Feasibility of Low Enriched Uranium Fuel for Space Nuclear Propulsion

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1. Introduction

This paper will present a study of the Small Nuclear Rocket Engine (SNRE) and the feasibility of using low enriched Uranium (LEU) instead of the traditional high enriched Uranium (HEU) fuels. The purpose of this initial study is to create a baseline with which to perform further analysis and to build a solid understanding of the neutronic characteristics of a solid core for the nuclear thermal rocket. Once consistency with work done at Idaho National Laboratory (INL) is established, this paper will provide a study of other fuel types, such as low and medium-enriched uranium fuels. This paper will examine how the implementation of each fuel type affects the multiplication factor of the reactor, and will then explore different possibilities for alterations needed to accommodate their successful usage. The reactor core analysis was done using the MCNP5 code.

2. Description of the SNRE

The SNRE is the benchmark reactor design for nuclear rockets currently being designed and optimized by Idaho National Laboratory in cooperation with NASA. The design requirements for the SNRE include the ability to operate at two full power conditions, one for an extended single usage and the other for multiple startups totaling to about 2 hours of operation. Both modes require the reactor to operate at about 360 MWth, provide16,300 lbf, and at an impulse of 870 seconds[1]. In order to maximize the specific impulse, a hydrogen propellant is used, acting both as the propellant and the coolant of the reactor core.

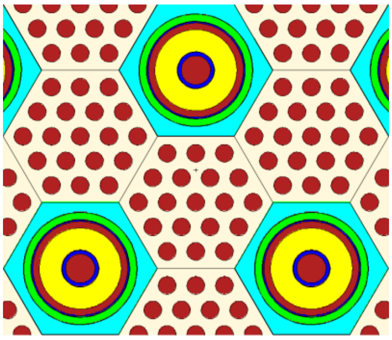

Fig. 1. Fuel element and tie tube arrangement

The reactor can be divided into two sections: the active core and the reflector region. The active core is a cylinder made up of 564 hexagonal fuel elements and 256 tie tubes of the same dimensions with the addition of beryllium on the outside to fill in the inside of the cylinder. The fuel type is a (U,Zr)C-graphite composite, providing both a high thermal conductivity, relatively high density, and a high melting point, ensuring the structural integrity of the fuel. The (U,Zr)C composite is based on 35% by volume free carbon content fuel with a .64 g/cm^3 uranium loading described by Taub[2]. The detail for the fuel element can be seen in Figure 1.

The tie tube elements are present in the core in order to ensure equal pressure throughout the core, provide structural stability by anchoring the core to the support plate, and to thermalize the neutrons produced in the fuel. The detailed geometry of the tie tube element can be seen in Figure 1 while the dimensions are given in Table I.

The reflector region of the reactor is made up of a beryllium reflector with 12 rotating beryllium drums evenly distributed radially inside the reflector. Each drum has a hafnium plate which is used to control the reactivity of the reactor.

Table 1. SNRE tie tube geometry

Component	Material	Inner Radius (cm)	Outer Radius (cm)
Inner Hydrogen	Hydrogen		.20955
Inner tie tube	Inc-718	.20955	.26035
Gap	Hydrogen	.26035	.26670
Moderator	ZrH	.26670	.58420
Gap	Hydrogen	.58420	.67818
Outer tie tube	Inc-718	.67818	.69850
Gap	Hydrogen	.69850	.70485
Insulator tube	ZrC (50%TD)	.70485	.80645
Gap	Hydrogen	.80645	.81280
Hexagonal element body	Graphite	1.89484 cm face to face	
Element cladding	ZrC (100%TD)	.00508 cm thick coating	

3. Analysis Scope and Method

In this study we looked varying two parameters in order to achieve a critical state for the lower enriched fuels: the moderator-to-fuel ratio and the size of the active core. Varying the moderator-to-fuel ratio served to thermalize the fast neutron spectrum while changing the size increases the available fuel and reduces the inherent neutron leakage due to the small size of the reactor.

In order to do a basic and preliminary study of the above listed possibilities, a simpler neutronics model for the SNRE was developed. Instead of having an explicit geometry, the active core is presented as a single homogenous region. The material composition is defined using the material composition for the entire region, including the fuel, tie tubes, and coolant. The values for material densities with the active region of the core were taken from the values given by Durham[3] for the inner core region. The difference between the explicit model and the single zone model were found to be well within acceptable error, the largest being about 3.68 %Δρ.

4. Results and Analysis

It can be assumed that for the given reflector geometry and size of the reactor, each different enrichment has a very specific ratio of moderator to fuel that allows it to achieve a critical state. To find this ratio, we simply varied the moderator density inside the active region of the core until the reactor achieved a critical state.

In varying the moderator, hydrogen, we ignored the effects its variation would have on the densities of the other core materials. It is assumed that their effect on the reactivity of the reactor is relatively small in comparison to those of hydrogen, and that their dependence on the hydrogen density is actually rather small. As is shown in Figure 2, we were able to find that given a certain moderator to fuel ratio, it is possible to achieve a critical reactor.

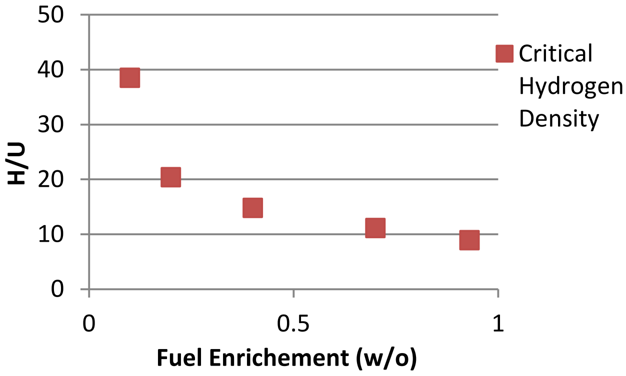

Fig. 2. Hydrogen to uranium critical ratio for different enrichment levels

With each enrichment level, we also assumed that there is minimum mass and volume needed for a particular enrichment level of fuel and moderator to fuel ratio in order to have a critical reactor. In order to find this, we made the assumption that we could treat the single zone core model as a cylindrical reactor. This allowed us to make the simplifying assumption that in order to maximize *k*, the height of the reactor is proportional to the radius by a factor[4] of 1.83. The results from our calculations are shown in Figure 3.

5. Comparison of LEU and HEU as Fuel

The major difference between the use of LEU and HEU fuels is the significant mass increase of the engine using LEU fuels. Typically, the mass of the engine in a rocket is considerably smaller than the accumulated mass of the propellant and payload of a rocket. In the case of a nuclear rocket engine, however, the mass of the engine is significantly larger than that of the typical rocket engine. Consequently, it has to be taken into account. In a preliminary analysis, we have found that through a combination of increased moderation and reflector size, it is possible to have a critical reactor with only about a 20% mass increase. Whether this mass increase is acceptable or not is dependent on the mission architecture and requirements weighed against the economics and cost of HEU and LEU fuels.

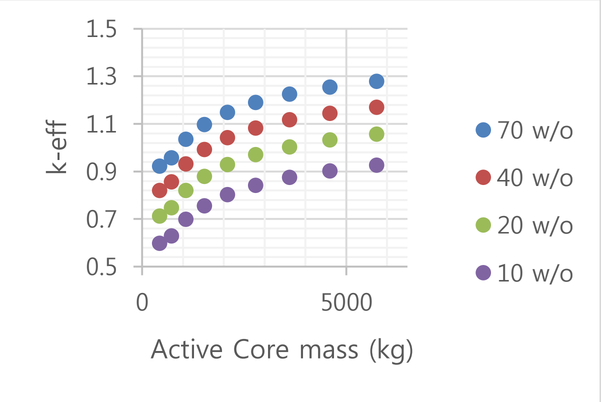

Fig. 3. Active core critical mass

6. Conclusions

While this study has not shown that the SNRE can be easily retrofitted for low-enriched U fuel, it has made a detailed study of the SNRE, and identified the difficulties of the implementation of low-enriched fuels in small nuclear rockets. These difficulties are the need for additional moderation and fuel mass in order to achieve a critical mass. Neither of these is insurmountable. Future work includes finding the best method by which to increase the internal moderation of the reactor balanced with appropriate sizing to prevent neutron leakage. Both of these are currently being studied.

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