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Low-enriched cermet-based fuel options for a nuclear thermal propulsion engine

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ABSTRACT

Nuclear thermal propulsion is the high thrust, high specific impulse rocket engine technology of choice for future missions to Mars and beyond. Previous engines designed and built under NASA's Rover program made use of highly enriched uranium, a significant barrier to development today due to the political climate. This paper focuses on developing a nuclear thermal rocket engine based on a low enriched uranium (LEU) tungsten cermet fuel. Generally, this design is based on the Pewee reactor built by NASA under the Rover program. However, multiple modifications are introduced to optimize the proposed LEU engine to produce the maximum efficiency while meeting NASA's ground rules as defined in the latest Mars reference missions. This paper presents numerous neutronic and thermal-hydraulic tradeoff studies to approach a near-optimum design. The result is an engine design capable of meeting, and in many cases surpassing, NASA's requirements of a 25 klb_f thrust engine with a thrust-to-weight ratio greater than 3.5 and a specific impulse greater than 900 s.

1. Introduction

Nuclear thermal propulsion (NTP) systems offer the greatest versatility for near-term deep space missions such as NASA's planned Mars and near-Earth-asteroid missions. Due to their ability to use fission as the energy source and H_2 as the propellant, even first generation NTP systems will have nearly twice the efficiency of the best chemical engines, while maintaining similar levels of thrust. Nuclear engines are the single best option for manned exploration of the objects within our solar system. The basic premise of nuclear thermal propulsion systems is to use a nuclear reactor to heat a light propellant, in most cases hydrogen, to a very high temperature and expel it through a converging-diverging nozzle. The key measures of engine performance in rocket engines are the specific impulse (I_{sp}) and thrust. The specific impulse corresponds to the total impulse provided to the vehicle by a particular quantity of propellant (thrust divided by mass flow rate) and hence measures the propellant efficiency of an engine. The specific impulse is primarily dependent on the temperature of the gas flowing through the nozzle. Thrust is simply the motive force provided by the engine when operating. Typical values for the I_{sp} and thrust (klb_f) for various engine types are as follows: 300–450 seconds and 100–500 klb_f for chemical rockets (Aerojet Rocketdyne, 2017), 1000+ seconds and 10 mlb_f for electric rockets (Goebel and Katz, 2008), and 800–1000 seconds and 10–100 klb_f for nuclear rockets (Finseth, 1991).

Nuclear thermal propulsion systems have a long and prolific history of research and development. From 1955 to 1973, NASA's Rover program laid the groundwork for all current research into nuclear propulsion systems. Over the span of 18 years, over 20 different reactors were built and tested, all making use of graphite based fuels and highly enriched uranium (Finseth, 1991). The engineering work accomplished during the Rover program was immense and garners at least a brief overview.

The program (Finseth, 1991) was divided into several smaller programs, named Kiwi, Phoebus, Pewee, and NERVA (Nuclear Engine for Rocket Vehicle Application), that looked at specific areas of interest related to building a working rocket engine. The first of these programs was called Kiwi and proved the feasibility of the nuclear thermal rocket engine from a nuclear and thermal-hydraulic standpoint. Early designs utilized plate-type fuel elements around a central moderating island. These showed significant corrosion and cracking and were soon replaced with inverted fuel rods consisting of an extruded rod with coolant channels bored through the center. Almost all of nuclear thermal rockets (NTR) designed under Rover and subsequent programs used the hexagonal variant of these fuel elements with 19 coolant channels. Additionally, Kiwi was the first program to use the control drums featured in most current reactor designs. These drums are arranged radially within the reflector around the core. They are made of the same material as the reflector, except one side, which is made of an absorber. Hence, when the absorber is turned towards the core, the core is subcritical and when turned away the core is supercritical. The Kiwi

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program also tackled the problem of hot hydrogen corrosion of the fuel elements. It was found that coating the elements with NbC would significantly reduce the corrosion of the fuel. Phoebus, the second program under Rover, was able to increase the power from Kiwi's 1100 MW to nearly 5000 MW, the highest power achieved by any reactor to date. Phoebus also was able to operate all of the reactors multiple times at near 100% power. In contrast to Phoebus, Pewee was the smallest core built during the Rover program. Pewee was originally intended to test fuel element coatings in order to reduce corrosion problems. Two major findings were the addition of a molybdenum overcoat to the traditional NbC coatings significantly reduced corrosion and, later, that ZrC nearly eliminated corrosion problems due to its very similar thermal properties to the graphite based fuel. Pewee operated at approximately 500 MW and achieved a higher specific impulse (892 s) than any previously built reactor. Pewee was also the first to use ZrH_x as a moderator material within the tie rods to maintain criticality. The most well-known program under Rover was the NERVA program, which applied the techniques from other programs to build flight-type systems to test. NERVA's culmination was the XE Prime test engine which operated over 24 times at nominal power levels. This was the first system to use all of the systems in a flight-type arrangement and hence represents the first real engine test for nuclear thermal rockets. Unfortunately, the Rover program was abandoned soon after NERVA as many deep space missions were delayed indefinitely. The last year of the Rover program did produce one more notable project, the Small Nuclear Rocket Engine (SNRE). This engine was designed for changing the orbits of various payloads sent to earth orbit and was required to be capable of fitting within the space shuttle's cargo bay. To meet the mass and volume requirements the SNRE made use of the best practices of the Rover program and further improved upon many of its novel systems. For example, it made use of a novel expander cycle that used the heat in the tie rods to operate the pump and a parallel flow system to cool the nozzle and structure. This allowed for a much smaller and more efficient pump in addition to a much lower weight. SNRE also increased the number of moderating elements to allow further reduction in the core size. Unfortunately, the SNRE never saw use, but it has been an influential design on many modern approaches to NTR design (Durham, 1972).

Despite the major advancements made in the Rover program, much work is yet to be done to create a working nuclear thermal rocket for NASA's current planned Mars missions. Specifically, all of the previous designs have focused on highly enriched uranium, a regulatory barrier to work on these systems. Many new designs, including this design, will make use of LEU as fuel to reduce some of the regulatory concerns (Messick and Galan, 2013). Additionally, newer mission architectures and safety practices define very specific performance needs for modern nuclear rockets, such as operation under engine-out scenarios and other requirements discussed in the next section (Drake et al., 2009a,b). Currently much work is being performed on various aspects of nuclear rocket design, from materials and manufacturing to efficient designs in respect to neutronics and thermal-hydraulics. One of the most important areas of research is in low enriched fuels. These fuels promise similar performance to highly enriched engine cores, but with fewer regulatory issues (Venneri and Kim, 2013).

The goal of this paper is to present a systematic approach, which enables identifying an optimized design for a small, tungsten cermet LEU fueled, nuclear rocket engine. The adopted approach is based on numerous neutronic and thermal-hydraulic sensitivity and tradeoff studies. There are many parameters that may affect the performance of the engine, which is measured by the specific impulse, thrust and thrust-to-weight ratio. The sensitivity studies included in this paper examined the effect of the radial and axial dimensions of the core, reflector thickness, moderator-to-fuel element (ME-to-FE) ratio, fuel enrichment, tungsten enrichment and mass flow rate. In order to identify the near-to-optimum design, a multi-dimensional design space was constructed by performing multiple neutronic and thermal-hydraulic analyses. This approach allows to identify trends and trade-offs between different variables, e.g. higher ME-to-FE ratio increases the criticality of the system, but reduces the specific impulse. For each of the analyzed cases, the power value was iteratively varied and converged for pre-determined maximum achievable T/H conditions (e.g. fuel center line temperature). Neutronic analyses of the various 3D core configurations were performed with the Monte-Carlo based Serpent code. Thermal-hydraulic (T/H) calculations relied on the in-house developed T/H module (denoted as THERMO), which simulated the axial flow of the propellant and the radial heat conduction (i.e. 1.5-dimensional model), but neglected the axial conduction. The optimum design was obtained by confining the design space with various constraints, defined in section 2, while maximizing the specific impulse.

Baseline assumptions for the design include the use of tungsten cermet based low enriched uranium fuel, hexagonal nineteen-channel fuel elements and to meet or exceed NASA's baseline performance assumptions in a reference Mars mission. The choice of LEU cermet fuel was based on a balance of technological readiness and expected performance. Cermet fuels promise better high-temperature properties, compatibility with hot hydrogen and high thermal conductivity. For such characteristics, these materials offer significant improvements in performance than older graphite based fuel materials. Additionally, recent advancements in the manufacturing of these materials make them far more feasible for use than ternary carbide fuels.

The analysis of these design parameters leads to an optimum system that demonstrates excellent thermal-hydraulic performance while maintaining a critical core using LEU. The design meets or exceeds NASA's baseline assumptions of NTR performance and is therefore viable for further verification.

2. Description of the mission and general objectives set by DRA 5.0

Of great importance to our design is the choice of nuclear thermal propulsion as the primary in-space propulsion system in NASA's Mars Design Reference Architecture 5.0 (Drake et al., 2009a). In this document and its subsequent addenda (Drake et al., 2009b; Drake et al., 2014), NASA defines all aspects of a potential Mars exploration campaign from potential scientific objectives to the particular flight paths and orbits used in various mission opportunities. NASA considered two space propulsion systems, nuclear thermal propulsion and advanced thermal propulsion systems with aerocapture at Mars. Nuclear thermal systems are preferred due to the significantly lower propellant requirements and hence higher efficiencies.

The primary ground rules and assumptions that relate to the performance of an NTP system and hence act as constraints for this design are the specific impulse, total thrust, and the thrust-to-weight ratio. The specific impulse assumed in DRA 5 is between 875 s and 950 s with all calculations performed using a value of 900 s. All DRA 5 designs assume three nuclear engines in a clustered configuration producing 75 klb_f total thrust. Therefore, all the calculations presented in the paper are performed using a value of 25 klb_f. In earlier releases, the NTP core stage dry mass is assumed to be on the order of 33 metric tons which corresponds to a thrust-to-weight ratio of 3.5. A final constraint on the nuclear propulsion system is the volume of the propulsion stage. This primarily means that the dimensions of the engine core must be sufficiently small to fit within the 10-meter diameter shroud. This generally means that a single engine may not be larger than about 4.6 m in diameter.

NASA also recommends several options to improve mission economics and trip times that mostly involve reducing unnecessary weight in the system, improving specific impulse, or increasing the engine thrust-to-weight ratio. In all of these cases, the predominate savings is in propellant mass taken to orbit which allows room for greater mission flexibility and lower overall cost.