# NEAR-TERM OPTIONS FOR A NUCLEAR THERMAL PROPULSION FLIGHT DEMONSTRATOR

S. J. Edwards, M. A. Rodriguez

National Aeronautics and Space Administration

Jacobs Space Exploration Group

Marshall Space Flight Center, Alabama

## ABSTRACT

The Appropriations Bill passed by the US Congress in February 2019 instructed NASA to direct “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.” [1] As part of NASA’s response to this direction, the Advanced Concepts Office (ACO) at the Marshall Space Flight Center (MSFC) was tasked with leading a study to develop a nuclear thermal propulsion (NTP) flight demonstration (FD) concept and evaluate its feasibility with respect to the near-term schedule goal.

During formulation for the NTP FD study, two perspectives emerged with regards to FD concept design. The first seeks to strictly observe the immediate near-term schedule goal, embracing a completely “off-the-shelf,” high-TRL approach to subsystem design and component selection. The downside to this approach is that the propulsion performance to be expected from such a design is significantly lower than what NTP promises for operational systems, and the value of the flight demo is potentially reduced due to a lack of traceability. The second approach advocates for an FD concept that shows increased traceability to the projected designs of operational systems, providing risk reduction for future NTP-enabled missions. This option comes at the cost of schedule and development risks, as it requires some new investments in nuclear reactor fuels and design.

In order to understand the implications and differences between these two approaches, the ACO team elected to perform a concept design of each type, labeling the immediate near-term concept Flight Demo 1 (FD1), and the higher traceability concept Flight Demo 2 (FD2). This paper will present a summary of the mission profiles and system designs for both FD1 and FD2, identifying key drivers and challenges for each design.

## INTRODUCTION

This paper reviews the FD1 and FD2 demonstrator concepts that were investigated, providing a brief description of the main and auxiliary propulsion systems, the power and avionics systems, configuration and structures, as well as a concept of operations for each system. Ground rules and assumptions will be discussed, as well as how they influenced the design philosophies for each system.

## DEMONSTRATION MISSION CONCEPT OF OPERATIONS

In both the FD1 and FD2 mission profiles, two types of burns will be performed with the NTP system. The first is considered to be a “performance burn”, where the reactor operates at maximum power in order to obtain the highest possible thrust level and specific impulse. The minimum threshold for the duration of this burn is set by the time required to achieve thermal equilibrium in the reactor. The second burn would then be a “demonstration burn” that will demonstrate restart capability, and if able, will demonstrate operations at various power levels. No specific duration requirement is set for this burn; however, the more propellant available, the more data that can be collected on characterizing engine/reactor dynamics.

The most significant difference in conops between FD1 and FD2 is a switch in targeted graveyard orbits. During execution of the FD1 design, a heliocentric graveyard orbit was targeted; for FD2, this was changed to a medium altitude circular Earth orbit.

## FD1 - HELIOCENTRIC ORBIT GRAVEYARD MISSION

The FD1 system used a mission profile featuring an insertion into a heliocentric “graveyard orbit” with an aphelion lower than one AU. This profile was selected in order to minimize risks regarding nuclear safety and re-entry of nuclear components in an off-nominal situation. A trade study evaluating the most efficient ways of achieving this orbit led to the selection of a trajectory leveraging an unpowered Venus flyby for lowering the spacecraft’s aphelion. Because of the low-thrust nature of the FD1 system, the critical trajectory maneuvers will be handled by the launch vehicle, as well as the onboard auxiliary propulsion system (APS). The mission profile can be described with the following sequences:

1) Injection into Earth escape trajectory via launch vehicle
2) NTP system and avionics checkout
3) NTP engine startup procedure
4) Performance burn – 10 minutes at 100lbf, 1 MWth (100% thrust)
5) NTP engine shutdown and engine block cooldown operations
6) Delivery of reactor/telemetry data
7) Second checkout of NTP and avionics systems
8) NTP engine startup procedure
9) Demonstration burn - >10 minutes at varied thrust levels <100 lbf, <1 MWth
10) NTP engine shutdown and engine block cooldown operations
11) Delivery of reactor/telemetry data
12) Ballistic coast
13) Trajectory correction maneuver (TCM)
14) Venus flyby
15) Final insertion into heliocentric graveyard orbit with an apoapsis < 1.0 AU, out of phase with Venusian orbit

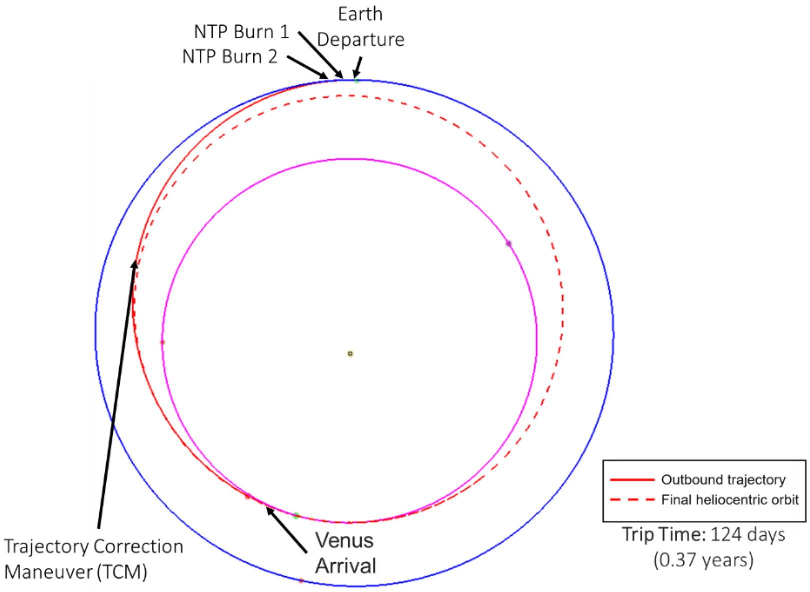

*Figure 1 Venus Flyby Mission Profile*

The mission elapsed time is approximately 124 days, with the mission-critical NTP burns occurring within the first few days after launch. This simplifies long-term hydrogen storage requirements and also reduces the power, range and data uplink requirements for critical avionics and reactor instrumentation during the NTP burns. Figure 1 shows the notional Venus flyby mission profile for FD1.

### FD2 – MEDIUM EARTH ORBIT GRAVEYARD MISSION

In contrast to FD1, FD2's mission profile takes it into a circular medium-Earth Orbit (MEO). This profile was selected in order to accommodate the increased mass of the FD2 system while also balancing the risk requirements for a nuclear-safe orbit. Unlike FD1, FD2's main propulsion system (MPS) is substantially more powerful, and when the NTP system is active, it will impart significant trajectory changes. As a result, the FD2 NTP system will perform its burns as orbital plane change maneuvers. In this way, the NTP system can perform at full power while imparting a minimal change to the MEO profile. The mission sequence for FD2 can be described as follows:

1) Injection into 2000-km circular MEO by launch vehicle
2) NTP system and avionics checkout
3) NTP engine startup procedure
4) Performance burn, positive plane change – up to 10 minutes at 12,500 lbf, 270 MWth (100% power output) with live feed of reactor/telemetry data
5) NTP engine shutdown and engine block cooldown operations
6) Second NTP system and avionics checkout
7) NTP engine startup procedure
8) Demonstration burn, negative plane change – up to 5 minutes at 12,500 lbf or less, up to 270 MWth, with live feed of reactor/telemetry data
9) NTP engine shutdown and engine block cooldown operations

Unlike FD1, FD2's elapsed time should be no more than a week, with both NTP burns occurring within the first 1-3 days of the mission. This is due to inserting into a MEO as opposed to a heliocentric orbit.

## FLIGHT DEMONSTRATOR CONCEPT DESIGNS

A general overview of both FD1 and FD2's system design features will be provided in this section. This section will cover the propulsion, thermal, avionics, structural and power systems, including some of the assumptions and approaches that went into sizing each system. In addition to high-level system summaries provided here, two other papers also being published provide more detailed descriptions of the propulsion systems and combined avionics/thermal/power systems for FD1 and FD2. [2] [3]

### FD1 CONCEPT DESIGN

### FD1 - REACTOR SYSTEM

The FD1 reactor features a HALEU ("High Assay Low-Enriched Uranium") monolithic design, with a 1 MWth power output. This configuration was designed based on the FD1 requirements for a reactor that could meet the 2024 deadline and feature as high-TRL technology as possible, with fuel manufacturing and testing considerations in mind. Although the FD1 reactor has a substantially lower power output than a NERVA-based reactor, the reactor is still of comparable size and mass. The FD1 reactor operates at temperatures on the order of 1100 K, with peak temperatures close to 1200 K, with a specific impulse of greater than 520 seconds.

## FD1 – MAIN PROPULSION SYSTEM

The main propulsion system (MPS) relies on gaseous hydrogen as the main propellant. Gaseous hydrogen was selected for the ease of propellant management and reduced thermal management requirements in comparison to cryogenic propellants such as liquid hydrogen, while still retaining many of the molecular and chemical characteristics that a fully-operational NTP system would deal with when working with liquid hydrogen. There are eight gaseous hydrogen tanks in the FD1 system, sized using COTS reference tanks.

The MPS uses a simple blow-down design, which obviates the need for complex turbomachinery. Additionally, the MPS system uses an uncooled stub nozzle, which foregoes performance in favor of simplicity, and means that no complex regenerative cooling system is required. The MPS supports up to 100lbf of thrust, a level which is driven entirely by the power provided by the immediate near-term reactor. The propellant load is sized to ~20 MW-minutes of operation, translating to approximately 190 kg of propellant. Because the reactor can be “throttled” to different power levels, this effectively means that at 1 MW power output, the FD1 system has 20 minutes of runtime, but can increase the runtime as the power output is throttled.

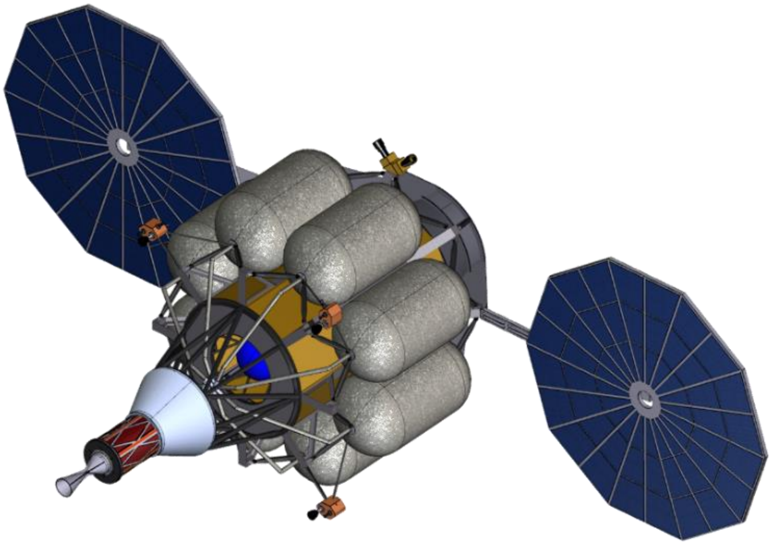

*Figure 2 FD1 Vehicle Concept*

## FD1 – AUXILIARY PROPULSION SYSTEM

Because of the low thrust inherent to the FD1 MPS, the APS for FD1 is design to perform all of the mission-critical ΔV maneuvers, including the deep space Trajectory Correction Maneuvers (TCMs). In order to meet both TCM and attitude control functional requirements, the FD1 APS is designed as a “dual mode” bipropellant system using MON-3 and Hydrazine. In the first mode of operations, the APS relies on four 100-lbf bipropellant thrusters for the larger ΔV maneuvers; in the second mode, twelve 5-lbf pulsing monopropellant engines are used for attitude control. This approach maintains the simplicity of a monopropellant feed system for attitude control, while allowing a higher thrust and propulsive efficiency for the larger trajectory maneuvers.

## FD1 – THERMAL SYSTEM

The FD1 system uses a series of radiator panels and heaters to manage thermal conditions during the mission. Thermal management systems were designed assuming the final heliocentric graveyard orbit as the most conservative passive heat load, and the radiators in particular were sized based on the thermal output from the NTP reactor during its peak temperature conditions, which occur during engine shutdown.

During the shutdown phase, the hydrogen flow is minimal and thus the reactor temperature briefly increases before decaying to deep space thermal conditions.

The gaseous hydrogen tanks and the engine rely on multilayer insulation (MLI), and the APS and avionics systems have their own independent heaters with MLI. In addition, a reactor shadow shield featuring a layer of FRCI-12 further helps thermally isolate the FD1 reactor from the rest of the system. The avionics and other instrumentation systems would be housed as far from the reactor as possible to minimize heat loads on those components, with insulated data lines running to sensors and camera equipment that need to be placed near the reactor.

The resulting thermal analysis indicates that the heat loads from reactor operations are sufficiently isolated by the combination of radiators, MLI and FRCI shielding. Avionics and other instrumentation were operating well within their temperature limits for the duration of the mission. In summary, the thermal system features a very high-TRL approach that was able to address the needs of the FD1 system.

## FD1 – POWER, AVIONICS AND INSTRUMENTATION SYSTEMS

The power system also features a very high-TRL, low-risk approach. The peak power load is assumed to be during the reactor startup and operation phase, due to the power requirements for the gaseous hydrogen tanks as well as the drum actuators in the reactor.

Primary power generation is provided by a pair of UltraFlex Solar Arrays that use Inverted Metamorphic (IMM) cells, with a total power generation in excess of 6.4 kW. FD1’s power systems feature integrated power electronics, with array regulators, battery controllers and power distributors all in a single control box. The battery system is sized using off-the-shelf battery components.

The avionics/comm systems include packaging and data handling for additional reactor and engine sensor systems. As a result, the avionics packages were more massive in comparison to comparable spacecraft systems. The control and data handling (C&DH) system is managed entirely by the spacecraft, with an S-band link to the Near-Earth Network (NEN) or the Tracking and Data Relay Satellite System (TDRSS) for near-Earth operations within geostationary earth orbit (GEO), and an X-band link to the Deep Space Network (DSN) for operations beyond GEO and into the heliocentric orbit.

Reactor instrumentation included a range of sensors to monitor reactor health, including stress and temperature sensors. In addition, radiation monitoring sensors, rad-tolerant cameras, IR thermal imaging sensors would be deployed, along with neutron detectors. These would all be installed on booms that faced the reactor and the region where the thrust plume would appear during NTP burns.

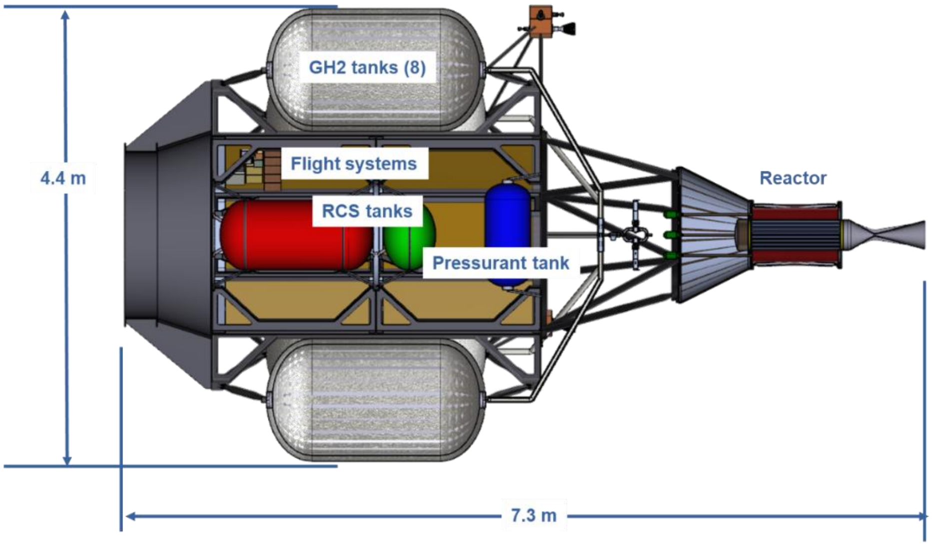

*Figure 3  FD1 Cutaway Configuration View*

### FD1 – CONFIGURATION AND STRUCTURES

The primary structure for FD1 was designed to meet or exceed requirements as defined in NASA STD-5001B for strength and stability. The launch loads were the heaviest structural loads, so they were used to envelop all load requirements. Structural and load-bearing components were made predominantly of aluminum, with stainless steel for some of the reactor jacketing components and attach structures. Selected truss supports leveraged titanium for its low thermal conductivity. A main bus framework was used to house the APS components, as well as provide attachment points for the hydrogen tanks and the avionics/instrumentation boxes. Figure 3 shows the configuration of the FD1 system.

## FD2 CONCEPT DESIGN

### FD2 – REACTOR SYSTEM

The FD2 reactor system features a moderated core that operates with a specific impulse of 880 seconds. The system has a more complex flow path, in order to support a larger thrust level as well as maintaining a stable thermal profile within the higher-performing core. The reactor's power output is just under 270 MW, with a peak operating temperature of 2800 K.

### FD2 – MAIN PROPULSION SYSTEM

The FD2 MPS system employs a turbopump-fed system with liquid hydrogen propellant, with a continuous flow loop from tank exit to nozzle exit. The thrust is rated at 12,500 lbf, with a propellant exit temperature just under 2800 K. The MPS system includes a regenerative cooling loop and at max thrust and reactor power, performs with a specific impulse of approximately 880 seconds.

For more details on the MPS for both FD1 and FD2, a separate paper is being published by Simpson et al. [2]

### FD2 – AUXILIARY PROPULSION SYSTEM

FD2's auxiliary propulsion involves a monopropellant APS system with clusters of 9-lbf Hydrazine thrusters.  Unlike FD1, there are no significant ΔV maneuvers performed by the APS in FD2, allowing for a low-thrust, simplified configuration in contrast to FD1's dual-mode system.  The only added complexity in FD2 resides in the fact that in addition to providing vehicle attitude control, the APS is also utilized to perform propellant settling maneuvers for hydrogen tank ullage venting.

## FD2 – THERMAL SYSTEM

FD2's thermal management system, like FD1, employs a combination of heaters, MLI and radiator panels. Due to the short mission duration, with the NTP demonstration operations completed within a few days of launch, a passive thermal system was sufficient to handle the liquid hydrogen propellant needs. This passive system consisted only of the standard multi-layer insulation (MLI) and spray-on foam insulation (SOFI). No Thermodynamic Vent System (TVS) was included in the design, as the cost and complexity of more sophisticated propellant conditioning was traded at the expense of increased boiloff rates. For ullage management, a simple venting system is employed in conjunction with propellant settling maneuvers performed by the APS.

## FD2 – POWER, AVIONICS AND INSTRUMENTATION SYSTEMS

The majority of components in the power, avionics and instrumentation systems were similar to the systems used in FD1. The major differences were the following:

1) Changes in power loads and battery capacities to accommodate eclipse operations in Earth orbit
2) Using increased bandwidth margin from X-band link to support a live HD video feed during reactor burns
3) Additional C&DH support for turbopump systems, thrust-vector control and propellant sensors

As with FD1, these systems were largely high-TRL and low-risk components.

## FD2 – CONFIGURATION AND STRUCTURES

As with FD1, FD2's structural requirements were intended to be high-TRL and low-risk. Differences in the ground rules for FD2 stemmed primarily from accommodations for a heavier and larger NTP system and the use of liquid propellant. The FD2 system configuration is depicted in figure 4. It features the larger FD2 reactor, along with a larger, structurally braced shield. The avionics and data handling systems are on the "far-side" of the FD2 system, to minimize radiation exposure during operation.

The larger FD2 system introduced potential concerns with meeting launch load stiffness requirements, and combined with the use of load-bearing tank structures, resulted in additional structural support to compensate for the vibrational modes.

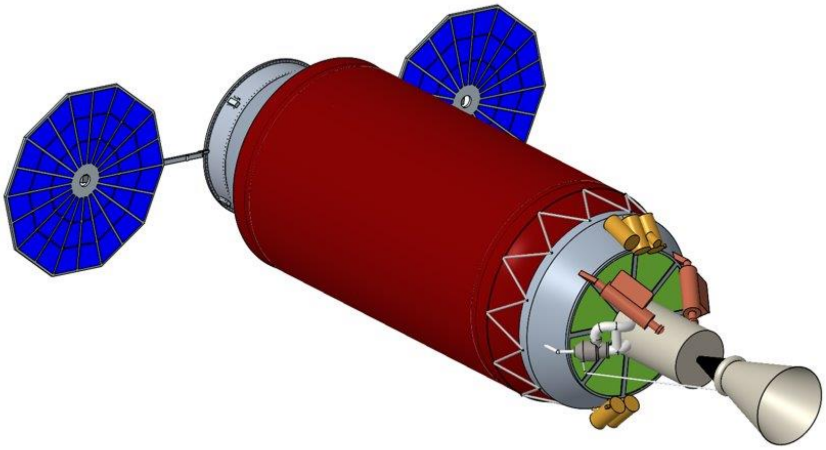

*Figure 4 FD2 Configuration View*

The shadow shield was optimized using an in-house optimizer package, where mass and shield thickness were optimized based on radiation attenuation and thermal management requirements. Due to the large mass of the shield, as well as it contributing to the aforementioned stiffness concerns, additional structural bracing was employed.

Structural materials for FD2 were largely similar to those used in FD1, with one important exception. In addition to Aluminum, Titanium and stainless steel elements, the use of fiberglass composite struts were considered for the purposes of improving thermal isolation of the reactor assembly from the liquid hydrogen tank and avionics components.

## CONCLUSIONS

The FD1 system is designed to address congressional requests for a project plan for NTP flight demo that would be launched in the immediate near term. As a result, the FD1 system features as many high-TRL, low-risk components as possible, with a conservatively-designed, low-power reactor system that is designed with existing procurement and fuel design capabilities in mind. The FD1 system is a lower-risk means of retiring many of the risks associated with reactor design and the legalities associated with nuclear-safe handling.

In contrast, the FD2 system is designed with future performance in mind. It is designed to be traceable to a future notional NTP system that would be used in robotic, deep space science missions, or human-rated interplanetary missions. As a result, the thrust and efficiency were designed to approach the performance requirements for such future notional missions. Thus, the FD2 system is a higher-risk approach that will retire more risk not just in the manufacturing and design requirements, but also in actual flight performance.

## REFERENCES

[1] H. Rep. No. 116-9, 2019.

[2] S. Simpson., Q. Bean and M. Rodriguez, "NTP Flight Demo Propulsion," 2019.

[3] W. Johnson, P. Capizzo, L. Fabisinski and S. Sutherlin, "NTP Demo Avionics," in *JANNAF*, 2019.