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SENSITIVITY STUDIES OF THE TUNGSTEN VECTOR ON THE PERFORMANCE OF A LEU NTP ENGINE

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This paper explores the sensitivity of the criticality to the tungsten vector for a nuclear thermal propulsion (NTP) core, utilizing low enriched uranium (LEU) fuel. Tungsten ceramic metal composite (cermet) fuel is required due to the extremely high temperatures achieved in the core. However, tungsten has a non-negligible thermal neutron absorption cross section. This requires the tungsten to be enriched to contain mostly ^{184}W to maintain a critical configuration. The results of this study show that the core favors a harder spectrum, as expected, to reduce the parasitic absorption in tungsten. In addition, inaccurate tungsten vector definition (or relatively high manufacturing tolerances) can have a detrimental effect on the prediction of criticality, i.e., above 1,000 pcms.

I. Introduction

A near optimal core design has be established by previous work done at Georgia Institute of Technology[1]. The design achieved a specific impulse, denoted as I_{SP}, of ~900s, 40 klb_f of thrust, and a thrust-to-weight ratio of 4. This design is based on cermet fuel elements with 95% enriched ^{184}W. This imposes a potential problem because the cost of enriching a thousand pounds of tungsten to 81.1% ^{184}W was estimated to be 79,800$ per pound[5, 6]. Reducing the required enrichment of tungsten from 81.1% to 60.0% would save 45,000$ per pound[5, 6]. Therefore reducing to the required enrichment while maintaining criticality would be a significant benefit to the feasibility of NTP systems.

I.B. NTP Core Design Description

Cermet fuel elements are the optimal choice because of their chemical compatibly with hot hydrogen, and high melting point[1]. However, the natural composition of tungsten contains five isotopes, detailed in Table 1, which are characterized by large thermal neutron absorption cross sections, shown in Figure 1. One strategy to decrease the parasitic absorption of neutrons in tungsten is to middle enrich the tungsten vector to contain mostly ^{184}W. Middle enrichment is a process used when the middle atomic mass isotopes of a material vector is enriched. In the case of tungsten ^{184}W and ^{183}W are the middle isotopes. The process involves using two enrichment cascades, one to remove the heavier isotopes, ^{186}W, and another to remove the lighter isotopes, ^{182}W. This can be accomplished by using a double cascade enrichment scheme, which has been investigated for enriching molybdenum for use as a structural material in light water reactors[2]. Tungsten ^{180}W has been ignored in the calculation of the total cross section, and in the vector definition due to it only being a trace element, and its capture cross section having a similar behavior to the other isotopes.[5].

TABLE 1. Natural Tungsten Vector

Isotope	Weight Percent, %	Thermal Neutron Absorption Cross Section, barns
^{180}W	0.12	60
^{182}W	26.50	20
^{183}W	14.31	11
^{184}W	30.64	2
^{186}W	28.43	35
Total Macroscopic Cross Section is 1.05 cm^{-1}		

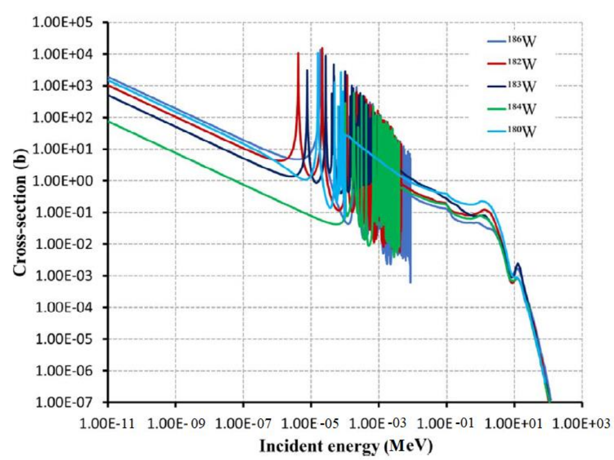

Fig. 1. Tungsten Isotopic Capture Cross Sections[1]

The cermet fuel contains 19.75% enriched UO_2 particles, which are embedded in a tungsten matrix with 6 mol% ThO_2 introduced as a stabilizer. A schematic view of the cermet fuel element is presented in Figure 2, where the red and blue regions represent the fuel and hydrogen coolant channels respectively. The LEU design requires to introduce moderating elements to achieve a critical core configuration. The moderating elements moderate fast neutrons, and heat the hydrogen gas before it enters the fuel elements. The H_2 flows through the supply channel and then the return channel of the moderating elements (ME) as one of the final steps of the engine's expander cycle. The moderating material in the ME is Zirconium Hydride (ZrH_x), represented by yellow in Figure 3. While a ring of zirconium carbide (ZrC) insulates the ZrH_x from high temperatures, represented by grey in Figure 3. An additional layer of graphite forms a hexagonal shape, represented by green. The inside of each hydrogen channel has a layer of Zircaloy-4, represented by black. The supply and return channels are represented by blue in Figure 3, with the supply channel being the inner blue circle and the return channel being the outer blue annulus.

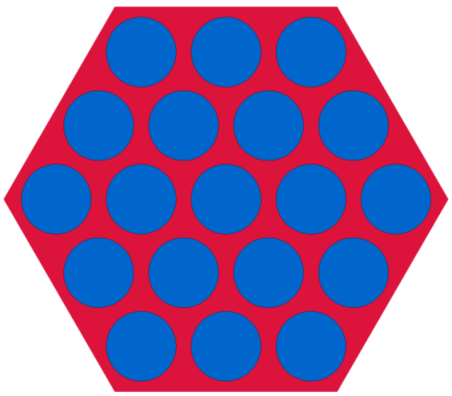

Fig. 2. NTR Fuel Element Cross Section

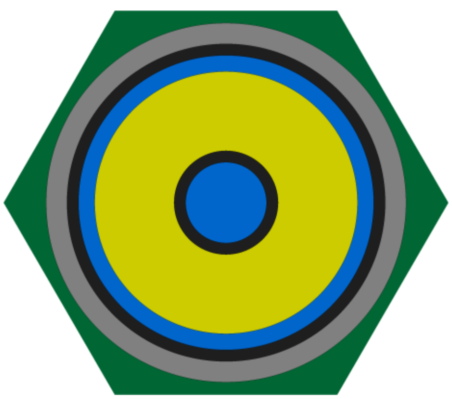

Fig. 3. Moderating Element Cross Section

Figure 4 shows an example of an NTP core with a moderating to fuel element (ME:FE) ratio of 2 to 1. The dark purple hexagons are fuel elements, and the yellow hexagons are moderating elements. Most NTP core designs have a regular lattice pattern like Pewee, SNRE, or Bullseye[8]. For this study a pseudo random element arrangement was used to model variable ME:FE ratios. This pattern was arbitrarily chosen simply to investigate the effect of Tungsten vector on the criticality. However, such random selection cannot be used to determine hot power peaking factors and this will be studied in the future. The control drums are located in the beryllium radial reflector, represented by blue in Figure 4. The control material is boron carbide, due to the fact that is has a high thermal neutron capture cross section. The control drums were rotated to 90°, which equates to being half way rotated in. The total number of elements in the core was kept constant at 1327.

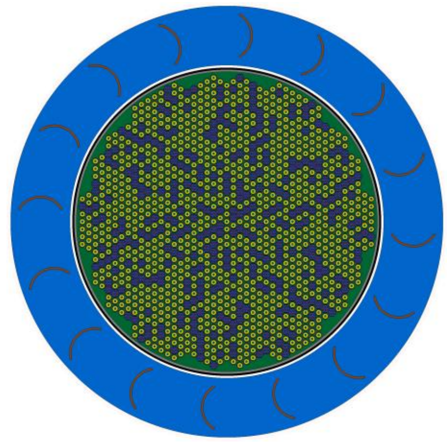

Fig. 4. NTR Core Cross Section with ME:FE Ratio of 2:1

II. Methodology

II.A Serpent Sensitivity Calculations

Serpent is a three-dimensional continuous-energy Monte Carlo particle transport code. The Serpent2 upgrade implemented a collision history based first order general perturbation theory equivalent to calculate sensitivities of various responses to perturbations of nuclear data[3]. The sensitivity of k_{eff} to the tungsten vector can be calculated by perturbing the total cross section of each isotope.

$$S = \left(\frac{dR}{R}\right) \Big/ \left(\frac{dP}{P}\right) \tag{1}$$

The sensitivity calculated by serpent is shown in Equation 1, where R is response variable and P is the perturbed variable. An energy grid was placed on the sensitivity study, ultimately yielding the energy dependent sensitivity of k_{eff}. The units of the each sensitivity would be $(dk_{eff}/k_{eff})/(d\sigma/\sigma)$. The output of these studies was processed using the serpentTools python package.[4] This package contains a sensitivity output file parser to read serpent output files and convert them into python objects. Several different ME:FE ratios were investigated using the sensitivity function.

II.B Tungsten Vector Definition

The enriched tungsten vector in this study was defined by specifying the weight percent of ^{184}W. Then redistributing the remaining weight percent based on the isotopic concentration of natural tungsten. Table 2 shows the tungsten vector for 87% enrichment tungsten. This vector is used for all the analysis conducted.

TABLE 2. Enriched Tungsten Vector.

Isotope	Weight Percent, %	Thermal Neutron Absorption Cross Section, barns
^{180}W	0.00	60
^{182}W	4.97	20
^{183}W	2.69	11
^{184}W	87.00	2
^{186}W	5.34	35
Total Macroscopic Cross Section is 0.30 cm^{-1}		

III. RESULTS

III.A Sensitivity Study Results

Figures 6 through 8 show the results of the sensitivity study for moderator to fuel element ratios of 1:1, 2:1, and 3:1 respectively. These results are based on the tungsten vector described in Table 2. Each isotope is listed in the legend as ZZAAA0, *e.g.*. ^{184}W is shown as 741840. The figures show a large negative well at approximately 10^{-7} MeV. This is expected because the peak of the thermal neutron flux occurs at 10^{-7} MeV[1]. As the ME:FE ratio increases, the depth of the negative sensitivity well increases. This can explained by the fact that as the ME:FE ratio increases the neutron spectrum in the core becomes softer, this effect is demonstrated in Figure 5. The spectrum across the entire core is shown in Figure 5, with the tungsten vector defined in Table 2.

TABLE 3. ME:FE Ratio Effect on Thermal Fissions

ME:FE Ratio	Fissions < 0.625 eV, %
3:1	77.49
2:1	70.05
1:1	53.16

Table 3 shows the fraction of fissions caused by neutrons with energy less than 0.625 eV. There is a clear negative trend on the fraction of thermal fissions as the ME:FE ratio decreases.

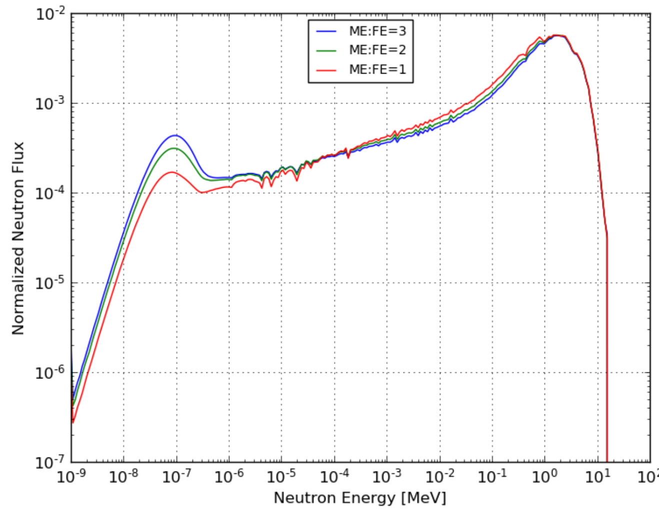

Fig. 5. Neutron Spectrum as a Function of ME:FE Ratio

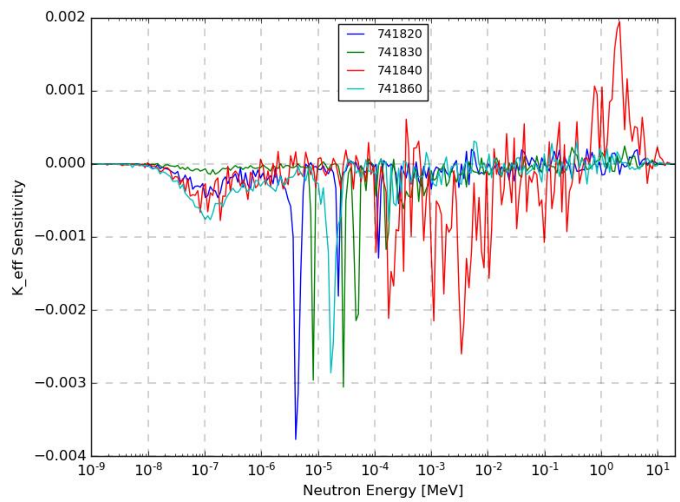

Fig. 6. Sensitivity of k_{eff} vs Energy for ME:FE = 1:1

The importance of the tail isotopes ^{186}W and ^{182}W is made apparent by the Figures 6, 7, and 8. ^{186}W has the largest impact on k_{eff} in the thermal region for all of the ME:FE ratios investigated, because it contains the largest thermal absorption cross section of all of the tungsten isotopes. ^{182}W has significant epithermal resonances, and also contains the largest negative sensitivity value for all of the isotopes across all ME:FE ratios.

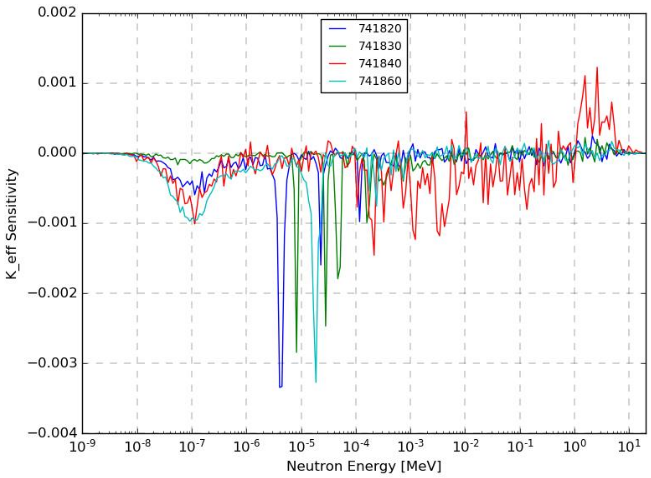

Fig. 7. Sensitivity of k_{eff} vs Energy for ME:FE = 2:1

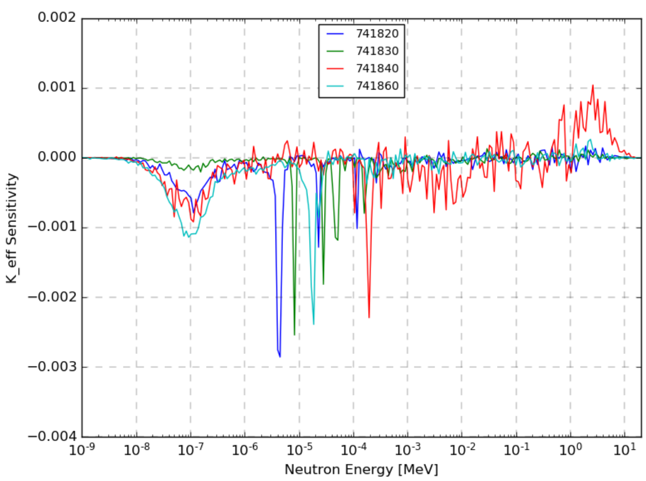

Fig. 8. Sensitivity of k_{eff} vs Energy for ME:FE = 3:1

III.B Tungsten Vector Definition Results

The methodology of renormalizing the enriched tungsten vector based on the natural composition of tungsten is not justifiable, however solving the vector to accurately model gas centrifuge enrichment is a non-trivial problem. Previous literature from NASA's water moderated nuclear rocket project contains a tungsten vector for 87% enriched tungsten post gas centrifuge enrichment[7]. Table 4 shows a significantly different vector where the weight percent of ^{183}W is considerable higher, while the tail isotopes are considerable lower than the weight percent's shown in Table 3. Table 3 results in an effective thermal cross section of 0.30 barns as compared to Table 4 vectors with 0.22 barns.

Table 5 shows that there is a significant reactivity gain achieved by modifying the tungsten vector to accurately model the gaseous centrifuge enrichment process. There is an average 1126 pcm increase in reactivity across the three ME:FE ratios investigated, with the highest reactivity gain of 1482 pcm with an ME:FE ratio of 3.

TABLE 4. Gas Centrifuge Enriched Tungsten Vector.

Isotope	Weight Percent, %	Thermal Neutron Absorption Cross Section, barns
^{180}W	0.00	60
^{182}W	1.58	20
^{183}W	9.95	11
^{184}W	87.05	2
^{186}W	1.42	35
Total Macroscopic Cross Section is 0.22 cm^{-1}		

TABLE 5. Tungsten Vector Definition Effect on k_{eff}.

ME:FE Ratio	Normalization Vector Definition k_{eff}	Gas Centrifuge Vector Definition k_{eff}
1:1	0.93485 ± 0.00052	0.94017 ± 0.00048
2:1	1.04557 ± 0.00049	1.05988 ± 0.00052
3:1	1.08765 ± 0.00049	1.10547 ± 0.00046

IV. CONCLUSIONS

The tungsten vector definition has a significant effect on k_{eff}. Using a renormalization methodology to adjust the tungsten vector can greatly underestimated the k_{eff} by up to 1482 pcm. By using a gas centrifuge vector definition the required tungsten enrichment to achieve a critical core can be significantly reduced. This will reduce the cost of manufacturing the NTP fuel elements. If the cost of 87% enriched tungsten fuel elements is acceptable, then lower ME:FE ratios could be utilized in the core. The advantage of this is that power density for fuel elements of the same size would be decreased. If the maximum fuel temperature is kept constant for all of the ME:FE ratios, then the lower ME:FE ratios can achieve a higher H_2 exit temperature and Higher I_{sp}. However there is a decrement to the Nusselt number due to the lower Reynolds number. This decrement is caused by the smaller mass flux from the increased flow area from increasing the number of fuel elements in the core. An ideal neutron spectrum would have the lowest possible thermal peak, for which the system is maintained at a critical level.

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