Preliminary Design of a NERVA TYPE Carbide LEU-NTR.

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Introduction: This paper presents the preliminary design study for a Carbide LEU-NTR. This study is a continuation of previous work where the feasibility of the LEU-NTR was shown [1], and is further developed into a preliminary reactor design with realistic performance values. This was done by doing a reactor mass optimization which takes into account the temperature effects on the nuclear cross sections. This preliminary design was done while keeping the mission requirements detailed in the NASA DRA 5.0 [2] in mind. The reactor design was then analyzed in various aspects in order to offer a better understanding as to its operating behavior and performance characteristics. It was analyzed in terms of the reactivity temperature dependence and operational life cycle.

All the neutronics calculations were done using MCNP5/MCNPX with the ENDF/B-VII library. The thermal hydraulics and mass optimization were accomplished using INROC currently being developed at CSNR.

Reactor Design and Performance: The Carbide LEU-NTR is a NERVA type NTR. This means that it is largely based on the traditional reactor configuration developed and implemented during the US NERVA program in the 1960s-70s [3][4].

This reactor design is characterized by two active core elements: the fuel and moderator elements. The fuel elements are the traditional 19 hole hexagonal fuel elements used in the SNRE design with the (U, Zr) C fuel implemented in the same design. The moderator elements use the same geometry as the standard SNRE tie tube elements except for two significant changes. First, the Inconel tie-tubes are replaced with Zircaloy tie tubes. This was done in order to minimize the parasitic neutron capture by the support elements in the active core. This material choice is critical in allowing the implementation of LEU in the NTR [1]. The second major change is the increase of the moderator volume inside of the moderator elements. This was done by increasing and decreasing the outer and inner radii, respectively, of the moderator sleeve.

The active core arrangement follows an inverse alpha arrangement in the core with a 2:1 moderator to fuel element ratio. This is different from other designs (the Tungsten LEU-NTR)[5] due to the additional moderation provided by the carbide fuel matrix. The additional moderation ensures that the arrangements with a higher moderator to fuel element ratio would create an over moderated core, thus decreasing the reactivity of the reactor. This allows for a larger number of fuel elements to be inserted into the reactor for a given reactor size. The radial geometry for the reactor is shown in Figure 1.

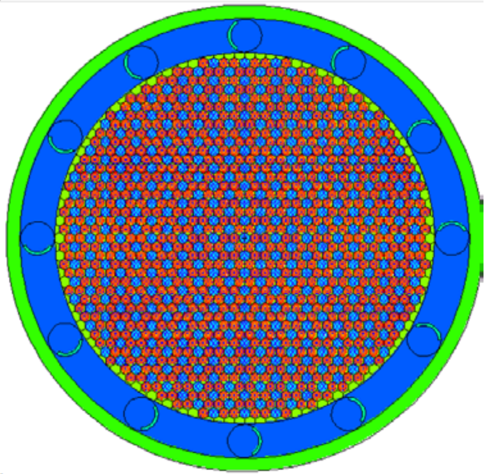

Figure. 1. Radial Core Geometry

Table 1. Carbide LEU-NTR Performance

Parameter	Value
Total System Mass	2364 kg
Reactor Mass	1179 kg
Est. Additional System Mass	658 kg
Est, Shadow Shield Mass	500 kg
Active Core Diameter	70 cm
Active Core Length	75 cm
Total U Mass	35.9 kg
Fissile Mass	14.58 kg
Thrust	110.89 kN
Thrust to Mass	4.8
Specific Impulse	775.33 seconds
Total Mass Flow Rate	14.58 kg/s
Total Reactor Power	375 MW
k-effective middle	1.00081
k-effective out	1.0186
k-effective in	.98209

The reactor itself was found to be able to fulfill the mission design requirements of having a low mass, relatively high thrust, and a similarly high specific impulse. The detailed performance characteristics are given in Table 1. The significant points in this table are the total fissile mass and the reactor mass. The mass is comparable, if not better than other NTR systems (both HEU and LEU), making it highly attractive for a future space system. The low heavy metal content, on the other hand, is a positive trait in that it would minimize the effect of the spread of heavy metals in the atmosphere in the case of an abort launch scenario with atmospheric re-entry. The comparison between different NTR designs is given in Table 2.

Table 2. NTR Comparison

Dimension	Pewee [3]	SNRE [4]	W LEU-NTR [5]	C LEU-NTR
Power [MW]	500	356	400	375
Isp [s]	875	875	802	775.33
Thrust [kN]	111.2	72.95	114.66	110.48
Mass [kg]	2570	2545	2303	2337
Thrust/Weight	4.8	2.92	5.08	5.15
Mass Flow Rate [kg/s]	18.8	14	14.58	14.58
^{235}U Mass [kg]	36.42	59.6	15.3	7.18
# of ME	134	241	636	780
# of FE	402	564	211	379
Fuel Exit Temp. [K]	2550	2695	1856	1748

Reactor Analysis: In order to verify the viability of the Carbide LEU-NTR beyond a mass-optimization, a series of operating parameters were further analyzed, including the fuel temperature coefficient (FTC) and reactor operating cycle with burn-up.

Fuel Temperature Coefficient: In the NTR, the fuel temperature effects are particularly important given that the reactor will be required to operate over a large temperature spectrum. Specifically, it will have to operate between 20K (when the reactor is first turned on) and 2800 K (the maximum fuel centerline temperature). The FTC was consequently found to be highly negative. This raises the interesting question of having to design an appropriate start-up and shut down sequence that takes into account the significant temperature effects on the reactivity. The reactivity dependence on the fuel temperature is shown in Figure 2.

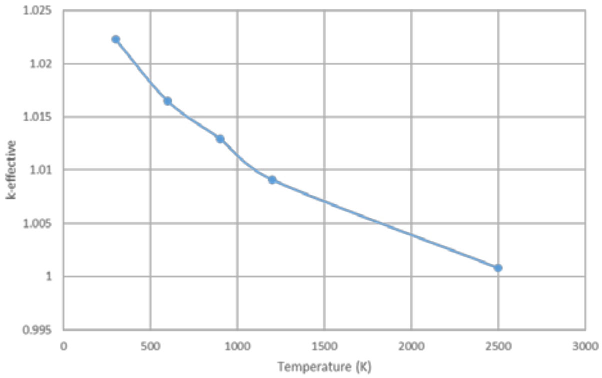

Figure. 2. Fuel Temperature Coefficient

Reactor Operating Cycle: Due to the use of a thermal spectrum in combination with an extremely small fissile content, the operating cycle of the Carbide LEU-NTR is highly dependent on the buildup of fission products in the core, and consequently, the reactor burn up. It was found that the maximum length of a single full power burn is approximately three hours when the reactor is first activated. However, the Carbide LEU-NTR can be successfully used for multiple full power burns if the fission products (namely Xenon-135) are allowed to decay between full power burns. It was found that in this instance, the Carbide LEU-NTR can be used for at least five full power burns lasting two hours each for a total of about 20 hours at full power. This behavior can be seen in Figure 3.

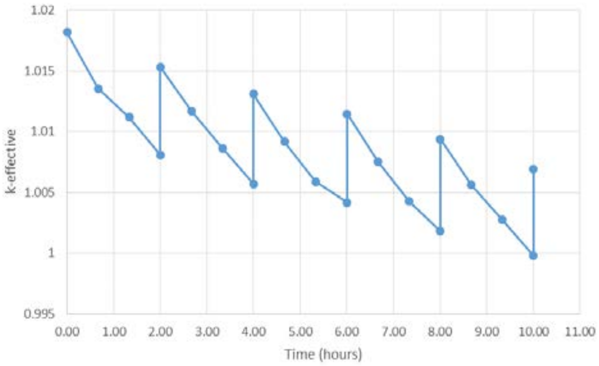

Figure 3. Reactor Operation Cycle

Conclusions: The current study has presented a preliminary reactor design showing the feasibility of the Carbide LEU-NTR. Its performance characteristics have been determined and compared with previous and current NTR design, and has been found to have comparable values. The study made a further analysis of the NTRs FTC as well as the total lifetime of at full power. Future work will consist of a more detailed analysis which takes into account not only the cross section temperature effects, but also looks at the change in density in fuel and non-fuel components of the reactor. Further work will also be done relating to the successful implementation of Zircaloy tie tubes.

References: [1]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., USA (2013). [2] Mars Architecture Stering Group, “Human Exploration of Mars Design Reference Architecture 5.0,” Houston, USA (2009). [3] Los Alamos National Laboratory N-Division Personnel, “Pewee I Reactor Test Report,” *Los Alamos National Laboratory Informal Report*, **LA-4217**, Los Alamos, USA (1969). [4] 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, USA (1972). [5] Venneri P., Husemeyer P., Deason W., Rosaire G., et al., “Nuclear Thermal Rocket Using LEU Tungsten Fuel”, *Transactions of the Korean Nuclear Society Fall Meeting 2013*, Gyeongu, ROK (2013).