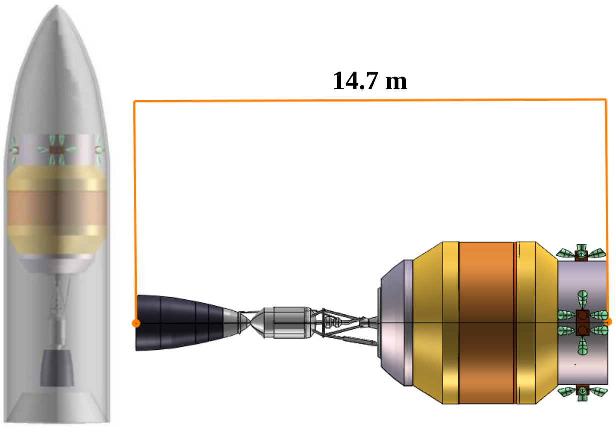

Fig. 7. Prototype NTP flight test vehicle sized to fit in the ULA Vulcan 5.4m diameter payload fairing

Figure 8 provides a summary mass roll-up for the 12.5 klbf / 20 mT NTP flight test vehicle. The flight test vehicle is envisioned to leverage CLV upper stage subsystems to the greatest extent possible, including: LH2 tank and primary structures, storable reaction control systems (RCS), batteries, command and data handling, guidance, navigation, and control, communications, passive CFM (spray-on foam insulation (SOFI), multilayer insulation (MLI)), and micro-meteoroid orbital debris (MMOD) shielding.

Subsystem	**Predicted Mass (kg)**
1.0 Structures	**3,018**
2.0 Propulsion	**5,625**
MPS	5,511
RCS/OMS	114
3.0 Power	**252**
4.0 Avionics	**405**
5.0 Thermal (SOFI, MLI, MMOD)	**685**
Dry Mass	**9,986**
6.0 Non-Propellant Fluids	**450**
Inert Mass	**10,436**
7.1 MPS Usable Propellant	**5,935**
7.2 RCS Usable Propellant	**180**
Gross Mass	**16,550**
Payload	**1,000**
LV Payload Attach Fitting	**500**
LV Payload Margin	**1,950**
LV Payload System Mass	**20,000**

Fig. 8. Summary mass roll-up of example NTP flight test vehicle sized to launch on a ULA Vulcan launch vehicle

IV. EVOLVED VEHICLE OPTIONS FOR OPERATIONAL MISSIONS

In addition to providing risk reduction for a full scale human rated NTP flight vehicle, the prototype NTP flight test vehicle can also provide an initial starting point for an evolved operational stage (Figure 9).

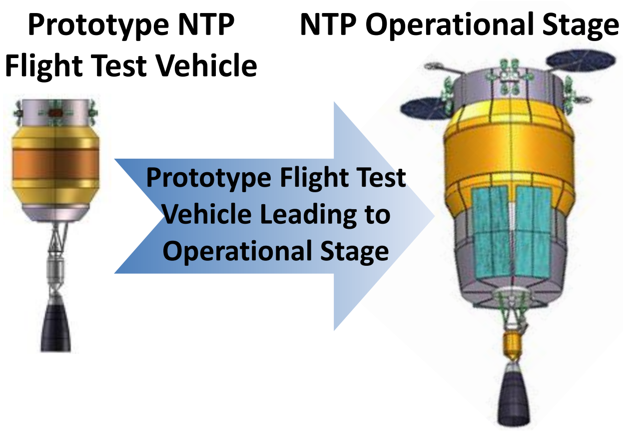

Fig. 9. A prototype NTP flight test vehicle can be evolved for use on future operational missions[1]

Missions such as outer planetary science, Cislunar cargo delivery, and Earth orbit altitude / plane changes could potentially benefit from an operational NTP in-space propulsive stage.

Example outer planetary science mission trade results are provided in Figures 10 and 11 for Jupiter and Uranus deep space science missions[2]. This NTP operational stage is sized to fit, along with a payload, within the Long SLS 8.4m diameter payload fairing. This stage has an estimated gross mass of 31 mT, approximately 50% larger than the NTP flight demonstrator vehicle discussed in Section III.

Unlike the NTP flight test vehicle, the NTP operational stage would require active CFM utilizing cryocoolers to maintain the LH2 in a liquid state for the duration of the potentially multi-year mission.

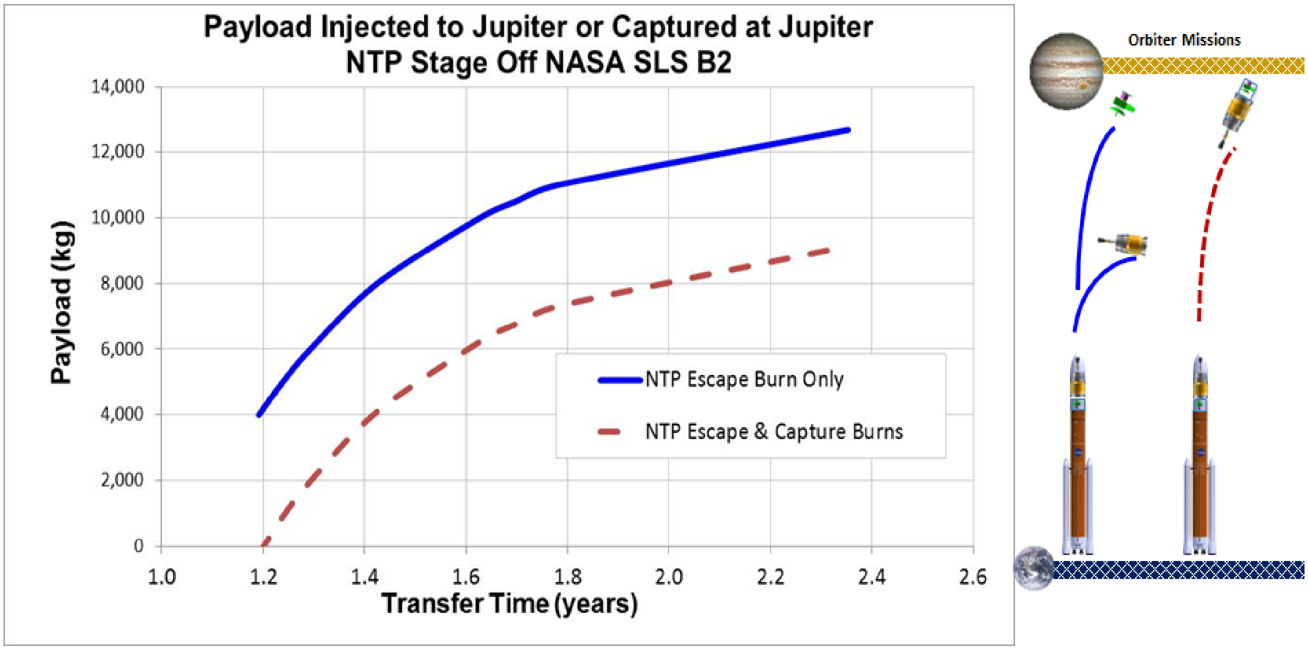

Fig. 10. Deep Space NTP Operational Stage for Jupiter Orbiter Missions using NASA SLS Block 2 Launch Vehicle

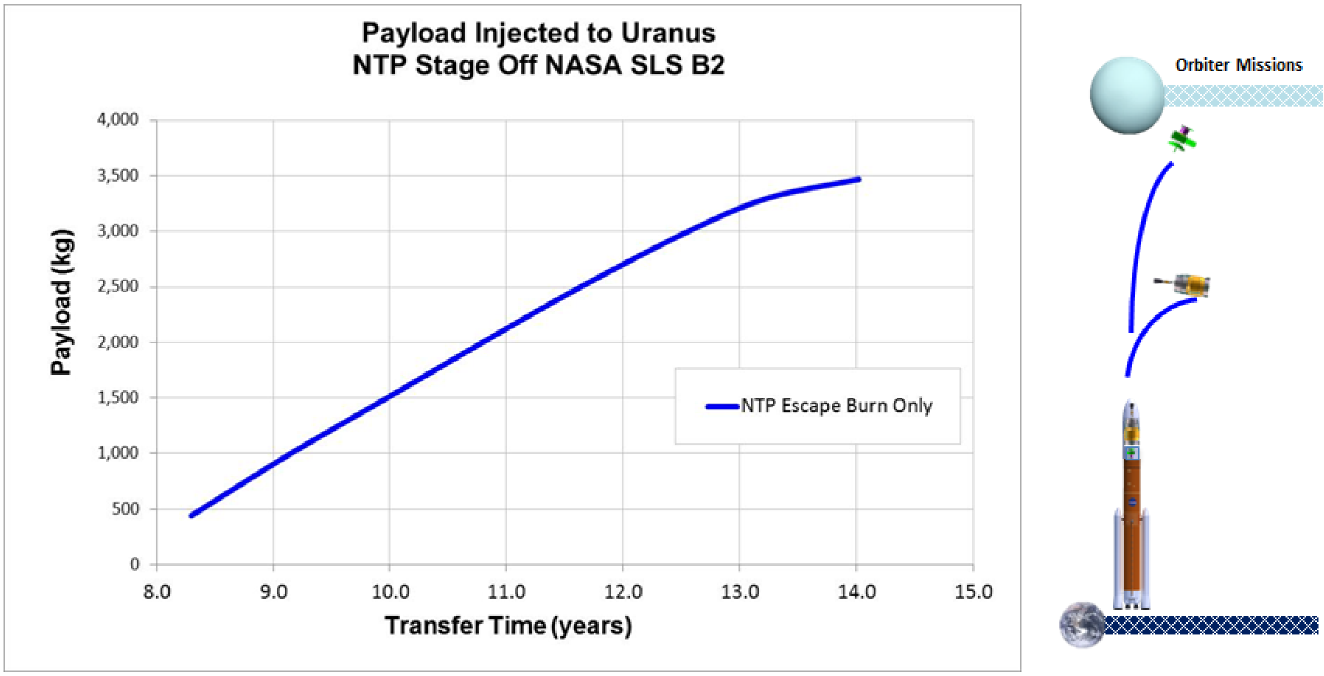

Fig. 11. Deep Space NTP Operational Stage for Uranus Orbiter Missions using NASA SLS Block 2 Launch Vehicle

V. CONCLUSIONS

Prototype NTP flight test vehicle options with applications to operational missions were defined. Flight test missions were identified that allow for the safe testing of the NTP flight test vehicle in space, demonstrate NTP engine operation in space with multiple engine burns with sufficient burn times to demonstrate main stage capability, provide risk reduction on NTP and stage CFM systems, and launch on CLV's. Furthermore, operational missions were identified that utilize an evolved NTP in-space propulsion stage to provide significant mission benefit. Examples were provided for outer planetary science missions to both Jupiter and Uranus.

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