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Spectral Shift Methodology for "Deep-Burnup" of Uranium-Thorium-Hydride Fuel

Z. Shayer
University of Denver, Denver, CO 80208-0202, zshayer@du.edu

This paper examines the possibility of using spectral shift methodology within the reactor core made of thorium-hydride rods, by introducing hollow tubes inside the assembly. The spectral shift option is simulated by means of the one-dimensional lattice code WIMSD-5B through changing fuel-to-water volume ratios at different burnup steps. The analysis shows that it is possible to increase the discharge burnup values by 50% for uniform core configuration. The thorium-hydride fuel also possesses very good inherent safety features such as a large prompt fuel temperature coefficient of reactivity that is twice larger that of oxide fuel. This fuel also has very favorable non-proliferation characteristics.

KEYWORDS: Thorium fuel, plutonium, hydride fuel, "deep-burnup", reactivity coefficients

1. Introduction

In recent years there has been increasing interest in the thorium based fuel cycle, because it possesses more proliferation resistance attributes than the conventional uranium oxide fuel. One of the main weaknesses for practical application of the different proposed uranium-thorium-oxide fuel cycle is economics. In order to overcome this obstacle, the thorium based fuel cycle should be significantly longer and with less heavy metal than traditional LWR fuel with UO_2. The thorium hydride fuel was proposed and patented by General Atomics (GA) about two decades ago for possible use in LWRs. The main goal of this paper is to examine the neutronic characteristic of this fuel to attain high burnup. The key issue of successful application of Th-232 in the LWR is the formation of the neutron spectrum as a function of time and location that would permit the breeding of U-233, with enough excess reactivity to keep the core running for relatively high burnup. It is very difficult to accomplish this task due to different neutron spectra needed for breeding and fissioning of the new fuel. The highest breeding efficiency of the U-233 from neutron capture in Th-232 occurs in resonance energy interval 20 eV to 370 eV, while the highest fission rate in U-233 occurs at the neutron thermal energy range. At the BOL of the reactor there is enough reactivity to keep the reactor critical and it would be reasonable to have a hard neutron spectrum to maximize the breeding rate. However, when the reactor core depletes excess reactivity as a function of irradiation time, it is well advised to move to a softer neutron spectrum in order to increase the fission rates. In the uranium thorium di-hydride fuel the moderator is also imbedded inside the fuel region. A couple of options were considered in this study to enhance the discharge burnup value. These options can be classified into the following two categories. The first one uses uniform fuel rods with the variation of neutron spectrum achieved by changing of neutron moderation inside the coolant or inside the fuel. The second option involves the use of a heterogeneous reactor configuration that consists of at least two different types of fuel rods. The leading reactor core configuration for this case is the stationary seed-blanket reactor core structure. In this paper we present an approach of uniform fuel pins and enhancing the burnup level by changing the moderation ratio through the variation of fuel-to-water volume ratio (V_f/V_w), along with favorable proliferation resistance characteristics. To ensure that this reactor core remains within the bounds of basic reactivity safety considerations, the reactivity coefficients are also presented along with comparison with a typical PWR fuel rod and with another hydride fuel made of uranium-zirconium-hydride.

2. Computational Procedure

The neutronic parametric study in this paper is limited to infinite pin cell calculations. Most of the analysis was performed by WIMSD-5B [1], a deterministic code system for reactor core lattice calculations. This code was benchmarked against well-established codes such as MCNP4B2 [2] and SCALE4.4 [3] to provide additional justification for the use of the WIMSD-5B code, for parametric study of hydride fuels.

3. Results

3.1 Burnup Study

Several preliminary uniform pin cell cases were analyzed prior to the spectral shift options. Samples of the various cases are summarized in Table 1 below, along with attainable burnup values and Internal Conversion Ratio (ICR). The End of Life (EOL) burnup values defined in this study are for discharge burnup at K_∞=1.0. All the calculations were performed for typical PWR rod dimensions (R_{fuel}=0.4095 cm; R_{gap}=0.4178 cm; R_{clad}=0.4748 cm). Note that uranium thorium di-hydride (U-ThH_2) fuel can reach the same burnup value as UO_2 (with 5% enrichment) only with 15% and 20% enrichment in U-235 and with 35 w/o and 25 w/o of uranium, respectively. Figure 1 shows the K_∞ variations as a function of pitch-to-diameter (P/D) ratio at different discharge burnup levels. As can be seen from this figure, slightly higher discharge burnups for U-ThH_2 fuel can be achieved with higher P/D ratios, in the ranges of 1.4 to 1.6. It is also possible to achieve in U-ThH_2 fuel higher burnup values than that of UO_2 fuel, for a very tight lattice, with P/D less than 1.2. Figure 2 shows the variation of K_∞ for maximum attainable burnup value for thorium di-hydride, case 7, along with the comparison with a typical UO_2 rod of 10% enrichment and U-$ZrH_{1.6}$ also with 10% enrichment and 45 w/o of uranium. The burnup value for U-ThH_2 fuel at K_∞=1.0 is only 61 GWd/Te as compared to 78 GWd/Te and 85 GWd/Te for UO_2 and U-$ThH_{1.6}$ fuel, respectively. Therefore, in order to make the reactor core based on uniform pin cell configuration economically attractive in the future, the fuel burnup must be significantly extended. An example of the spectral shift idea is demonstrated again in Figure 2 below. The discharge burnup is increased by 50%, from 60 GWd/Te to 90 GWd/Te. The hollow tube movement is simulated by the one-dimensional code WIMSD-5B via changing the fuel-to-water volume ratio in different burnup steps, in this example each 15 GWd/Te ihm, starting with a very tight lattice with P/D of 1.05 and progressing to a highly moderated lattice with P/D of 2.0. The fuel rod dimensions are kept the same during the fuel irradiation process. Any nuclear power concept that will require processing of U-233 has no likelihood of being adopted or accepted in the foreseeable future. Therefore, the only economically acceptable approach is to utilize the U-233 inside the core by burning it in place as it is formed in the thorium, and this spectrum shift idea is one of the ways that will require further investigation and study for keeping the reactor core in a uniform configuration.

Table 1: Evaluated Cases for U-ThH_2 Unit-Cell

Case Number	Uranium Enrichment	Uranium Fraction	P/D	K_∞ BOL	EOL Burnup (MWD/kg ihm)	ICR
1	15%	25%	1.05	1.08551	10.0	0.738
2	15%	25%	1.33	1.17954	28.8	0.603
3	15%	25%	1.77	1.26007	29.0	0.458
4	15%	35%	1.05	1.15473	28.0	0.615
5	15%	35%	1.33	1.26488	46.0	0.489
6	20%	25%	1.33	1.25330	45.0	0.507
7	20%	35%	1.33	1.32217	61.0	0.419
8	20%	35%	1.20	1.26119	57.0	0.477
9*	20%	35%	1.20	1.25588	56.5	0.484
10**	20%	35%	1.20	1.26251	57.0	0.475

* The size of the fuel rod increases to the same dimension as that of U-$ZrH_{1.6}$ namely, R_f=0.59903 cm; R_{gap}=0.60411 cm; R_{clad}=0.64475 cm; ** The size of the fuel rod decreases to the following dimensions, R_f=0.3000 cm; R_{gap}=0.3083 cm; R_{clad}=0.3653 cm

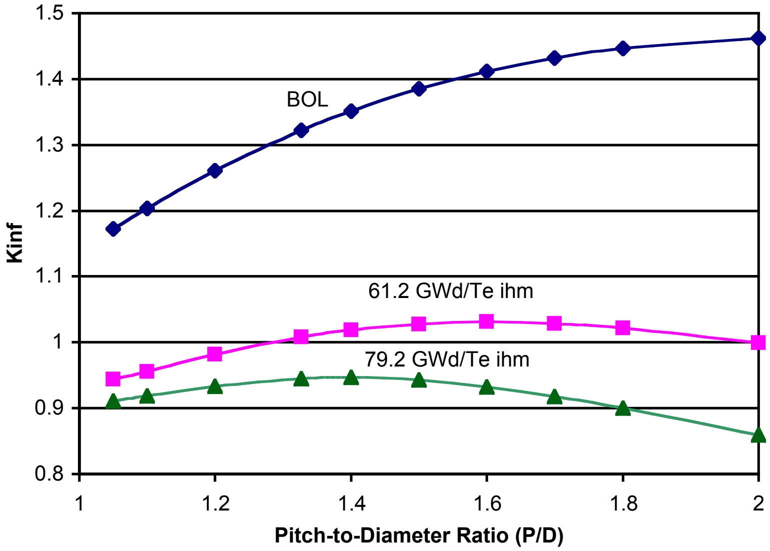

Figure 1: K_∞ variation as a function of P/D for 35w/o of uranium in U-ThH_2 pin with 20% U-235 enrichment at three-discharge burnup levels

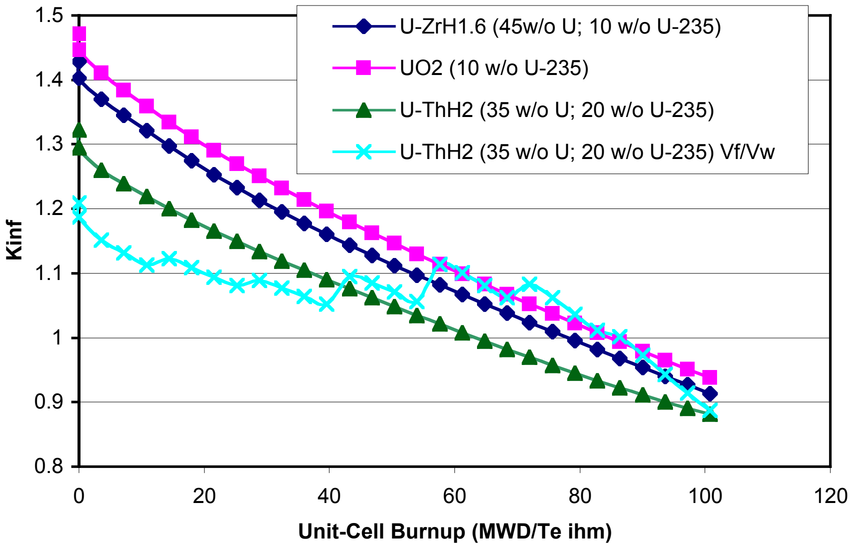

Figure 2: The effect of U-ThH$_2$ fuel with V_f/V_w variation as a function of burnup on K_∞

The uranium contents in Case 7 are shown in Figures 3 and 4, where Figure 3 depicts the variation of uranium mass as a function of fuel burnup, while Figure 4 shows the fraction of each isotope. Note that the U-233 increases while the U-235 is consumed. At a discharge burnup of 75 GWd/Te ihm, the fissile content is still 8.8w/o of the total uranium, which is close to 50% of the initial loaded U-235. U-233 content is about 50% of the total fissile material. U-236 content is about 3.3 w/o compared with 0.6 w/o in the case of a typical UO$_2$ rod, leading to relatively high production of Pu-238, which has significant impact on the proliferation resistance. Also note that the fraction of U-238 continuously increases as a function of burnup. The variations of mass and isotopic composition of the plutonium in case 7 are shown in Figure 5. The plutonium fissile materials (Pu-239 and Pu-241) are only about 15% of total fissile materials (plutonium and uranium) after 75 GWd/Te ihm. However, the plutonium composition has significant impact on the proliferation resistance of this type of fuel. The Pu-238 fraction is about 2.7% at 45Gwd/Te ihm, increasing to 7.4% at 75 GWd/Te ihm, as compared to about 1% to 2% in the conventional uranium dioxide fuel. The high decay heat and spontaneous neutron production of Pu-238 poses a strong obstacle for the handling of the plutonium. Table 2 shows the plutonium composition of the U-ThH$_2$ with 35 w/o uranium and 20% enrichment as compared with other fuel types. As can be seen this fuel is very favorable from the proliferation resistance point of view.

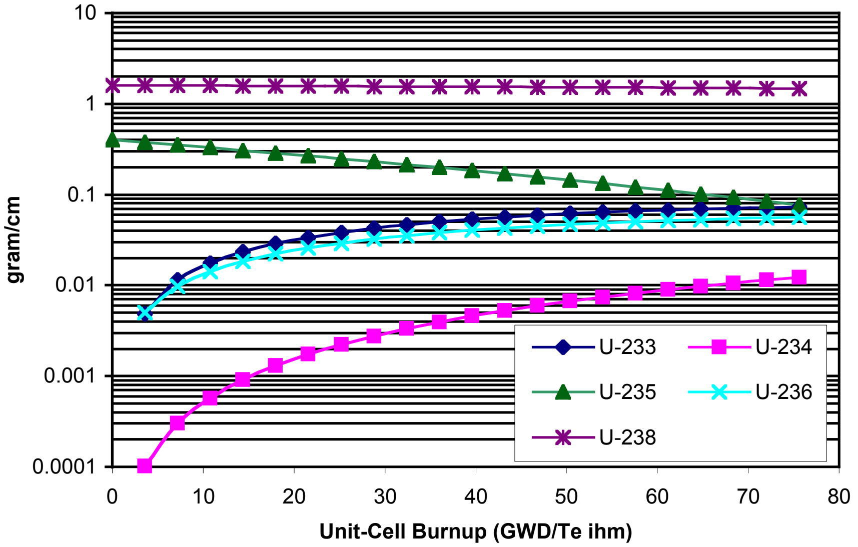

Figure 3: Gram per cm of uranium in unit-cell in a 65w/oThH$_2$ – 35w/oU (20% U-235) burned to 75 GWd/Te.

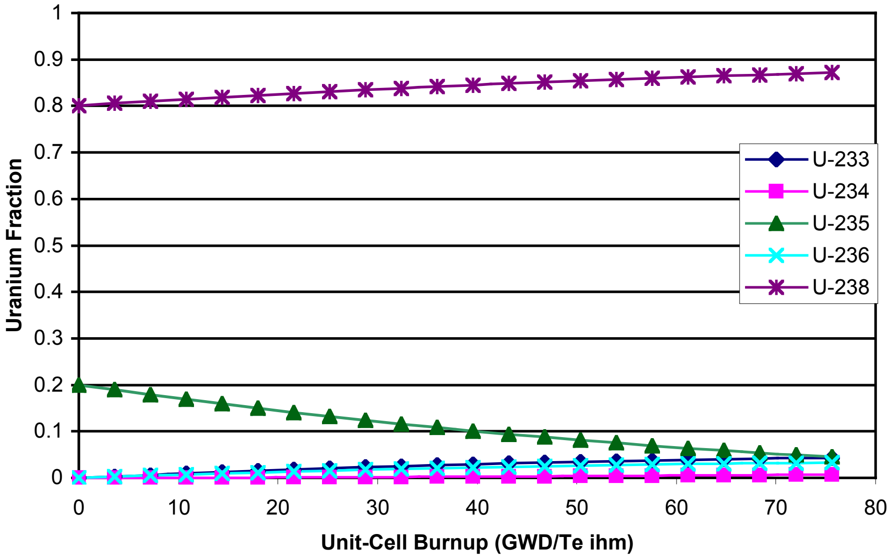

Figure 4: Uranium composition in unit-cell in a 35w/oU - 65w/oThH$_2$ (20% U-235) burned to 75 GWd/Te.

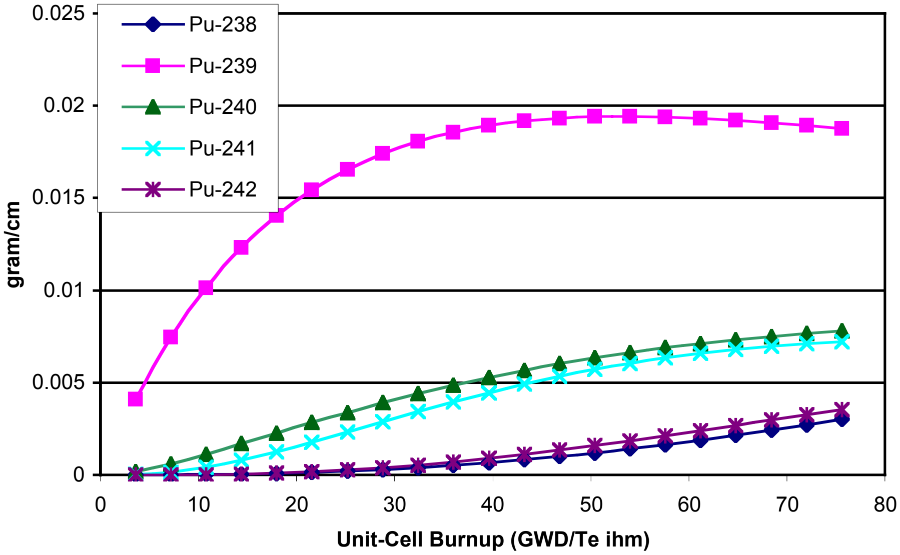

Figure 5: Gram per cm of plutonium in unit-cell in a 65w/oThH$_2$ – 35w/oU (20% U-235) burned to 75 GWd/Te.

Table 2: Isotopic Composition of Various Plutonium Grades

Isotope (mass %)	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
Weapons Grade	< 0.05	93.6	6.0	0.4	<0.05
Fuel Grade	0.1	86.1	12	1.6	0.2
Power Grade	1.0	62.0	22.0	12.0	3.0
MOX Grade	1.9	40.4	32.1	17.8	7.8
U-ZrH$_{1.6}$	1.4	61.1	19.3	13.5	4.72
U-ThH$_2$ (45GWd/T)	2.7	59	18	15.8	4.5
U-ThH$_2$ (75GWd/T)	7.4	46.8	19.3	17.9	8.6

3.2. Reactivity Study

3.2.1. Doppler and Hydrogen Effect

The prompt fuel temperature coefficient is more negative for uranium-thorium-hydride fuel due to the contribution of hydrogen inside the fuel. As the fuel temperature is raised, the probability that a thermal neutron inside the fuel will gain energy from an excited state of an oscillating hydrogen atom in the lattice increases. The neutrons gain more energy and the thermal neutron spectrum inside the fuel shifts to a higher average energy, toward the strong resonance absorption of Th-232 in addition to U-238, and these values are double those of UO$_2$ and U-ZrH$_{1.6}$. As shown in Table 3, the prompt fuel temperature coefficient is significantly higher than that of uranium oxide and zirconium hydride fuels. This highly negative prompt fuel temperature coefficient remains negative for the entire life of the thorium hydride fuel as opposed to the zirconium hydride fuel, which is less negative at the end of life due to accumulation of plutonium. The results were calculated for typical PWR fuel rod dimensions at a reactor operating temperature of 978 ^{o}K.

Table 3: Doppler Coefficient

Fuel Type	Doppler Coefficient plus Hydrogen Effect	
	BOL	EOL
UO_2 (5w/o U-235)	-2.0E-05	-3.2E-5
UO_2 (10w/o U-235)	-1.7E-05	-3.0E-5
45w/oU-$ZrH_{1.6}$ (10w/o U-235)	-2.3E-05	-1.2E-5
25w/oU-ThH_2 (20w/o U-235)	-4.1E-05	-4.4E-5
35w/oU-ThH_2 (20w/o U-235)	-3.5E-05	4.0E-5

3.2.2. Coolant Temperature Coefficient

The coolant temperature coefficient (CTC) of reactivity is an important safety parameter in LWRs. Defined as the variation of reactivity induced by a change in the coolant temperature and divided by the coolant-average temperature, the CTC plays a major role in the feedback mechanism of the reactor and has to be negative so that reactor core in all circumstances would be stable. Reducing effective water density in the reactor core by temperature expansion (or increases) or void (steam or air bubble) directly affects the neutron moderation capability of water. This may affect reactivity in negative or positive ways, dependent mainly on P/D ratio and soluble boron concentration. In this report, only the reactivity changes in the fuel region (unit-cell) are analyzed. The water density as a function of temperature is taken from an ANS proposed benchmark problem for LWRs and is given in Table 4 below.

Table 4: BOL Water Atom Densities

Isotope	Coolant (300 ^{o}K; 0 ppm)	Coolant (570 ^{o}K; 0 ppm)
Hydrogen (1001)	6.68896E-02	4.87959E-02
Oxygen (8016)	3.34448E-02	2.43980E-02

Figure 6 below shows the CTC values of uranium-thorium-hydride fuel at the BOL of the core without soluble boron. It is seen that 25w/o U-ThH_2 with 20% enrichment have almost the same CTC behavior as UO_2 fuel with 5% of U-235 enrichment for P/D ratio greater than 1.4, and have larger CTC values than that of U-$ZrH_{1.6}$ fuel.

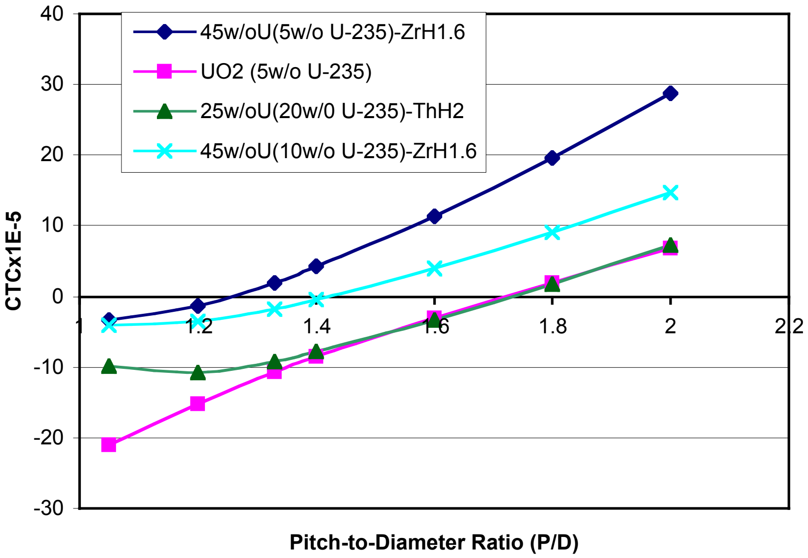

Figure 6: CTC comparison as a function P/D ratio between U-ThH_2, U-$ZrH_{1.6}$ and UO_2 rods in square lattice for typical PWR rod dimensions.

4. Conclusion

The thorium hydride fuel would be economically attractive for future use in nuclear power plants with significant increases in the burnup and fuel cycle length beyond the current fuel cycle intervals. The spectral shift with hollow tubes demonstrates that it is possible to increase the discharge burnup by 50% in the uniform core configuration, which requires further detailed study beyond this preliminary analysis. The thorium hydride fuel also has very favorable non-proliferation characteristics.

5. References

1) WIMSD-5B (98/11), Deterministic Code System for Reactor-Lattice Calculations, RSICC CCC-656, user manual.
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3) SAS2H: A Coupled One-dimensional Depletion and Shielding Analysis ModuleNUREG/CR-0200 Revision 6, September 1998.