Neutronic Effects of Rhenium, Gadolinia and UO₂ Addition to a Tungsten Based Fast Spectrum Space Reactor

Jonathan A. Webb^{a,b,*}, Indrajit Charit^{a,1}

^aIdaho National Laboratory, N. Yellowstone Hwy., Idaho Falls, ID 83415-3855, USA

^bUniversity of Idaho, 875 Perimeter Drive MS 3024, Moscow, ID 83844-3024, USA

Abstract

The neutronic effects of rhenium (Re), gadolinia (Gd₂O₃) and uranium dioxide (UO₂) addition to a W-60vol.%UO₂ fast spectrum fuel form were investigated relative to a prismatic reactor type using the MCNP5 Monte Carlo code with the ENDF/B-VII.1 cross-section database. The effects of rhenium addition to the cladding tubes and sleeves were studied over the range of 2 to 25 at.% as well as the corresponding effects on the reactor mass and control drum reactivity swing and neutron energy spectrum. The effects of rhenium addition to the tungsten matrix over the range of 1 to 5 at.% was also investigated. Lastly, the UO₂ concentration was varied from 55 vol.% to 60 vol.% UO₂ and the UO₂ was mixed with Gd₂O₃ at concentrations ranging from 2 to 10 mol.%. Each configuration was investigated for its effects on the control drum shut down margin both in a dry state and in a submerged state where the reactor was surrounded and flooded with fresh water. The high thermal spectrum absorption cross-section of tungsten, rhenium and gadolinium proved excellent in maintaining the reactor in a subcritical state when submerged in fresh water. However, increases in the concentration of rhenium and

¹ Corresponding author: Tel +1-208-885-5964; fax: +1-208-885-0154

E-mail address: icharit@uidaho.edu

* Currently at Areva NP, Richland, WA, USA

gadolinia to the matrix, cladding and fuel kernels were also accompanied by an increase in reactor mass. The control swing within the drums was not influenced by the material compositions; however, the increase in reactor size with varying UO_2 and Gd_2O_3 concentrations did prevent a large fraction of the neutron population from reaching the control drums. The decrease in neutron population with access to the reflector region containing the control drums caused a loss of reactivity swing in the drums by up to 2.8% $\Delta k/k$ (\$4.36).

Keywords: Tungsten; Rhenium; Gadolinia; Fast Spectrum Space Reactor; MCNP5

1. Introduction

Over the past 40 years there have been many attempts to develop and deploy space reactors fueled with tungsten based Ceramic-Metallic (CERMET) fuel elements [1-3]. The base constituents within CERMET fuels used for high temperature space operations are usually tungsten (W) and uranium dioxide (UO_2). There have been many development efforts to fabricate and test W- UO_2 fuel forms at the General Electric (GE) [2,3], Argonne National Laboratory (ANL) [1] and National Aeronautics and Space Administration (NASA)[4-10] as well as basic attempts at characterizing the neutronic effects of tungsten and rhenium additions to critical geometries [11]. The traditional formula for fabricating W- UO_2 elements involves coating spherical UO_2 particles with tungsten to a pre-determined tungsten volume fraction [12,13]. Once the UO_2 particles are coated with tungsten, they are sintered into a highly dense state of the appropriate geometry by a process such as Hot Isostatic Pressing (HIP) [10], Hot Uniaxial Pressing (HUP) [5] or Pulsed Electric Current Sintering (PECS).

While tungsten and uranium dioxide are the primary constituents in W- UO_2 CERMET fuels, there are also other elements which can be added to the UO_2 fuel or the tungsten matrix to improve mechanical strength and high temperature fuel stability. Most nuclear propulsion reactors conceived for space flight require operational temperatures at or above 2700 K for up to 4 hours of lifetime [14,15]. Uranium dioxide fuel has a very high vapor pressure and will vaporize if exposed to vacuum conditions at these temperatures. The coolant of choice for nuclear propulsion reactors is hydrogen, which is highly mobile and will migrate through tungsten by grain boundary diffusion [6]. Once the hydrogen reaches the UO_2 kernels it can reduce the UO_2 leading to the formation of

free oxygen and liquid uranium, both of which have deleterious consequences for long term fuel stability. One option that has been successfully demonstrated to resist fuel vaporization and hydrogen reduction is the use of stabilizers such as CeO_2 , Y_2O_3 and Gd_2O_3 [16]. These stabilizers develop a fluorite lattice structure with UO_2 raising the decomposition temperature with a slight decrease in the melting temperature. Of all stabilizers tested with W- UO_2 fuel, Gd_2O_3 (gadolinia) seemed to have the greatest effect in reducing fuel loss as a function of thermal cycles at temperatures above 2700 K [17]. The ANL rocket program conducted the most rigorous testing of Gd_2O_3 within the kernels at concentrations ranging from 2.5 to 10 mol.%. The optimum Gd_2O_3 concentration is very much dependent on the operational requirements of high temperatures and the need for many start-up-shut-down cycles. The GE program was able to manufacture and design reactors for UO_2 concentrations as high as 55 vol.%, whereas the ANL program was able to fabricate fuels at 60 vol.% UO_2 .

The GE high temperature reactor program of the late 1960's and early 1970's investigated tungsten based CERMET fuels for use in nuclear propulsion and power production [2,3]. The pre-conceptual design for a closed cycle power reactor proposed by GE was to operate at lower temperatures than were required for propulsion. The design temperatures ranged from 1900 K to 2400 K, which were also accompanied by higher levels of burnup over many months to years of continuous operations. The high values of burnup added another mechanical issue to the survivability of the fuel in the form of creep induced by gaseous fission products trapped in the lattice structure. One method of increasing the mechanical strength of the tungsten matrix was to alloy it with rhenium (Re). Rhenium has long been known to cause dramatic increases in the strength

of tungsten while decreasing the ductile to brittle transition temperature.[18-20] While rhenium does increase the creep strength of tungsten at temperatures in the range of 1900 K to 2400 K, test data indicates that it actually decreases the creep strength of interest to propulsion reactors, which operate above 2400 K[21]. Rhenium is also a neutron absorber which can cause radical increases in the critical dimensions of a reactor if used at high concentrations within the tungsten matrix. The General Electric company experimented with the use of solid solution W-Re alloys as a matrix material with Re concentrations as high as 5 at.%. Previous testing has indicated that the formation of liquid uranium in CERMET fuels containing rhenium can also lead to the formation of a URe_2 intermetallic compound, which melts at low temperatures and is accompanied by a large volume change.[22,23] Both the GE company and the ANL programs investigated the use of cladding materials that consisted of W-Re alloys with a Re concentration up to 25 at.%.

To date there is no comprehensive parameter survey which details the effects of varying UO_2 , Gd_2O_3 and Re concentrations on a baseline space reactor design with respect to critical mass, reactor control, neutron energy spectrum and water submersion scenarios. This study uses the MCNP5 version 1.40 Monte Carlo computer code [24] with the ENDF/B-VII cross section database to investigate the neutronic effects of varying species loading on a pre-conceptual space reactor design.

2. Reactor Physics Analysis

The dimensions, mass, controllability and shutdown margin of any reactor is based on the fission, absorption and scattering cross-sections within the individual species present

in the reactor. Traditional W-UO₂ CERMET reactor designs operate in the fast neutron energy spectrum where tungsten, rhenium, gadolinium and oxygen are relatively transparent to scattering events and are usually forward biased when a scattering event does occur. The lack of an appreciable scattering cross-section within the primary fuel nuclides leaves the absorption and fission cross-sections as the dominant drivers to neutronic performance.

Figure 1 shows the energy dependent cross sections for U²³³, U²³⁵ and Pu²³⁹ over the energy range of 0.0001 eV to 30 MeV, which were extracted from the ENDF/B-VII.1 cross section database provided by the National Nuclear Data Center.

There are many tradeoffs that can be made when determining what portion of the neutron energy spectrum one desires a space reactor to operate in. The choice of the average neutron energy can affect the reactor mass, moderator mass, mass of highly enriched uranium and the reactor physics parameters. However, operating a reactor in the fast neutron energy spectrum allows for the use of spectral shift absorbers which can help control the fission reactor in the event of an unintended excursion [25].

If for some reason a reactor system finds itself surrounded by a high density, low molecular mass medium such as water, a series of unintended events may occur. First, the water molecules have a high lethargy for decrementing the neutron energy in each collision. On average a fast spectrum neutron need only undergo 16 collisions to become a thermal spectrum neutron, where its cross-section for fission is orders of magnitude higher[26,27]. Water molecules also have a high scattering cross section with an isotropic bias, which acts as a very good reflector to increase the neutron population within the fission core of a submerged reactor. The combination of the increased neutron

population and radically increased fission cross-section can push an otherwise subcritical reactor into a critical excursion. The possibility of a water submersion scenario is particularly acute to the space reactor community since over 70% of the Earth's surface is covered by water. If a reactor system were to fall back to the surface of the Earth, it is likely that it may land in a submerged state.

Spectral shift absorbers may help alleviate, if not eradicate, the potential for submersion criticality events in fast spectrum reactors. Spectral shift absorbers only have slightly elevated fast spectrum absorption cross-sections and large spikes in their thermal spectrum cross sections, which can terminate low energy neutron tracks before they can induce a fission event. Tungsten, rhenium and gadolinium all have small to large spikes in their absorption cross-sections at thermal energies, qualifying all of these materials as spectral shift absorbers. Figure 2 shows the energy dependent cross-sections of tungsten, rhenium and gadolinium over the range of 0.001 eV to 30 MeV. The fast spectrum absorption cross-section of gadolinium is noticeably higher than the W and Re, indicating a larger increase in the dry critical dimensions for fast spectrum reactor with higher Gd_2O_3 concentrations. Tungsten has the smallest cross section spike at an energy of 0.05 eV with a magnitude of 100 barns. Rhenium has the highest spike in absorption cross-section with a magnitude of 12,000 barns at 0.02 eV.

3. Pre-Conceptual Reactor Design

In order to assess the effects of varying concentrations of UO_2 , Gd_2O_3 and rhenium within the fuel elements, a pre-conceptual reactor design was developed based on inputs from the GE and ANL reactor designs. In the absence of any appreciable burnup an

excess reactivity of 1.5% $\Delta k/k$ ($k_{eff} = 1.015$) was deemed adequate for a total of 50 startup-shutdown cycles. An excess reactivity of 1.5% $\Delta k/k$ also allows the reactor to maintain a critical state when accounting for the expansion of the fuel and reactor components at operational temperatures[28]. Each reactor with varying isotopic concentrations was designed to have this peak reactivity in its most reactive cold-critical state.

3.1. Fuel Elements

The basic fuel element geometry developed by the ANL small engine design was adopted as the baseline for this study. The fuel element is prismatic in cross-section with a hex flat-to-flat distance of 2.77 cm. The element contains 61 coolant channels each with a diameter of 0.17 cm and a pitch distance of 0.345 cm between channels. Each coolant channel is lined with a 0.118 mm thick cladding tube that is comprised of a W-Re ranging from 0 to 25 at.% Re. The entire hex is surrounded by a hexagonal cladding sleeve comprised of a W-Re also ranging from 0 to 25at.% Re. The fuel meat consists of a W-UO₂-Gd₂O₃ composite where the UO₂-Gd₂O₃ concentrations range from 55 to 60 vol.% and the Gd₂O₃ content ranges from 2 to 10 mol.% within the UO₂ kernels. The W-UO₂ fuel meat within the first 20 cm of the fuel element is replaced by beryllium oxide (BeO) that acts as an axial neutron reflector. Figure 3 shows a cross-sectional view of the fuel element to include cladding tubes, cladding sleeve and fuel meat.

3.2. Reactor System

The prismatic fuel elements are arranged into a hexagonal array which is surrounded by a cylindrical 0.635 cm thick INCO-718 pressure vessel, which itself is surrounded by a radial reflector of beryllium. The inner radius of the pressure vessel varies based on the critical dimensions of the test case, but ranges from 17 cm for 5 hex rows and 23 cm for 7 hex rows. The thickness of the radial reflector also varies from 13 to 17.5 cm depending on the number of hex rows that range from 5 to 7 for the different atomic constituents. The radial reflector is embedded with 12 cylindrical control drums, which consist of a cylindrical INCO-718 pressure vessel, a beryllium shim fill, a centerline drum rod and a 0.5 cm thick crescent boron carbide sheath with a wrap angle of 120° . The boron carbide sheath is enriched to 90 at.% B^{10} so as to maximize the neutron absorption cross-section of the sheath for neutron control. When the drums are rotated to an angle of 0° where the B_4C sheath is the furthest from the fission core, the reactor is in the most reactive state. The entire radial neutron reflector is surrounded by a second 0.635 cm thick INCO-718 pressure vessel. Figure 4 shows a top-down view of the reactor system with all 12 control drums and 5 hex rows of prismatic fuel elements.

All reactor geometries in this study were analyzed using the MCNP5 V1.40 Monte Carlo code operating in the *kcode* mode[24]. The Monte Carlo method is a direct simulation of particle transport through a reactor geometry where a user specifies one or multiple start points for fission neutrons within the geometry. With respect to this computational parameter survey, reactor geometries and MCNP5 input decks are created by a FORTRAN program that can easily update geometries for new reactor dimensions.

Each code is programmed to track 15,000 neutrons per generation for 1,500 generations. The result of the first 100 neutron generations are skipped so that only the neutrons produced after spatial convergence are considered for a value of k_{eff} .

The length of the fuel region is varied until the reactor configuration reaches a drums-out k_{eff} of 1.015 and then the process is repeated by varying the number of hex rows and thereby the reactor radius until a k_{eff} of 1.015 is obtained. The reactor geometry with the lowest mass is accepted as the appropriate geometry. The computer code is then re-written with the same geometry but a differing control drum rotation angle that ranges from 0 to 180^0 to track the angle dependent neutron multiplication number. The critical drum angle is determined and the geometry is analyzed with the *totnu no* card which generates a neutron multiplication number in the absence of any delayed neutrons (k_2). The delayed neutron fraction (β) is determined from the ratio of the two neutron multiplication numbers as described in Equation 1. The excess reactivity (ρ_{ex}) is shown in Equation 2.

$$\beta = 1 - \frac{k_2}{k_{eff}} \quad (1)$$

$$\rho_{ex} = \left(\frac{1}{\beta} \right) \frac{k_{eff} - 1}{k_{eff}} \quad (2)$$

Each reactor configuration was also analyzed using mesh tallies to determine the neutron energy spectrum. Lastly, each reactor configuration was analyzed in a state where the reactor was surrounded sphere of fresh water, 200 cm in diameter and in a scenario where it was surrounded by a 200 cm diameter sphere of fresh water and the

coolant channels were flooded with fresh water. Each water submersion scenario was analyzed in a full drums-in and drums-out state to determine the effects of rhenium, gadolinia and tungsten concentration on submersion criticality.

4. Tungsten and Tungsten-Rhenium Cladding

The baseline reactor configuration consists of a W-60vol.%UO₂ fuel where the UO₂ kernels contain 5 mol.% Gd₂O₃. The configurations were analyzed based on three different datasets. The first dataset includes W-Re cladding sleeves that consist of 0, to 25 at.% Re, the second dataset includes W-Re cladding tubes of the same rhenium percentages, and the third data set includes W-Re cladding tubes and cladding sleeves of 0, to 25 at.% Re.

4.1. Reactor Mass

The reactor mass increases as the rhenium concentration increases in the cladding tubes and sleeves. The increase in reactor mass was predicted based on the fast spectrum absorption cross sections of rhenium over tungsten shown in Figure 2. Every increase in rhenium content of 1 at.% within the sleeves is associated with 0.018% $\Delta k/k$ (-2.83 cents) reactivity insertion. Every 1 at.% increase in rhenium content within the cladding tubes was found to be associated with a -0.043% $\Delta k/k$ (-8.23 cents) reactivity insertion. A simultaneous increase of 1 at.% Re within the tubes and sleeves was found to be associated with a reactivity insertion of -0.062% $\Delta k/k$ (-8.9 cents). The rhenium content within the cladding materials was found to have no effect on the delayed neutron fraction

which averaged to be 0.00679. The mass of the reactor system ranged from 2,493 kg in the case where pure tungsten was used in the cladding sleeves and tubes to 2,521 kg when the sleeves contained W-25 at.%Re. The mass of the reactor was found to increase to 2,586 kg when the tubes contained W-25at.%Re and 2,617 kg when both the sleeves and tubes contained W-25at.%Re. Figure 5 shows the reactor mass as a function of rhenium content for Case-1 where the rhenium only exists in the sleeves, Case-2 where the rhenium only exists in the sleeves, and Case-3 where it exists in both the sleeves and tubes.

4.2. Effects on Reactor Control

The rhenium additions to the cladding sleeves and tubes contribute to the neutronics in two different ways. First the addition of rhenium to the cladding increases the density of the cladding, which increases the collisional density between neutrons and atoms of tungsten and rhenium. The rhenium additions to the cladding also increase the macroscopic absorption cross-section of the cladding. It has been thought that additions of rhenium to the sleeve material can prevent neutrons from escaping the fuel into the reflector region. If neutrons cannot stream into the reflector region, they cannot interact with the control drums and as such the reactor may lose reactivity control. The neutron multiplication number (k_{eff}) was determined as a function of control drum rotation angle at 10^0 increments between 0 and 180^0 for cases where the tungsten cladding sleeves consisted of 0, 5, 10, 15, 20 and 25 at.% Re. The results indicated that the rhenium concentrations within the sleeve had no effect on the reactivity control outside the bounds of normal statistical variations. Figure 6 shows a plot of the computational values of k_{eff}

for each case with the values fitted to a 6th order polynomial. The standard deviations for each computational scenario never exceed 0.00014 and as such they were not plotted in Figure 6 because they could not be noticed relative to the mean values.

4.3. Neutron Energy Spectrum

The neutron energy spectrum was also determined for scenarios where the cladding tubes and cladding sleeved both consist of W-25at.%Re and where the sleeves and tubes consists only of tungsten. Each neutron energy spectrum was developed using MCNP5 with 103 logarithmically spaced energy groups. Figure 7 shows the neutron energy distribution over the range of 0.0001 eV to 30 MeV. The rhenium addition has almost no effect on the fast spectrum neutron energy distribution, but clearly demonstrates a change in the low energy distribution from 0.01 eV to 200 eV.

4.4. Submersion Criticality Scenarios

Reactor geometries were computationally submerged in a neutronically infinite medium of fresh water in states where the control drums were rotated to the least and most reactive angles. The same configurations were repeated for case scenarios where the reactor was not only submerged, but the coolant channels were also flooded with water. The neutron multiplication number was plotted as a function of rhenium content for geometries where the rhenium existed in the cladding sleeve, cladding tubes and both the tubes and sleeves.

In the case where the reactor was surrounded by and flooded with fresh water, the reactor remained deeply subcritical even when the drums were rotated to the most reactive angle. The rhenium increase within the cladding materials was accompanied by

a linear decrease in the neutron multiplication number. The addition of rhenium to the cladding tubes has a greater effect on the value of k_{eff} than when added to the sleeves because the sleeves are directly adjacent to the water where the majority of the neutrons are being thermalized. However, it should be noted that even in the case where the cladding materials consisted of pure tungsten, the reactor was maintained in a deep subcritical state when the drums were rotated to their most and least reactive positions. Figure 8 shows a plot of the neutron multiplication number as a function of rhenium content within the cladding sleeves, cladding tubes and both the cladding tubes and sleeves for geometries with the control drums in their most and least reactive angles.

The case where the reactor is only submerged and not flooded yielded very different results than in the case where the channels were flooded. The neutron multiplication number was only subcritical when the drums were rotated to their least reactive angle of 180° . When the drums were rotated to their most reactive state the neutron multiplication number actually increased from 1.015 to an approximate value of 1.03. The rhenium addition appeared to have a very minor effect on the neutron multiplication value. The number of neutrons which are able to access the water in this scenario is greatly reduced over the flooded case. Few neutrons are able to migrate through the radial reflector to be thermalized and reflected back into the core. Most neutrons that are thermalized access the water at the ends of the reactor, where only a small percentage stream back into the cladding. Figure 9 shows a plot of the neutron multiplication number as a function of rhenium content in the cladding tubes, cladding sleeves and both tubes and sleeves for the control drums rotated to their most and least reactive states.

5. Tungsten and Tungsten-Rhenium Matrix Materials

The same process carried out for the cladding tubes and sleeves was repeated for cases where rhenium was added to the tungsten matrix material. The UO_2 volume loading was maintained at 60% and the Gd_2O_3 concentration in the fuel kernels was maintained at 5 mol.%. The cladding tubes and sleeves consisted of pure tungsten for this portion of the study.

The addition of rhenium to the tungsten matrix had a slightly larger impact on the reactivity insertion than in the case of the cladding tubes. On average every increase in rhenium concentration of 1 at.% led to a reactivity insertion of $-0.142\% \Delta k/k$ (-20.98 cents). However, a small increase in the rhenium concentration within the fuel creates an increase in the net fuel region density. The increase in the length of the fuel region required to maintain a k_{eff} of 1.015 created a much larger increase in the mass of the reactor than when the cladding material was enriched in rhenium. The reactor mass was found to range from 2493 kg to 2556 kg over the range of 0 to 5 at.% rhenium within the tungsten matrix. The value of the delayed neutron fraction (β) did not differ based on rhenium addition and was found to have an average value of 0.00676. Figure 10 shows the mass of each reactor configuration as a function of rhenium content in the tungsten matrix.

The effects of rhenium on control drum reactivity swing, neutron energy spectrum and submersion criticality scenarios were nearly identical to that of the cases where rhenium was alloyed with tungsten in the cladding materials and as such was not plotted again.

6. Effects of Varying Gd_2O_3 and UO_2 Concentrations

The UO_2 concentration within the W- UO_2 fuel will obviously have an effect on the net reactor mass and possibly the controllability of the reactor. The Gd_2O_3 concentration within the UO_2 fuel will also have an effect on the reactor mass as evidenced in the high neutron absorption cross sections shown in Figure 2. The reactor designs proposed by GE involved peak UO_2 fuel loadings of 55 vol.% with stabilizer concentrations as high as 10 mol.%. The designs proposed by the ANL involved fuel loadings of 60 vol.% and stabilizer concentrations of 2 to 10 mol.%.

6.1. Reactor Mass

The reactor mass of a system produced by a fuel loading of 55 and 60 vol.% UO_2 with Gd_2O_3 concentrations ranging from 2 to 10 mol.% are produced using the MCNP5 V1.40 computer code. Each reactor configuration was based on the geometry shown in Figures 3 and 4 and was designed to have a k_{eff} of 1.015 with the drums rotated to their most reactive position. The addition of Gd_2O_3 to the fuel kernels was shown to increase the reactor mass by 1711 kg in the case of 60 vol.% UO_2 to 2222 kg in the case of 55 vol.% UO_2 . The addition of 5 vol.% UO_2 increased the reactor mass by 500 kg in the case of 2 mol.% Gd_2O_3 to 1006 kg in the case of 10 mol.% UO_2 . Each 1 at.% increase in Gd_2O_3 concentration was accompanied by a -1.66% $\Delta k/k$ (-\$2.44) reactivity insertion and each 1 at.% increase in UO_2 volume percentage was accompanied by a 1.04% $\Delta k/k$

(\$1.53) reactivity insertion. Figure 11 shows a plot of reactor mass for fuel materials containing 55 and 60 vol.% UO_2 with Gd_2O_3 concentrations ranging from 2 to 10 mol.%.

6.2. Reactor Control

The addition of Gd_2O_3 and UO_2 to the reactor system was found to have little if any effect on reactor control. However, increases in the Gd_2O_3 concentration and decreases in the UO_2 concentration had an effect on the reactor radius. The minimized reactor mass occurs over a narrow range of reactor length to radius ratios. The increased Gd_2O_3 concentration and variable UO_2 concentration necessitates an increase in reactor length to achieve criticality; however, at some point it becomes necessary to increase the reactor radius to preserve the minimum mass configuration.

Over the range of 2 to 10 mol.% Gd_2O_3 and 55 to 60 vol.% UO_2 , the reactor increases from 5 to 7 hex rows, causing a growth in the inner pressure vessel radius from 17 cm to 23 cm. As the reactor radius increases, the fraction of the total neutron population that is able to migrate into the reflector region decreases, which makes the control drums less effective. In the case where the control drums are rotated to their least reactive angle in a non-submerged dry state, the neutron multiplication number ranged from 0.9519 ± 0.00014 with 5 hex rows to 0.978 ± 0.00014 when the minimum mass involved 7 hex rows. Figure 12 shows the neutron multiplication number as a function of drum rotation angle for configurations involving 5, 6 and 7 hex rows, which correspond to a peak core radius of 17, 20 and 23 cm.

6.3. Neutron Energy Spectrum

The energy spectrum for fuel types consisting of W-UO₂ with 0, 2 and 10 mol.% Gd₂O₃ were developed in MCNP using 103 logarithmically spaced energy groups over the range of 0.001 eV to 30 MeV. As would be expected, the Gd₂O₃ had a profound effect on the low energy neutron flux. A mere addition of 2 mol.% Gd₂O₃ erased very low energy neutrons from the system; however, it only had a slight effect on the high energy neutron population. The addition of higher quantities of Gd₂O₃ reduced the neutron population at all energies observed. The UO₂ volume fraction within the fuel was found to have a negligible effect on the energy spectrum over the range of 55 to 60 vol.%. Figure 13 shows a plot of the neutron energy spectrum for reactor configurations with 0, 2 and 10 mol.% Gd₂O₃.

7. Conclusion

The effects of Re, W, UO₂ and Gd₂O₃ concentrations within the matrix, fuel and cladding materials of W-UO₂ fuel was investigated relative to a conceptual space reactor design. The addition of rhenium to the tungsten cladding sleeves and tubes inherent in prismatic fuel designs was found to increase the mass and dimensions of the reactor such that it could achieve a neutron multiplication number of 1.015. The addition of rhenium to the tungsten cladding causes a slight increase in the fast spectrum neutron absorption, The increase in the neutron absorption caused an increase in the net mass to achieve the desired level of criticality. The rhenium also caused an increase in the thermal spectrum absorption cross-section which aided in submersion criticality scenarios. In cases where a reactor system becomes submerged in fresh water and the coolant channels become

flooded with water, the reactor was deeply subcritical even if the drums were rotated to their most reactive position. However, it should also be mentioned that even in cases where the cladding materials contained no rhenium, the reactor was still deeply subcritical. In scenarios where the reactor system was submerged but not flooded, the reactor could only be kept subcritical if the control drums were rotated to their least reactive angle. The rhenium addition within the cladding had no noticeable effect on the ability to control the reactor in a non-submerged dry state.

The effects of rhenium addition within the matrix material were also investigated. Surprisingly, the addition of rhenium to the matrix material cause only a slightly larger reactivity decrease than experienced for rhenium additions to the cladding materials. However, rhenium addition to the matrix material resulted in a rather large increase in reactor mass, due to the increase of the fuel region with increasing rhenium content.

The UO_2 concentration was varied from 55 to 60 vol.% and the Gd_2O_3 content within the fuel kernels was varied from 2 to 10 mol.%. As expected a mere 5% decrease in the concentration of UO_2 caused a rather large increase in reactor mass. The reactor mass increased by 500 kg in the case with 2 mol.% Gd_2O_3 and 1006 kg in the case with 10 mol.% Gd_2O_3 . At a fuel loading of 60 vol.% UO_2 , the reactor mass increased by 1711 kg over the range of 2 to 10 mol.% Gd_2O_3 and the reactor mass also increased by 2222 kg over the range of 2 to 10 mol.% Gd_2O_3 at 55 vol.% UO_2 .

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FIGURES

Figure 1. Fission cross sections for uranium-233 (blue) uranium-235 (red) and plutonium-239 (orange), courtesy of the National Nuclear Data Center.

Figure 2. Absorption cross sections for elemental tungsten (blue), elemental rhenium (red) and elemental gadolinium (orange), courtesy of the National Nuclear Data Center.

Cladding Thickness = 0.1178 mm
Hex Flat-to-Flat Distance = 2.77 cm
Fuel Meat = W-60 vol.% UO_2

Figure 3. Cross sectional diagram of the pre-conceptual W- UO_2 prismatic fuel element.

Figure 4. Top-down view of the pre-conceptual W-UO₂ CERMET reactor design with the control drums rotated to their most reactive state.

Figure 5. Reactor mass associated with Case-1 where the clad sleeves contain variable rhenium content, Case-2 where the clad tubes contain a variable rhenium content and Case-3 where both the tubes and sleeves contain a variable rhenium content.

Figure 6. Neutron multiplication number (k_{eff}) as a function of control drum rotation angle for cladding sleeves consisting of W, W-5at.%Re, W-10at.%Re, W-15at.%Re, W-20at.%Re and W-25at.%Re as determined by MCNPR-V1.40 using the ENDF/B-VII cross section library.

Figure 7. Neutron energy spectrum for a W-60vol.%UO₂-5mol.%Gd₂O₃ reactor with pure tungsten cladding and both cladding tubes and sleeves of W-25at.%Re.

Figure 8. Neutron multiplication number for submerged reactor scenarios with flooded coolant channels where the control drums are rotated fully in and out for geometries with rhenium additions in the cladding tubes, cladding sleeves and both the tubes and sleeves.

Figure 9. Neutron multiplication number for a submerged reactor scenario without flooded channels where the control drums are rotated to a full in and full out position for geometries with rhenium additions in the cladding tubes, cladding sleeves and both the tubes and sleeves.

Figure 10. Reactor mass as a function of increasing rhenium content within the tungsten matrix for a W-60vol.%UO₂-5mol.%Gd₂O₃ fuel form with tungsten cladding sleeves and tubes.

Figure 11. Reactor mass as a function of increasing Gd₂O₃ molar concentration within the UO₂ kernels for UO₂ loadings of 55 and 60 vol.%.

Figure 12. Neutron multiplication number (k_{eff}) as a function of drum rotation angle for reactor geometries involving 5, 6 and 7 hex rows.

Figure 13. Neutron energy spectrum for fuel types consisting of W-60vol.% UO_2 - Gd_2O_3 with Gd_2O_3 concentrations consisting of 0, 2 and 10 mol.%.