OVERVIEW OF THE MAIN PROPULSION SYSTEM FOR A NUCLEAR THERMAL PROPULSION FLIGHT DEMONSTRATOR

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ABSTRACT

A demonstration of a Nuclear Thermal Propulsion (NTP) engine has not been conducted in over 50 years. Several tests were conducted during the NERVA program but no NTP engine was ever flown in space. In the last several years there has been a considerable amount of conceptual design work on NTP engines conducted. With the prospect of human Mars missions in the 2030's there has been a renewed interest in NTP engines. A concept design study was conducted with the intent to design 2 flight demonstrator vehicles that would buy down programmatic and technical risks associated with launching and operating nuclear reactors in space. The intent of the first demonstrator mission would be to employ a simplified NTP engine and buy down programmatic risks whereas the second demonstrator would buy down technical risks with a NTP engine designed to be similar to an operational NTP model. The results of the study showed that a simplified NTP engine demonstrator could be feasibly built and flown in the near term with mostly high TRL, commercial off-the-shelf components.

INTRODUCTION

The Advanced Concepts Office (ACO) at the Marshall Space Flight Center (MSFC) has conducted conceptual design studies into nuclear thermal propulsion (NTP) flight demonstration (FD) concepts that could fly by 2024 [1]. As a part of this study, two design concepts were evaluated. The first, titled FD1, is a concept that could fly by 2024; as a result, it would prioritize "off-the-shelf" materials and equipment with a high technology readiness level (TRL), while sacrificing flight performance. FD1 will utilize gaseous hydrogen propellant so the demonstration will not be reliant upon low TRL cyrofluid management (CFM) systems. The second concept, titled FD2, would be a concept that prioritizes performance and traceability to future manned Mars and unmanned deep space missions; however, this concept would launch considerably later than 2024 and would have additional risks associated with using materials and equipment with a lower TRL. FD2 will utilize liquid hydrogen propellant.

The purpose of this paper is to provide an overview of the main propulsion system (MPS) features for both FD1 and FD2. This will include a brief overview of the reactor configurations and performance, and an overview of the MPS systems, including valves and tankage. A comparison between the two MPS systems will also be presented, highlighting how the MPS system in each case contributes to the design philosophies driving FD1 and FD2 respectively.

FLIGHT DEMONSTRATOR CONCEPT DESIGNS

FLIGHT DEMONSTRATION 1 (FD1)

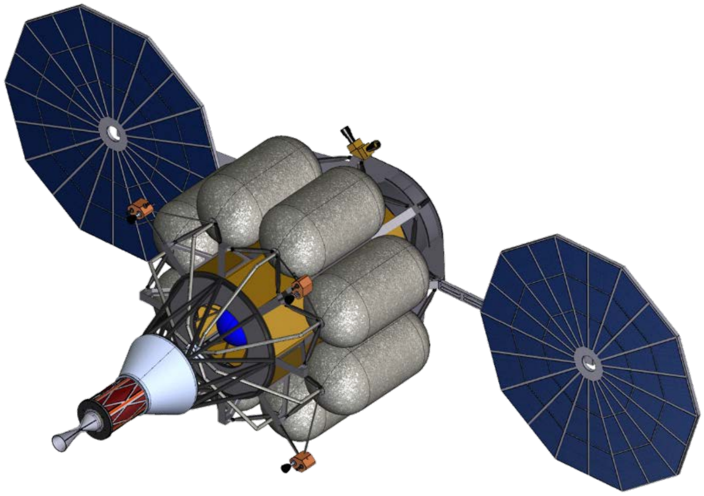

Figure 1 FD1 Vehicle Concept

REACTOR SYSTEM

The reactor is a low-enriched uranium (HALEU, or “High assay Low-Enriched Uranium”) monolithic design, with 1 MW thermal output. This configuration was selected based on the FD1 requirements for a high-TRL, easily-accessible reactor that would meet the 2024 requirements. In comparison to previous reactor designs such as those used in the NERVA program, this reactor provides a much lower power output, and subsequently a lower specific impulse, at approximately 520 seconds. However, the reactor’s size does not scale linearly with power output, so the reactor dimensions and masses are nevertheless comparable to NERVA-style reactors. It is also important to note that the switch from high-enriched uranium (HEU) to HALEU reduces the enriched uranium amount to < 20%, which can result in increases in reactor mass to compensate.

MAIN PROPULSION SYSTEM

The FD1 main propulsion system (MPS) uses 190 kg of gaseous Hydrogen as its main propellant. Gaseous Hydrogen is easier to handle than liquid Hydrogen, from a thermal management standpoint, which drastically reduces overall system complexity and power requirements. Operating with gaseous Hydrogen also results in less sensitivity to thermal environments, allowing for some of the CONOPS profiles as discussed earlier.

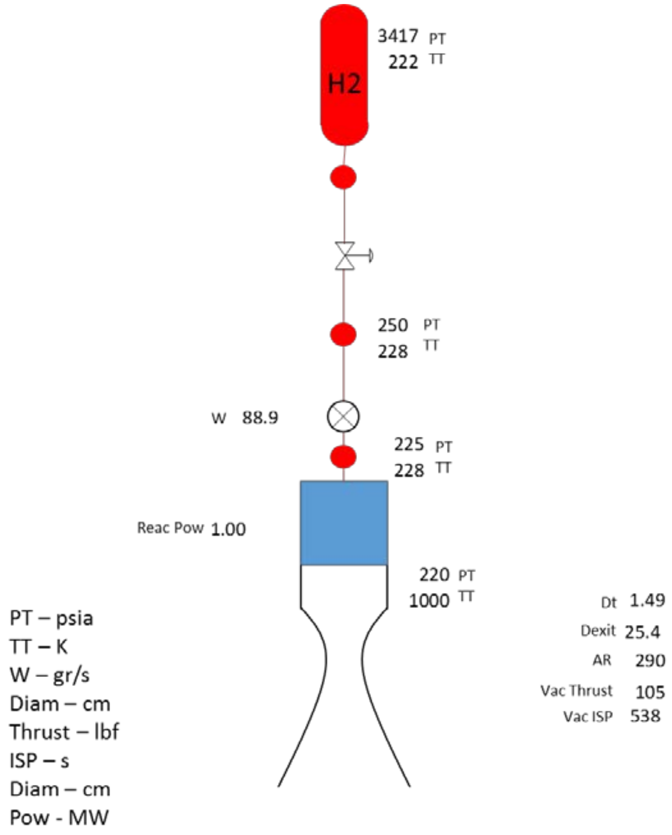

Figure 2 FD1 Vehicle MPS Diagram

The propellant feed system is pressure regulated and designed similarly to typical gaseous pressurant systems. The propellant load is sized to ~20 MW-minutes of run time. Because the reactor's peak operation power is at 1 MW, this means that with a throttling system, a reduced power level can be used in order to extend the total burn time. The propellant exits the system at 1000 K, with peak reactor temperatures around 1200 K. This results in a lower specific impulse, and the use of gaseous Hydrogen also results in a low mass flow rate, with the thrust output around 100 lb_f. As a consequence, the mission CONOPS assumes that the reactor itself does not contribute to any critical mission burns, with the RCS taking over that task instead.

The nozzle is an uncooled stub nozzle. Because of the FD1 system requirements, nozzle performance was not critical to FD1's performance and thus the simplest nozzle configuration was selected. An uncooled configuration was also selected for simplicity, although it meant stricter material requirements for the nozzle, given the exit temperature for the propellant.

In order to fulfill the requirements that the main propulsion system use 190 kg of gaseous hydrogen (GH2) propellant as well as high TRL components a survey of COTS pressurant tanks was conducted. Most pressurant tanks were found to be too small requiring an excessive quantity of tanks to practically store the GH2. Metal tanks were researched, however it was found that the masses were prohibitively high. Composite overwrap pressure vessels (COPVs) proved to be much lighter mass options and are generally available in larger sizes. Maximum expected operating pressure (MEOP) is also an important factor that determines how much gas the tanks can hold. The optimum tank would have a large volume and a high MEOP thus able to hold the maximum amount of gas but still fit within the launch vehicle shroud. In general the larger COPV tanks are not qualified for high MEOPs but there are several exceptions. The tank that best fit the ground rules and assumptions was the General Dynamics 220141-1, 1,088 liter tank. This tank provides for the maximum storage capacity and lowest mass compared to other tank options. Eight (8) 220141-1 tanks will be needed to store the GH2 at a MEOP of 317 bar (4600 psig).

AUXILIARY PROPULSION SYSTEM

A MON3/Hydrazine RCS system handles all mission critical maneuvers as well as attitude control. The system is comprised of four (4) Aerojet Rocketdyne HiPAT 100-lb_f thrusters for trajectory correction maneuvers and twelve (12) Aerojet Rocketdyne MR-106 5-lb_f thrusters for attitude control. By using a dual-mode design, the RCS system can rely on a simplified feed system with a monopropellant attitude control while maintaining the superior specific impulse of a bipropellant engine for the larger trajectory correction burns. All of the components are high TRL with extensive heritage on Earth orbit and deep space missions. The RCS tanks are sized for total propellant loads of 267 kg of hydrazine and 115 kg of MON3. The propellant and pressurant tanks will likely need to be custom designed in order to fit within the vehicle and not be needlessly oversized. However it is also likely that the designs can be modified from existing tank designs thereby minimizing development cost and production lead time.

FLIGHT DEMONSTRATION 2 (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.

MAIN PROPULSION SYSTEM

In contrast to FD1, the FD2 reactor system is designed with an emphasis on performance that is traceable to an operational NTP system. As a result, the system requirements were derived from anticipated mission requirements such as those found in NASA’s DRA 5.0 document, as well as mission requirements from NASA decadal surveys for potential deep space mission targets.

The FD2 MPS system thus uses 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 lb_f, with a propellant exit temperature just under 2800 K. This thrust level is consistent with robotic mission profiles, and is also an informative starting point on the path towards a human-rated NTP system for deep space missions.

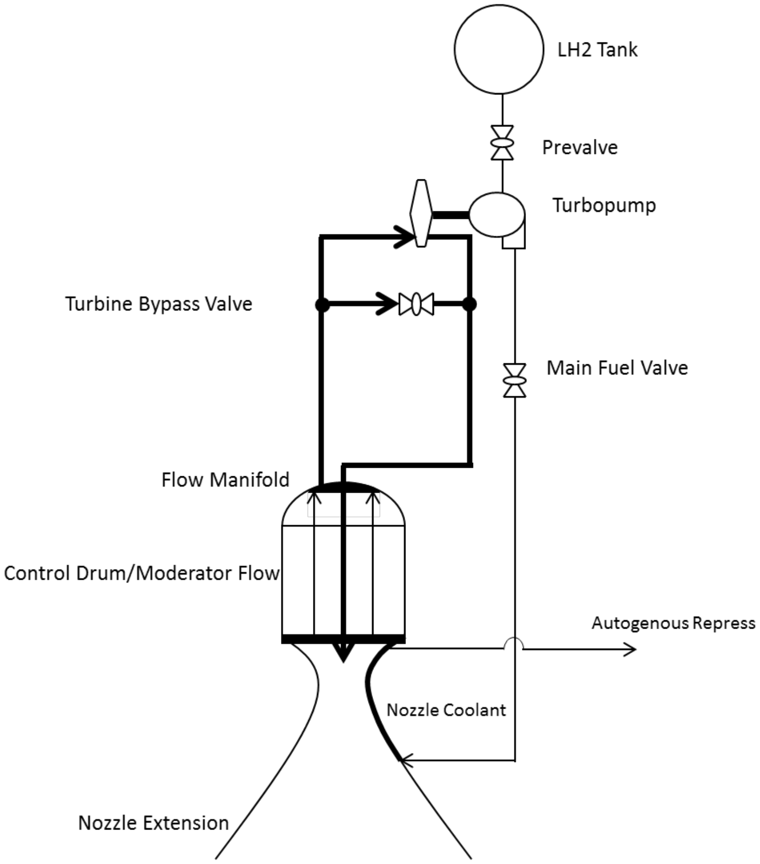

Figure 3 FD2 Vehicle MPS Diagram

The flow sequence is as shown below:

1) The turbopump would first provide flow to the nozzle coolant channels.
2) In the nozzle coolant path, an autogeneous repressurization line is installed that feeds back into the tank.
3) The flow then goes through the reactor moderator and control drum regions, and then collects in the flow manifold.
4) From there, the flow goes into the turbine bypass valve, and finally through the fuel pins in the reactor, subsequently exiting via the nozzle.

The resulting specific impulse from this configuration is approximately 880 seconds, which is close to expected operational performances on the order of 900 seconds. The pressure drop through the chamber coolant passages was derived from testing performed at MSFC. The high pressure drop of 500 psi, is due to the NTP coolant channels requiring a larger flow rate than would be expected in a comparable bipropellant rocket engine. The high pressure drop will present issues for cooling and turbomachinery, but can be mitigated by optimizing the nozzle coolant flow paths.

AUXILIARY PROPULSION SYSTEM

FD2's auxiliary propulsion involves a simple monopropellant RCS system with 9-lbf Hydrazine thrusters. Since the RCS system is not providing mission-critical thrust and only attitude control, this allows for a low-thrust, simplified configuration in contrast to FD1's dual-mode system.

COMPARISON AND CONCLUSIONS

FD1's MPS system is a relatively simple design. Using a gaseous propellant also simplifies thermal management requirements, in exchange for a modest increase in tankage mass. The MPS components involved are all high-heritage, high-TRL components, save for the additional thermal/radiation shielding requirements that will be imposed by the reactor. There is nothing in the FD1 system that requires a novel MPS redesign, and this supports the FD1 requirement for a simple, high-TRL MPS system that supports the reactor. Ultimately, the FD1 MPS system intends to support the goal of flowing Hydrogen through a simple reactor and evaluating the reactor performance, moreso than supporting any specific propulsion performance requirements.

The FD2 system, in contrast, features a more complex MPS system. The higher flow rates, use of turbopumps and a regenerative nozzle cooling loop, combined with the requirement to use liquid Hydrogen, introduces additional complexities and risks to the NTP system. However, the resulting performance is much more traceable to an operational transportation system that would be used either in science-based missions or a human-rated mission, such as previously proposed human missions to Mars [2]. Thus, the FD2 MPS system provides a useful way to retire more risk in the course of NTP development.

REFERENCES

1. H. Rep. No. 116-9. 2019.

2. NASA/SP-2009-566, "Human Exploration of Mars - Design Reference Architecture 5.0." 2009.