DESIGN OF A TUNGSTEN CERMET LEU-NTR.
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Introduction: This paper presents a preliminary design for a mass optimized low enriched uranium nuclear thermal rocket (LEU-NTR) using a Tungsten CERMET fuel. This design was done at the Center for Space Nuclear Research (CSNR) at Idaho National Laboratory with support 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] and apply it to a system which uses the Tungsten CERMET being researched at CSNR. The successful application of LEU to the Tungsten CERMET is a non-trivial task in part because of the large absorption cross-section of natural Tungsten. The final result of the study is a design for a 114.66 kN thrust rocket engine, with a specific impulse of 801 seconds, 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/MCNP-X using ENDF-B/VI cross sections with a purpose-built finite difference thermal hydraulics code.

Reactor Performance: The reactor performance characteristics of the Tungsten LEU-NTR are largely driven by a combination of the reactor using a thermal neutron spectrum and making use of LEU fuel. These result directly in the reactor having an extremely low fissile content and a reactor mass that is comparable, if not better than a HEU fast fission reactor system. The calculated performance values are shown in Table 1.

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	.9995

In implementing the LEU fuel, the reactor neutron spectrum is heavily thermalized, which results in a direct increase in the fission cross section while the fissile density is reduced. The net result is an increase in homogenized macroscopic fission cross section for the fuel. In softening the neutron spectrum, the majority of the core is by necessity dedicated to housing the moderating material in the core. Consequently, due to the relative lightness of the moderator element in comparison with the fuel element, the core is significantly lighter than a solid tungsten fast reactor core.

When compared with previous reactor designs, the proposed Tungsten LEU-NTR shows promise. It has a relatively low mass in comparison with designs having a similar thrust, and consequently has a higher thrust-to-weight ratio. This is summarized in Table 2, where the Tungsten LEU-NTR is compared with three previous designs: Pewee, SNRE, and ANL-200.

Table 2. Reactor Comparison [3]

Dimension	Pewee	SNRE	Cermet (ANL-200)	W 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 currently not optimized, however, is the fuel exit temperature and therefore the Isp. While it is still significantly higher than existing chemical rockets, it is relatively low in comparison to the desired minimum of 900 seconds. This deficit is largely due to the un-optimized radial power peaking factor. This results in the reactor having a significantly lower average temperature because the hottest element is at a significantly higher operating temperature, which in turn is limited by the material characteristic of the fuel. In its current state, the reactor has a radial power peaking factor of 1.43. It was found that if the radial power profile is flattened such that the power peaking factor becomes 1.265, the Isp of the reactor can be increased up to 935 seconds with an average exit fuel temperature of about 2311 K. This optimization has been successfully accomplished in a separate study through the implementation of radial enrichment zoning and coolant channel orificing.

Reactor Design: The Tungsten LEU-NTR design is based on the proven technologies and baseline reactor design of the US NERVA program (Pewee, SNRE) [4][5]. This resulted in a reactor configuration that is still composed of the traditional moderator and fuel elements with changes limited to the material selection, minor geometry changes, and a new moderator to fuel element arrangement. An example of the active core arrangement is shown in Fig. 1. In an effort to ensure the cross-compatibility of the current design to existing NASA missions and current and previous NTR development, the LEU-NTR was designed using the mission parameters for the extended Earth to Mars mission planned for the NASA Nuclear Cryogenic Propulsion Stage specified by Houts et al [1].

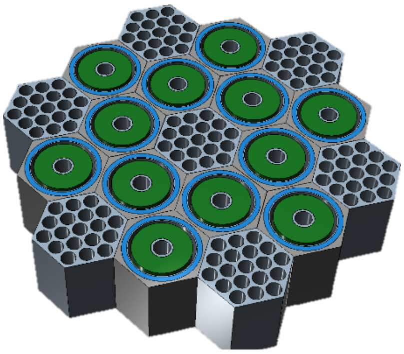

Fig. 1. Fuel and moderator element arrangement

The fuel elements are hexagonal elements each with 19 coolant channels. The fuel elements are made of a Tungsten CERMET using 95 w/o enriched W-184 due to it having a relatively lower neutron absorption cross-section in the thermal spectrum. By enriching to these levels, the average absorption cross-section of the Tungsten fuel is significantly decreased, reducing the non-fission neutron loss in the reactor. The CERMET fuel is a 45 %vol W with the remainder being UO_2 with a 6 mol% ThO_2 stabilizer agent. The fuel element deviates from the traditional fuel element design by having slightly larger coolant channels in order to improve the heat transfer to the coolant/propellant and to reduce the coolant pressure drop across the active core.

In the Tungsten LEU-NTR design, the moderator elements are the majority element in the active core. This increase relative to previous HEU designs stems from the need to include as much moderation in the active core as possible in order to thermalize the neutron spectrum. The differences between the current and legacy moderator elements stem from the change in critical roles. Previously, due to the use of a carbide fuel, the main purpose of the moderating elements was to provide structural support for the core, while the housing and protecting the moderator was secondary due to the fast nature of the neutron spectrum used. In the LEU-NTR, specifically in the Tungsten LEU-NTR, these roles are reversed in order of importance. This is due to the increased importance of ensuring and maintaining a thermal spectrum [2] and the inherent strength of the Tungsten CERMET which allows it be its own structural support.

This reversal of roles resulted in a couple minor, yet significant changes to the moderator element design. First, the size of the ZrH moderator sleeve in the element was increased by increasing the outer radius of the tube and reducing the volume of the graphite insulating sleeve. This was done in order to maximize the amount of moderator in each element. Second, the tie tube material was changed from an Inconel steel to Zircaloy-4. This switch minimizes the absorption of thermal neutrons by the structural material in the core.

Outside of the active core, the Tungsten 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 $7.60 with a considerable shut down margin of about $3.54.

Conclusions: We have proposed a proof-of-concept Tungsten LEU-NTR design. It shows that not only can an LEU-NTR have comparable performance characteristics as traditional designs, but provided further optimization, it promises to perform significantly better.

Further work includes the optimization of the axial power profile, implementing temperature effects, addressing the full water immersion accident scenario, and studies regarding the breeding potential in the reactor.

References:

[1] Houts M. G., Kim T., & et al., “A Nuclear Cryogenic Propulsion Stage for Near-Term Space Missions,” *Proceedings of Nuclear and Emerging Technologies for Space 2013*, Albuquerque, United States (2013). [2] Venneri P., and Kim Y.H., “Low Enriched Uranium Fuels in NERVA Type Nuclear Thermal Rockets”, *Transactions of the 2013 ANS Winter Meeting*, Washington D.C., United States (2013). [3] Schnitzler B.G., “Small Reactor Designs Suitable for Direct Nuclear Thermal Propulsion: Interim Report,” *Idaho National Laboratory Report*, INL/EXT-12-24776, Idaho Falls, United States (2012). [4] Los Alamos National Laboratory N-Division Personnel, “Pewee I Reactor Test Report,” *Los Alamos National Laboratory Informal Report*, **LA-4217**, Los Alamos, United States (1969). [5] Durham F. P., “Nuclear Engine Definition Study Preliminary Report, Volume 1 – Engine Description,” *Los Alamos National Laboratory Informal Report*, **LA-5044-MS Vol 1**, Los Alamos, United States (1972).