Comparison of Th-232 and U-238 Fuel Performance in a Tight Lattice High Conversion BWR

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ABSTRACT

Several innovative tight lattice High Conversion Boiling Water Reactor (HCBWR) designs have been proposed over the past few years that provide substantial increases in the fuel conversion ratio by hardening the neutron spectrum. However, a significant problem for tight lattice designs is the potential for a positive void reactivity coefficient (VRC). Some tight lattice cores achieve a negative VRC by enhancing neutron leakage through various design strategies such as flattening the core, adding axial blankets, or using fuel assemblies with void tubes [1]. However, a previous study demonstrated that simply replacing U-238 with Th-232 as fertile material in a HCBWR can mitigate the positive void reactivity effect [2], [3]. This paper examines the detailed neutronics behavior of Th-232 and U-238 in a tight lattice BWR core. The core performance for the void reactivity, reactivity control, and cycle length are compared for a HCBWR fueled with U-238 and Th-232 fertile fuels. The favorable performance of a thorium fueled core is shown to be a direct result of the favorable neutronics characteristics of Th-232 relative to U-238 in a hard neutron spectrum, such as a larger thermal capture cross section, a smaller fast fission cross section, and a smaller resonance integral. The only significant drawbacks of Pu-Th fuel in a tight lattice core are a shorter cycle length than a comparable Pu-U core and the possibility of the void reactivity coefficient that is too negative. However, an axially heterogeneous design is described which utilizes both Pu-Th and Pu-U fuel to recover the longer cycle performance and provides a void coefficient that is comparable to existing BWRs.

1. INTRODUCTION

Currently, light water reactors (LWR) are the principal design option for generating nuclear power. Since LWRs have a relatively low conversion ratio (fissile atoms produced per fissile atoms consumed) they require relatively frequent refueling and the quantity of spent fuel and the accumulation of Pu can become economic and proliferation issues. The development of Fast Breeder Reactors as an alternative technology to alleviate some of these concerns has been delayed for various reasons. An intermediate solution has been to examine tight pitch light water reactors which can provide significant improvements in the fuel cycle performance of the existing LWRs by taking advantage of the increased conversion ratios from the reduced moderation and harder neutron

spectrum in the tight pitch lattice. Several High Conversion BWR designs have been proposed by researchers at Japan Atomic Energy Research Institute (JAERI) and elsewhere. As part of the U.S. Department of Energy's (DOE) Nuclear Energy Research Initiative (NERI), a "Generation IV" high conversion Boiling Water Reactor (HCBWR) design was investigated at Purdue University and Brookhaven National Laboratory.

One of the more promising HCR designs is the Reduced Moderation Water Reactor (RMWR) proposed by JAERI. Their design showed significant improvements in fuel cycle performance compared to conventional BWRs. However, one of the drawbacks of their design was the potential for a positive void coefficient. In order to insure a negative void coefficient, the JAERI researchers designed a "flat core" and introduced void tube assemblies in order to enhance neutron leakage in the event of core voiding. In a previous paper we showed that Th-232 provides advantages regarding the void reactivity coefficient and a core design was proposed with Pu-Th fuel which showed a negative void coefficient throughout the core life. The purpose of this paper is to provide a detailed neutronics analysis of Th-232 and U-238 as fertile materials in a HCBWR.

2. COMPARSION OF ASSEMBLY PERFORMANCE WITH Pu-U AND Pu-Th FUEL

2.1 ASSEMBLY CONFIGURATION

The design parameters for the HCBWR fuel assembly used in the work here are shown in Table 1 and the assembly geometry is depicted in Figure 1. The assembly deisgns have been simplified somewhat to provide a consistent comparison. All the fuel rods in each assembly are identical and only Pu-239 and Pu-240 are considered in the weapons grade Plutonium. The nuclide densities of the fuel rods are listed in Table II.

Table I Design Parameters for HCBWR Fuel Assembly

Assembly geometry	Hexagonal
Assembly pitch	304.2 mm
Channel outer distance	299 mm
Channel inner distance	289 mm
Number of rods/assembly	469 mm
Number of fuel rods/assembly	468 mm
Fuel pin arrangement	Triangle
Fuel Element Pitch	13.21 mm
Fuel Element O.D.	11.91 mm
Clad Thickness	0.4 mm
Fuel Pellet Diameter	11.11 mm
Moderator/coolant	H2O

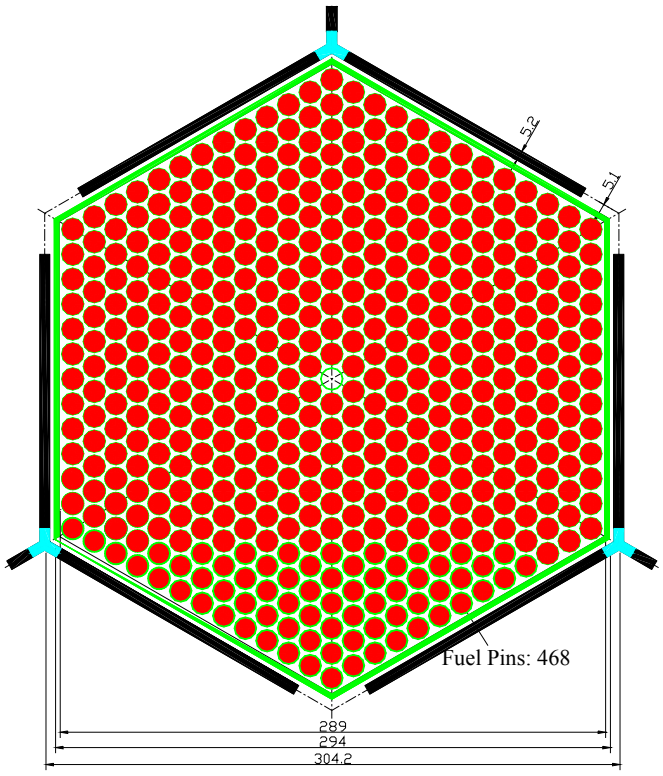

Figure 1. Assembly in HCBWR

Table II. Nuclide Densities in HCBWR Fuel Rod (10^{24}/cm^3)

Assembly Type	Pu-U Fuel	Pu-Th Fuel
Th-232	0.00000	0.01800
U-238	0.01800	0.00000
Pu-239	0.00188	0.00188
Pu-240	0.00012	0.00012
O-16	0.04000	0.04000

2.2 RESULTS OF FUEL ASSEMBLY PERFORMANCE

Fuel assembly calculations were performed using a 190 energy group library of the HELIOS commercial lattice physics code [4]. The infinite multiplication factors of the fuel assemblies at the core average 40% void fraction are plotted as function of burnup in Figure 2. The results show that the assembly with Pu-Th fuel has a smaller initial excess reactivity than the assembly fueled with Pu-U. The lower initial excess reactivity simplifies reactivity control for the reactor with Pu-Th fuel.

The void reactivity coefficient (VRC) as a function of burnup is shown in Figure 3 for a transition from 40% to 80% voids. As indicated in the Figure, the VRC of assembly with Pu-U is about –12

pcm/%void at zero burnup, but it becomes positive at burnups larger than 6 GWD/T. Conversely, the VRC of assemblies with Pu-Th Fuel is about –100pcm/%void at all burnups.

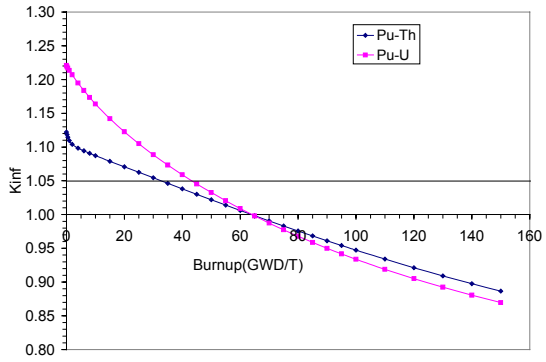

Figure 2. K-inf vrs Burnup at 40% void

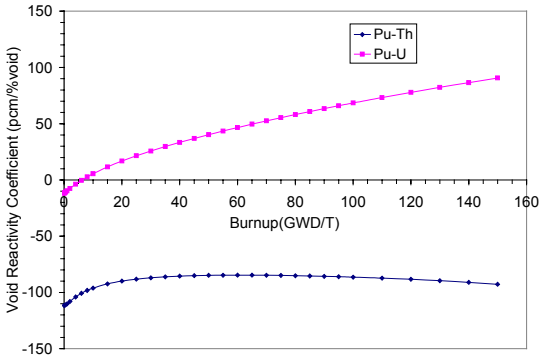

Figure 3. VRC from 40% to 80% void

2.3 ANALYSIS FOR FUEL ASSEMBLY RESULTS

One of the most important differences in the fuel assembly results is the lower initial excess reactivity observed with Pu-Th fuel. This can be explained by a detailed examination of the the cross sections and reaction rates in Th-232 and U-238. The absorption and fast fission cross sections of U-238 and Th-232 are compared in Figure 4.

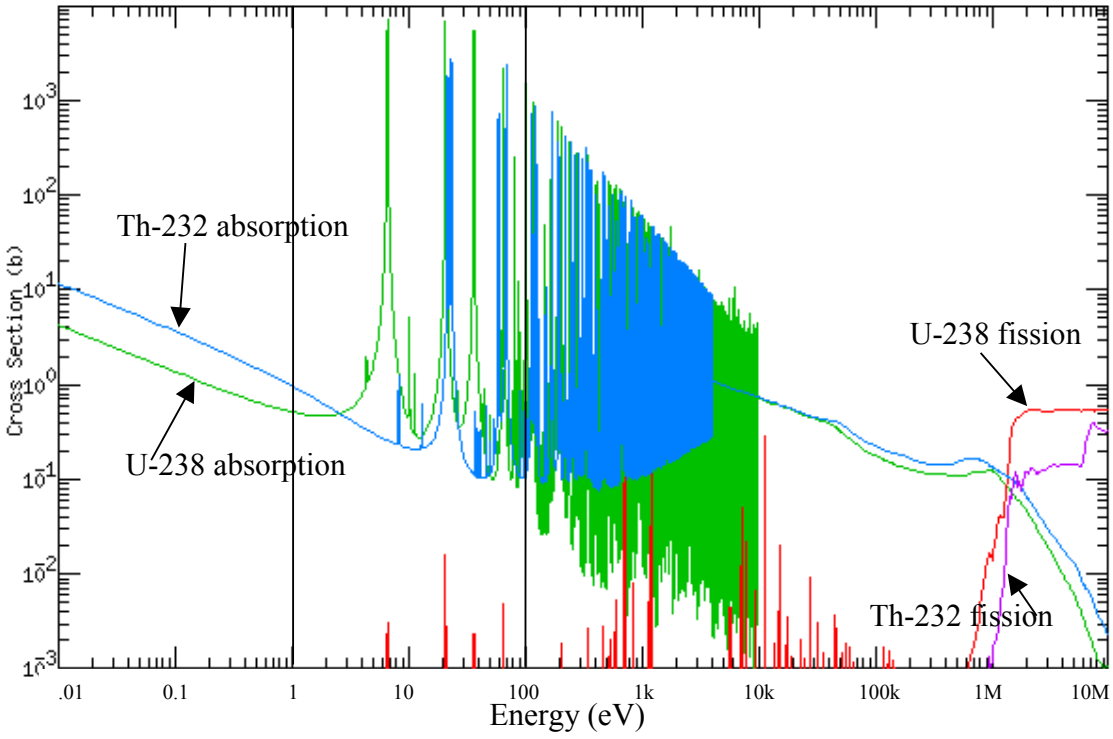

Figure 4. Comparison of Absorption and Fast Fission Cross Sections of U-238 and Th-232

As indicated in the Figure, the Th-232 thermal absorption cross section is about 2.7 times larger than that of U-238, the resonance integral of U-238 is about 3 times larger than that of Th-232 in the overall energy range, and the fast fission cross section of U-238 is about 4 times larger than that of Th-232. However, a more detailed comparison of the absorption cross sections of U-238 and Th-232 can be made by separating the energy spectrum into six different energy regions as indicated in Table III. As indicated in the Table, Th-232 has a smaller absorption cross section in the 1eV~100eV range, but is larger or comparable to U-238 in all other energy regions. Table III also shows the relative reaction rates in the six energy ranges at 40% void and zero burnup. The total absorption and fission rates are shown in Table IV.

Table III Comparison of Absorption Cross sections of U-238 and Th-232 and the Relative Reaction Rates[1)] at 40% void and Zero Burnup

Energy range	Cross section Comparison	Relative Absorption Rates **U-238**	Relative Absorption Rates **Th-232**
0.04~10MeV	$\sigma_a^{Th} > \sigma_a^{U8}$	8.68	6.32
10~40keV	$\sigma_a^{Th} \approx \sigma_a^{U8}$	2.29	2.63
4~10keV	$\sigma_a^{Th} > \overline{\sigma_a^{U8}}$ *	1.53	2.28
0.1~4keV	$RI_a^{Th} > RI_a^{U8}$	9.23	13.44
1~100eV	$RI_a^{Th} < RI_a^{U8}$	9.06	5.73
0~1eV	$\sigma_a^{Th} \approx 2.7\sigma_a^{U8}$	0.18	0.52
Total		30.99	30.93

1) The unit is percent. The isotopic relative reaction rate=$100\times\Sigma^{isotope}/\nu\Sigma_f$
2) According to results from Assembly calculation

Table IV. The Isotopic Relative Reaction Rates at 40% Void and Zero Burnup

Assembly	**Pu-U**			**Pu-Th**		
Reaction	Absorption	n-Fission[3)]	Reactivity[4)]	Absorption	n-Fission	Reactivity
Th-232	0	0	0	30.93	2.96	-27.97
U-238	30.99	14.06	-16.93	0	0	0
Pu-239	44.17	85.29	41.12	50.11	96.39	46.28
Pu-240	4.95	0.65	-4.30	6.14	0.65	-5.49
Other	1.81	0	-1.81	1.93	0	-1.93
Total	81.91	100.00	18.09	89.11	100.00	10.89

3) Fission neutron production
4) The isotopic reactivity = (fission neutron production rate)-(absorption rate)

As indicated in Table IV, the fast fission neutron production in U-238 is about 11% higher than in Th-232, whereas the total absorption rates are comparable. Therefore, the most important factor in the higher initial excess reactivity of Pu-U fuel is the larger fast fission effect in U-238.

A detailed understanding of the difference in the void reactivity between Pu-Th and Pu-U fuel can be provided by examining the changes in the isotoptic relative reaction rates when the void fraction is increased from 40% to 80% void as shown in Table V.

Table V. The Relative Isotopic Reaction Rate Change from 40% to 80% Voids at BOC

Assembly	**Pu-U**			**Pu-Th**		
Reaction	Absorption	n-Fission	Reactivity	Absorption	n-Fission	Reactivity
Th-232	0	0	0	**6.92**	**0.50**	-6.43
U-238	**3.70**	**2.15**	-1.54	0	0	0
Pu-239	-2.06	-2.29	-0.23	-1.26	-0.66	0.60
Pu-240	-1.37	0.14	1.52	-1.48	0.16	1.64
Other	0.21	0	-0.21	0.28	0	-0.28
Total	0.48	0	-0.48	4.46	0	-4.46

When the void fraction is increased and the neutron spectrum is hardened, the Th-232 fission rate change is smaller than that of U-238 by about 1.65%. However, the more important effect is that the Th-232 absorption rate change is smaller than that of U-238 by about 3.22%. This is because the spectrum of a tight lattice is much harder than the spectrum of a normal light water reactor lattice. As shown Figure 5, when the void fraction increases, the spectrums for both Pu-Th and Pu-U harden significantly. However, because the Th-232 absorption cross section is larger in the important energy range of 100eV~1MeV, the increase of absorption by Th232 is much larger than that by U-238 and the void reactivity coefficient will be more negative.

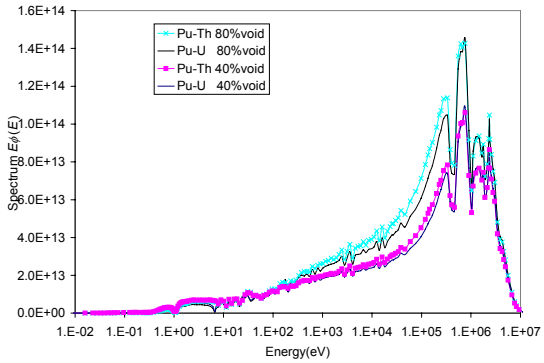

Fig 5 Assembly Neutron Spectrums

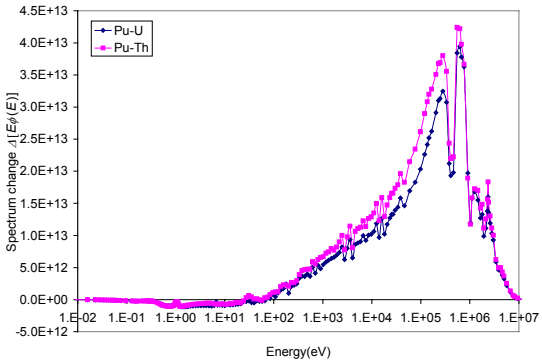

Fig 6 Spectrum Change from 40% to 80% Void

3. COMPARSION OF HCBWR CORES WITH Pu-U AND Pu-Th FUEL

3.1 CORE CONFIGURATION

The tight pitch Pu-U and Pu-Th fuel assemblies were then used to design equilibrium cycle HCBWR cores. The primary design parameters of the core analyzed here are shown in Table VI. An equilibrium core loading was developed as shown in Figure 7 by arranging fuel assemblies from four fuel batches.

Table VI Primary Design Parameters of the HCBWR Core

Thermal Power	3926 MW
Core diameter	5.8m
Core height	2.2m
HM loading in core	259.4 T
Specific power	15.14 kw/kg
Average linear power	14.7 kw/m
No. of fuel assemblies	313
System Pressure	1040 psia
Coolant inlet temperature	551.15 K
Total mass flow rate	14.53 T/s
Bypass mass flow rate	1.45 T/s

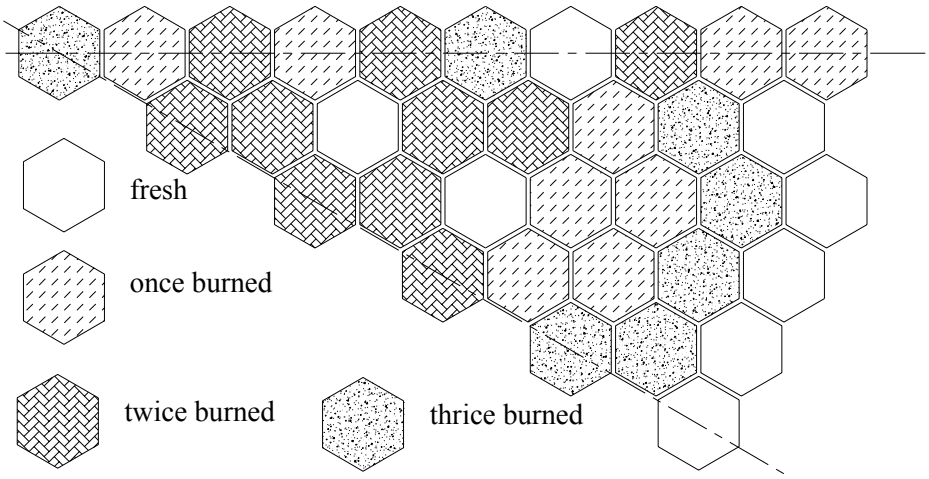

Figure 7 Equilibrium Cycle HCBWR Core (1/12 Core Symmetry)

3.2 RESULTS OF CORE PERFORMANCE

The core neutronics calculations were performed using the core neutronics simulator PARCS with eight energy groups and a RELAP5 core thermal-hydraulics model [5]. The T/H model used here represented each neutronics fuel assembly with a separate thermal-hydraulics channel. A schematic of the RELAP5 model is shown in Figure 8.

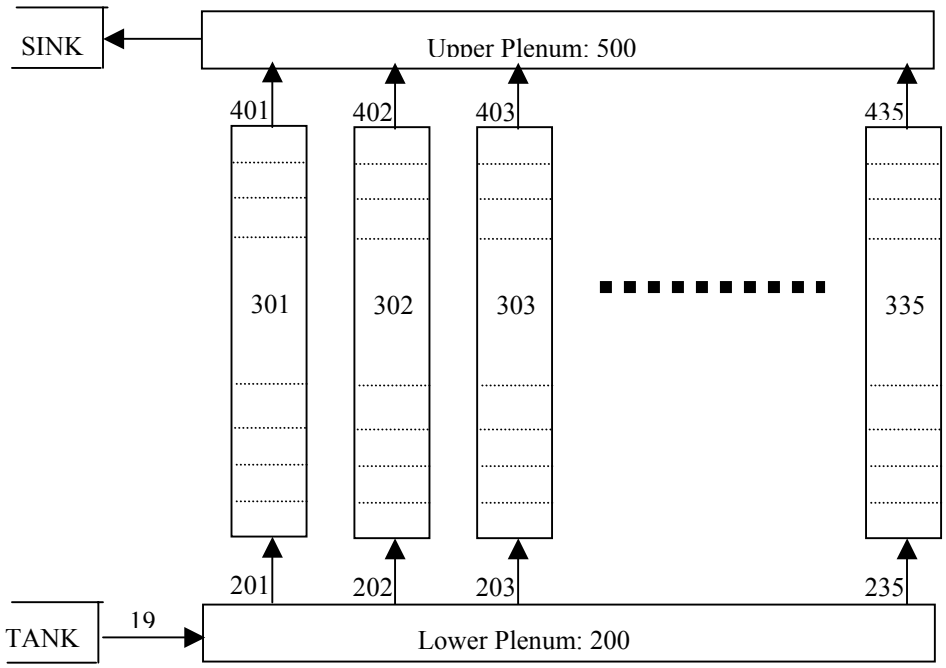

Figure 8. RELAP5 HCBWR Thermal Hydraulic Model

The core excess reactivity and void reactivity coefficients for the HCBWR with Pu-U and with Pu-Th fuel are shown in Figures 9 and 10, respectively. The Case C core is an axially heterogeneous design which be described in the next section.

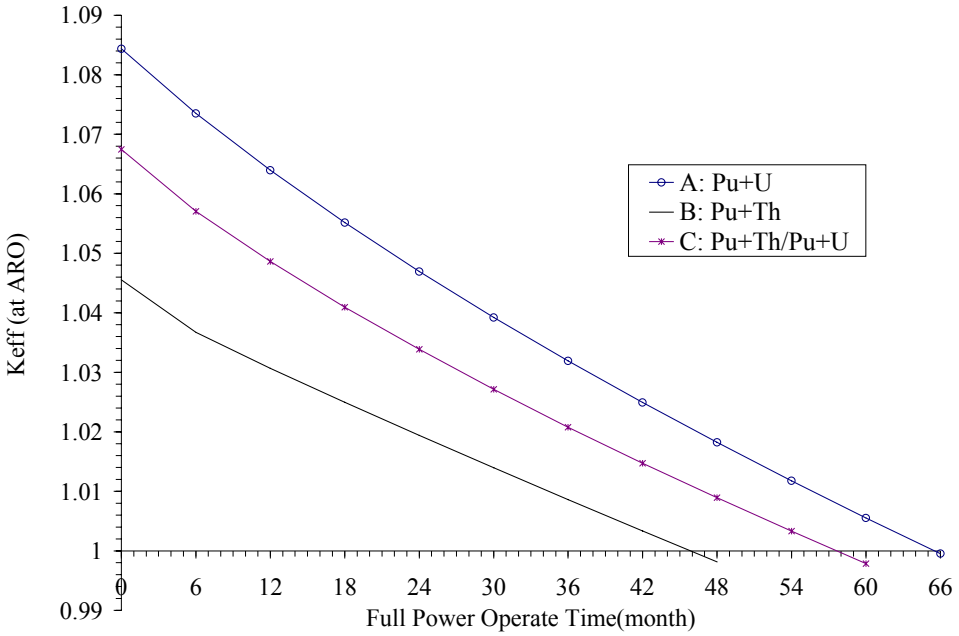

Figure 9. Excess Reactivity for Alternative HCBWR Core Designs

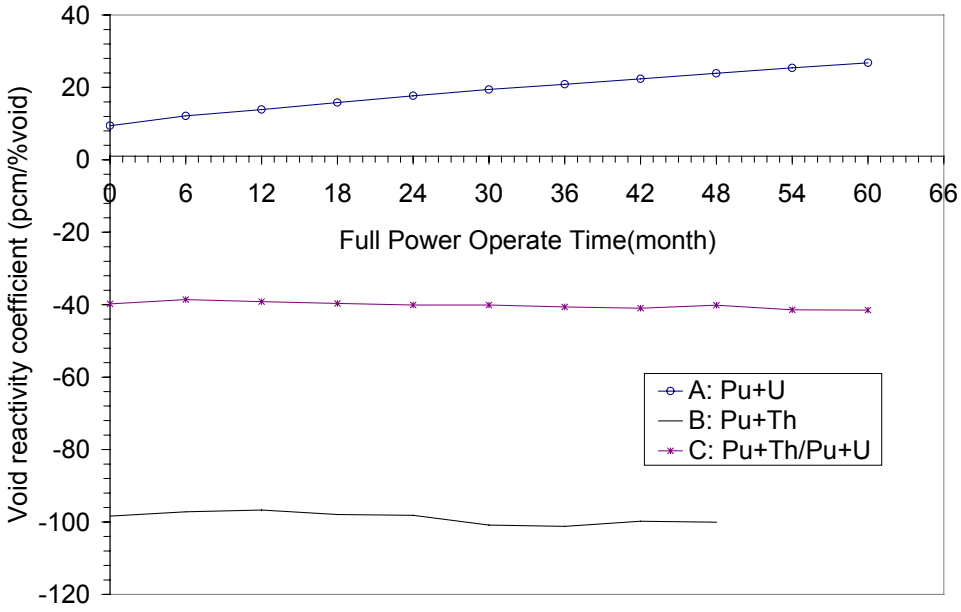

Figure 10 Void Reactivity Coefficient for Alternative HCBWR Core Designs

The Case B core with Pu-Th fuel shows a negative void reactivity coefficient thoughtout the core life and a smaller initial exceed reactivity. This considerably simplifies reactivity control compared to the Case A core with Pu-U fuel which at BOC has a larger excess reactivity and a positive VRC. Because the core average burnup at the beginning of the equilibrium cycle is about 40GWD/T this result is consistent with the assembly results shown in Figure 3.

The only significant drawbacks of Pu-Th fuel is short cycle length compared to the core fueled with Pu-U and the potential for the void reactivity coefficient being too negative in the event of a void collapse transient. Therefore, an axial heterogeneous design was developed which uses both Pu-Th and Pu-U fuel in order to extend the cycle length and to achieve a less negative void coefficient.

4. AXIAL HETEROGENEOUS HCBWR DESIGN WITH Pu-U AND Pu-Th FUEL

4.1 CONFIGURATION OF AXIAL HETEROGENEOUS CORE

The axial zoning of the Pu-U and Pu-Th fuel used in the heterogeneous HCBWR is shown in Figure 11.

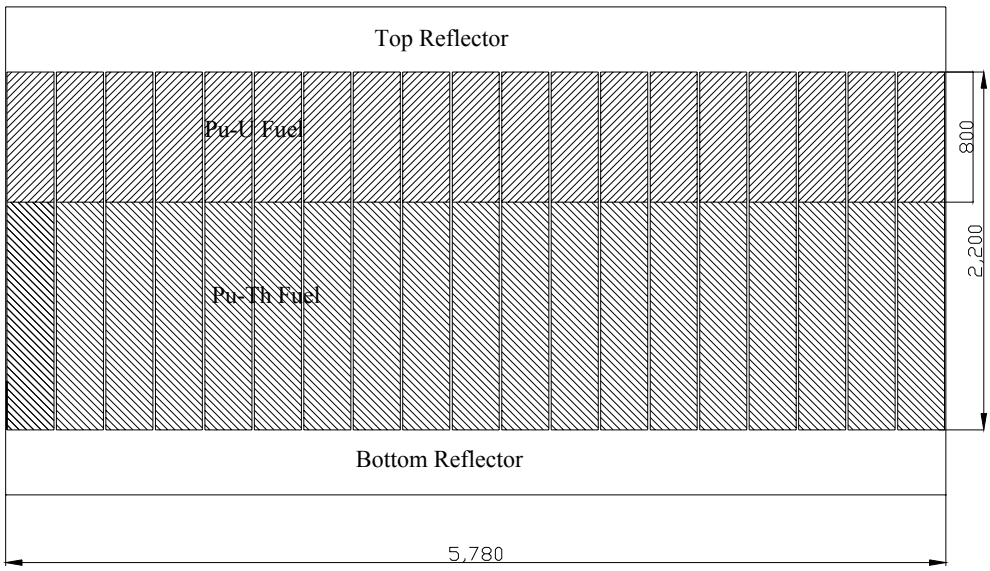

Figure 11. Vertical View of Axial Heterogeneous Core

4.2 RESULTS OF AXIAL HETEROGENEOUS CORE

The excess reactivity and void reactivity coefficient for an axial heterogeneous core were shown as Case C in Figures 9 and 10, respectively. The void reactivity coefficient throughout the core life is about 40 pcm/%void which is comparable to current BWR cores. And the 58 month cycle length is an increase of about 30% over the Pu-Th only core.

The axial power shapes for BOC (0GWD/T), MOC (13.6GWD/T), and EOC (27GWD/T) are shown in Figure 12 and the radial power distributions at BOC and EOC are shown in Figures 13 and 14.

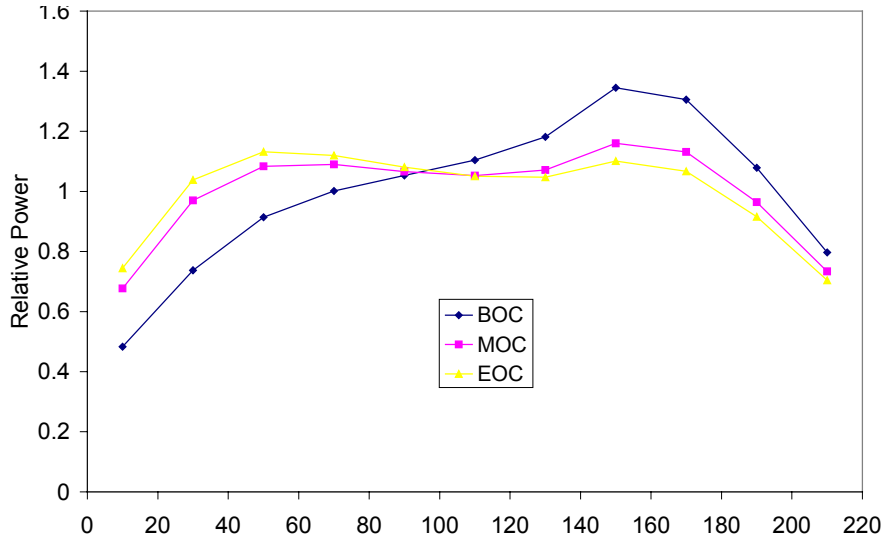

Figure 12. Axial Power Profiles for the Heterogeneous HCBWR Core

Figure 13 Relative Radial Power distribution at BOC

0.9898 1.0997 1.0764 1.2753 1.2070 1.0780 1.2833 0.9900 0.8679 0.6331

1.0519 1.1409 1.3686 1.1972 1.1833 1.1405 0.8232 0.8172

1.2033 1.2254 1.3777 1.2192 0.9801 0.6900 0.6267

1.2372 1.2160 0.9984 0.7006 0.6666

0.8653 0.6784 0.6788

0.6762

Figure 14 Radial Power distribution at EOC

1.0278 1.1162 1.0664 1.1806 1.1157 1.0327 1.2187 1.0248 0.9378 0.6412

1.0578 1.0897 1.2408 1.1121 1.1232 1.1317 0.9032 0.8677

1.1153 1.1284 1.2623 1.1790 1.0352 0.7907 0.6523

1.1485 1.1688 1.0449 0.8119 0.7376

0.9310 0.7966 0.7528

0.7509

5. SUMMARY AND CONCLUSIONS

Several innovative tight lattice High Conversion Boiling Water Reactor (HCBWR) designs have been proposed over the past few years that provide substantial increases in the fuel conversion ratio by hardening the neutron spectrum. However, a significant problem for tight lattice designs is the potential for a positive void reactivity coefficient (VRC). Some tight lattice cores achieve a negative VRC by enhancing neutron leakage through various design strategies such as flattening the core, adding axial blankets, or using fuel assemblies with void tubes. However, in a previous study we demonstrated that simply replacing U-238 with Th-232 as fertile material in a HCBWR can mitigate the positive void reactivity effect.

The work here examined the detailed neutronics behavior of Th-232 and U-238 in a tight lattice BWR core. The core performance for the void reactivity, conversion ratio, reactivity control, and cycle length are compared for a HCBWR fueled with U-238 and Th-232 fertile fuels. The favorable performance of a thorium fueled core is shown to be a direct result of the favorable neutronics characteristics of Th-232 relative to U-238 in a hard neutron spectrum, such as a larger thermal capture cross section, a smaller fast fission cross section, and a smaller resonance integral. The only significant drawbacks of Pu-Th fuel in a tight lattice core are a shorter cycle length than a comparable Pu-U core and the possibility of the void reactivity coefficient that is too negative. However, an axially heterogeneous design was described which utilizes both Pu-Th and Pu-U fuel to recover the longer cycle performance and provides a void coefficient that is comparable to existing BWRs.

ACKNOWLEGEMENTS

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