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Nuclear Thermal Rocket Design Using LEU Tungsten Fuel

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1. Introduction

This paper will present a preliminary design for a mass optimized low enriched uranium nuclear thermal rocket (LEU-NTR) using a W CERMET fuel. This design was done at the Center for Space Nuclear Research at Idaho national laboratory with funding from the NASA Marshall Space Flight Center.[1] The impetus for the design was to verify the possibility of using LEU fuels in a nuclear thermal rocket.[2] This would then open the possibility for the commercial development and implementation of an NTR. The result was a design for a 114.66 kN thrust rocket engine, with an optimized specific impulse of 801 second, and a thrust-to-weight ratio 5.08. The development and analysis of the reactor was done using an integrated neutronics and thermal hydraulics code that combines MCNP5 using ENDF-B/VI cross sections with a purpose-built thermal hydraulics code.

2. Reactor Performance

The reactor performance characteristics of the W LEU-NTR are given in Table 1. There are two characteristics that make the W LEU-NTR stand out: the fissile material content and the reactor mass.

Table 1. Tungsten LEU-NTR Performance

Parameter	Value
Total System Mass	2302 kg
Reactor Mass	1110 kg
Est. Additional System Mass	692 kg
Est, Shadow Shield Mass	500 kg
Active Core Diameter	60 cm
Active Core Length	58 cm
Total U Mass	78.3 kg
Fissile Mass	15.3 kg
Thrust	114.66 kN
Thrust to Mass	5.08
Specific Impulse	801.65 seconds
Total Mass Flow Rate	14.58 kg/s
Total Reactor Power	400 MW
Neutral Drum Position k-effective	.99953

The low fissile material is due to the combination of using a low enriched fuel and the requirement for a high moderator-to-fuel ratio. Due to this, there is a significantly lower inherent proliferation risk in the fuel used. The total reactor mass is also significantly lower than in previous designs because the majority component of the active core is the moderator element, which is significantly lighter than the tungsten fuel elements.

In comparison with previous reactor designs, the proposed W LEU-NTR shows definite promise. It has a low mass when compared with similar thrust rockets and a high thrust-to-weight ratio. This is summarized in Table 2, where the W LEU-NTR is compared with three previous designs: Pewee, the SNRE, and the ANL-200.

Table 2. Reactor Comparison [3]

Dimension	Pewee	SNRE	Cermet (ANL-200)	LEU-NTR
Power [MW]	500	356	172	400
Isp [s]	875	875	832	802
Thrust [kN]	111.2	72.95	39.6	114.66
Mass [kg]	2570	2545	1268	2303
Thrust/Weight	4.8	2.92	3.18	5.08
Mass Flow Rate [kg/s]	18.8	14	~4.85	14.58
^{235}U Mass [kg]	36.42	59.6	177.3	15.3
# of Tie Tubes	134	241	0	636
# of Fuel Elements	402	564	121	211
Fuel Exit Temp. [K]	2550	2695	~2400	1856

The one characteristic where the current design is lacking, however, is the fuel exit temperature and therefore the Isp. While the Isp is still significantly higher than any existing chemical rocket, it is relatively low in comparison to previous NTR designs. The reason the current exit fuel temperature and Isp are so low is because the current design has not been optimized in terms of the radial power peaking factor. Currently, the reactor has a power peaking factor of 1.43 in the central fuel pin. This significantly reduces the average fuel temperature. It was found that if the radial profile is flattened such that the power peaking factor becomes 1.12, the Isp of the reactor can be increased up to 900 seconds with an average exit fuel temperature of about 2300 K.

3. Reactor Design

The LEU-NTR design is largely based on the proven technologies developed during the US NERVA program in the 1960s and 70s. The culmination of this program were the Pewee reactor tests [4] and the Small Nuclear Rocket Engine (SNRE) [5]. In an effort to maintain backwards compatibility with previous NTR development, the LEU-NTR was designed using the design specification for the extended Earth to Mars mission planned for the NASA Nuclear Cryogenic Propulsion Stage [1].

The reactor is designed around two hexagonal elements: the fuel elements and the moderator elements. The active core configuration is shown in Fig. 1. The detailed geometry of the active core elements is given in Table 3.

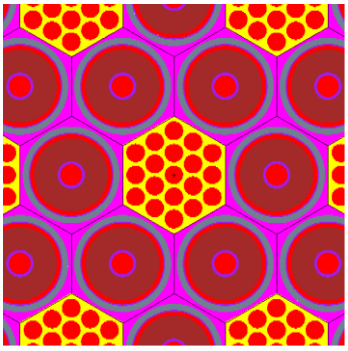

Fig. 1. Fuel element and tie tube arrangement

The fuel elements are hexagonal elements each with 19 coolant channels. The fuel elements are made of a W CERMET using 95 w/o enriched W-184. The reason for the W enrichment and other material selections was the need to minimize the thermal neutron absorption by non-fissile material. The CERMET fuel is a 45 %vol W with the remainder being UO_2 with a 6 mol % ThO_2 bonding agent. The fuel element design differs from traditional fuel element designs only in that the diameter of the coolant channels have been increased in order to improve the heat transfer from the fuel to the coolant and to decrease the coolant pressure drop across the active core.

The moderator elements are critical for enabling the use of LEU fuel because they house the moderating material in the active core. The major differences between the current and previous moderator element designs are the size of the moderator component and the material of the tie tubes. The size of the ZrH moderator tube was increased by increasing the outer radius of the tube and reducing the volume of the graphite insulating sleeve. The tie tubes are made of Zircaloy-4. The importance of the tie tube material in terms of the neutronics of the reactor has been previously shown [2], and resulted in the selection of the tie tube material being driven chiefly by the need to reduce the thermal neutron absorption by the tie tubes.

Outside of the active core, the W LEU-NTR follows a traditional design path. It has a 9 cm thick radial and upper beryllium reflector. The radial reflector has 15 rotating beryllium control drums, each with a .5 cm thick B_4C plate covering a 120 degree sector as the reactivity control system. The whole control drum system has a total worth of 7.6$ with a considerable shut down margin of about 3.54$.

Table 3. Tungsten LEU-NTR Active Core Element Geometry

Component	Material	Inner Radius (cm)	Outer Radius (cm)
Supply Hydrogen	Hydrogen		.203
Inner tie tube	Zircaloy-4	.203	.254
Moderator	ZrH	.254	.684
Return Hydrogen	Hydrogen	.684	.7605
Outer tie tube	Zircaloy-4	.7605	.786
Insulator tube	ZrC (50%TD)	.786	.9
Hexagonal element body	Graphite	1.89484 cm face to face	
Element cladding	ZrC (100%TD)	.00508 cm thick coating	
Fuel Element	W CERMET (45 vol% W, UO_2 with 6 mol% ThO_2)	1.905 cm flat to flat	
Fuel Coolant Channels	Hydrogen	.3454 cm diameter	

4. Conclusions

A proof of concept has been proposed for W LEU-NTR design. The current design is built upon traditional NTR design work and implements many of the proven design characteristics and materials from previous designs. Despite the current reactor design being preliminary, it already shows promise in being able to have similar, if not better performance characteristics than current and previous NTR designs.

Future work will involve the flattening of radial power profile, optimization of the axial power profile, researching methods to address the full water immersion accident scenario, and further studies regarding the breeding potential in the reactor.

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