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Nuclear Design Study on Once-Through Thorium Fuel Cycle for PWR

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ABSTRACT

A design optimization of heterogeneous thorium fuel assembly was performed based on sensitivity analysis of design parameters for various measuring indices. Optimization goals were the maximization of both proliferation resistance and thorium fertile utilization and the minimization of radio-toxicity. Five kinds of indices were measured for many design candidates including WASB and RTF. They are FIR, SNS, TG, BCM, and Time Integrated Toxicity. In this paper, a new design optimization index was defined for the once-through thorium fuel cycle option for PWR. Fuel cycle Economic Index (FEI) was introduced for a measuring index for fissile utilization.

Based on the optimization with FEI, a modified design concept of seed and blanket assembly module, KTF was found and tested for the application to advanced PWR, APR-1400. Feasibility of multi-cycle core design with thorium blanket was examined to check the safety concerns related to pin peaking and MTC. It was shown that heterogeneous thorium fuel core option is acceptable for the first two cycles. Design modification will be done for the acceptable equilibrium cycle core design for 9 years transition period.

1. INTRODUCTION

Utilization of thorium fertile for high conversion LWR applications has been studied in many options. Homogeneous fuel pellet options have penalty in fuel cycle economics even though its practicality in design.[1] The heterogeneous assembly options, represented by separate seed and blanket fuel pin zones either within an assembly or across neighboring assemblies, showed potential in economics and proliferation-resistance.[2] However, an isolated seed zone surrounded by blanket fuels bring troubles in high power peaking and steep k-infinite letdown. Therefore, assembly design should be optimized within the limitation on thermal-hydraulic safety limit and complexity in reloading scheme. Design optimization works have been done for the realization of potential benefits from thorium fuels.[3], [4]

The primary goal of initial design optimization stage was to maximize multiple indices all together; for conversion, proliferation resistance and toxicity reduction. For this stage global optimization index was defined and measured for candidate concepts. At the second stage of optimization, design goal was focused only for effective fissile utilization. Proliferation resistance and radio-toxicity of spent fuel from thorium cycle are inherently better than those from conventional PWR cycle.[5] Impact of seed and blanket thorium fuel module to the core design was tested for the Korean next-generation plant, APR-1400 core.

2. ASSEMBLY DESIGN OPTIMIZATION

2.1 Global Optimization Study

Parametric optimization study was carried out for the optimization of previous KTF design.[4] Design optimization at this stage is sought for the achievement of multiple objectives; high conversion for better fuel cycle economics, high proliferation resistance, low production of high-level radioactive waste. Sensitivity analysis for design parameters was repeated to cover all possible choices of thorium fuels for PWR.[2], [3] Design parameters are fuel material, pin radius, enrichment and volume content of fuel in seed and blanket. In this study, assembly design was applied for APR-1400. Table 1 compared the design specifications of three concepts of thorium fuel modules.

Table 1. Design Parameters of Seed/Blanket Assemblies of Three Concepts

Volume Ratio (Seed / Blanket)	Seed				Blanket					Fuel Cell Pitch [cm]
	Seed Fuel	U-235 Enrich. [w/o]	Seed Pin Radius [cm]	V_m/V_f	Blanket Fuel	U-235 Enrich. [w/o]	Uranium Content [v/o]	Blanket Pin Radius [cm]	V_m/V_f	
1:1[bc] 1:3 [a]	UO$_2$[c] U/Zr[ab]	6[a] 20[bc]	0.336[a] 0.377[c] 0.385[b]	3.32[b] 3.65[a] 5.46[c]	(U,Th)O$_2$ abc	10[a] 12[c] 20[b]	10[bc] 20[a]	0.4759[a] 0.4075[bc]	1.24[b] 1.67[c] 1.75[a]	1.2600[bc] 1.2660[a]

[a] KTF - KHU Design (June, 2002)
[b] SBU - Galperin Design (Dec. 2001)
[c] WASB - MIT Design (Dec. 2001)

Characteristics of fuel material choices were evaluated as a primary stage. Among four options, it was found that choice of U/Zr alloy for seed and UO_2+ThO_2 ceramic for blanket was the best consistently. The second parametric study for V_m/V_f and enrichment showed many different findings, most of them were consistent with physics. However, maximization of conversion ratio for U-233 makes proliferation resistance minimum in some cases. Table 2 shows the range of values of each measuring index. Fig.1 shows the sensitivity of Fissile Inventory Ratio to the choice of fuel material and moderator to fuel volume ratio. Calculations were done for the unit module consisting of seed and blanket by 2-D transport code, HELIOS. [6]

Table 2. Values of each Index for Choices of Fuel Types

Seed	Blanket	INDEX			
		FIR	BCM [kg]	SNS [#/kg.sec]	TG [W/kg]
U/Zr	(U,Th)O$_2$	0.68~0.80	13.75~14.81	1.54E+3~1.80E+3	4.20E-2~4.91E-2
UO$_2$	(U,Th)O$_2$	0.60~0.71	14.43~15.85	1.64E+3~1.94E+3	4.44E-2~5.29E-2
U/Zr	(U,Th)CO	0.71~0.79	14.28~14.97	1.19E+3~1.31E+3	3.12E-2~3.44E-2
UO$_2$	(U,Th)CO	0.65~0.73	14.66~15.61	1.21E+3~1.37E+3	3.14E-2~3.48E-2

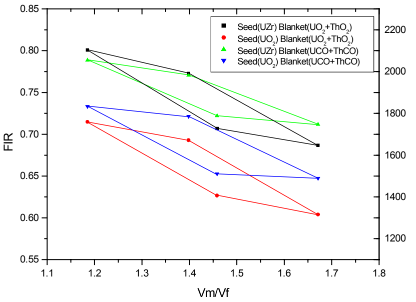


Figure 1. Sensivity of FIR to M/F Ratio

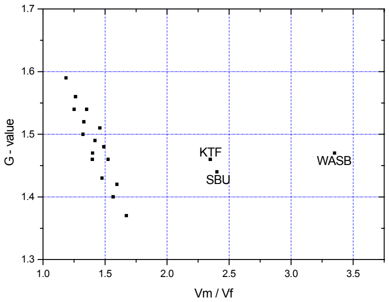


Figure 2. G-values of Design Options

It was found that characteristics of 6 performance indices (FIR, SNS, TG, BCM, I_S, I_L) are not consistent among themselves. In order to have an overall index to sort out the best design option, the following definition was designed. In this study, basis for the comparison was adjusted to existing PWR fuels in operation. Weighting factors of each indices; fissile inventory ratio(FIR), bare critical mass (BCM), spontaneous neutron source rate (SNS) and thermal decay heat generation rate (TG) are chosen to be 0.6, 0.2, 0.1 and 0.1.

Global performance index is defined as, $G = \sum w_i \left[\frac{f_i - f_{io}}{f_{io}} \right]$ (1)

where w_i = weighting factor of index type i,
f_i = value of index type i, and
f_{io} = base value of index type i .

G-values are calculated for all cases in parametric studies. Compared with 0.0 of G value for PWR, G-values of SBU for RTF, WASB for MIT design, and KTF are 1.44, 1.47 and 1.46 respectively. However, some design options showed higher values as shown in Figure 2. Points located at the left side of figure shows that there is a need of design optimization.

2.2 Local Optimization for Fuel Cycle Economy

We used FIR index to measure a fuel cycle economy because FIR represent well the performance of Th-232 conversion to U-233 in seed and blanket module. For the maximization of FIR, U-235 enrichment for seed and blanket fuel should be high up to 20 w/o. Highly reactive fuel generate and provide neutrons to thorium blanket and make conversion ratio high. However, fissile content of discharged seed fuel remains high as about 15w/o. Fuel cycle economy can not be high without fissile recycling from this limitation. Once-through cycle strategy should be kept for thorium fuel utilization to PWR. From this reasoning, a new index is defined for the measurement of fissile utilization economy. Fissile Economic Index (FEI) represents the minimization of enrichment requirement for the feed fuel and the maximization of fissile utilization throughout the refueling cycle.

$$FEI = \frac{Burnup^2}{initial\ fissile\ number\ density * final\ fissile\ number\ density}$$

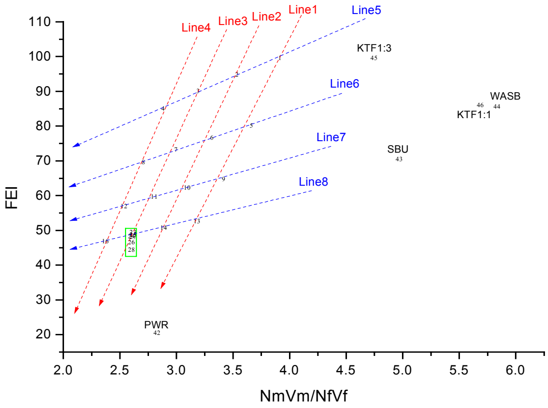


Figure 3. FEI value for M/F ratio change

Figure 3 shows result of new parameter studies. In this optimization stage, proliferation resistance and radio-toxicity were not optimized because they are much more favorable than values of existing PWR fuels once we used thorium fuels as blanket. As shown in Fig.3, optimized design point of KTF has higher value of FEI than WASB and SBU design. Table 3 shows the design parameters chosen as a modified KTF design resulting from the local optimization.

Table 3. Fuel Assembly Parameters of Optimized KTF Design

Parameter	**Seed**	**Blanket**
Fuel Assembly Size, cm	20.778	
Fuel Material Composition	U/Zr Metal alloy U enrichment < 5%	$(U+Th)O_2$ U volume fraction ~0.2 U enrichment < 20%
Fuel Pellet Radius, cm	0.325	0.3895
Gas Gap, cm	No	0.0085
Cladding Thickness, cm	0.03	0.057
Fuel Rod Radius, cm	0.355	0.455
Fuel Cell Pitch, cm	1.285	1.285
Core Volume Fraction	25	75

3. CORE DESIGN

3.1 Core Design Constraint

Optimized KTF fuel assemblies use the same assembly configuration and geometry of APR-1400**.** It contains one instrument guide tube and 4 control rod guide tubes, which is two by two pin sizes. The initial U-235 enrichments are limited to less than 20 w/o U-235 in the uranium, and the bred U-233 to less than 12 w/o for non-proliferation. The cycle length is deigned to have eighteen months. Seed assemblies of three batches remain in-core for three cycles and blanket assemblies are of one batch for 6 seed cycles. The core heavy metal loadings are less than APR-1400, while specific power is 44.7 w/g higher than 32.25 W/g of APR-1400. Low leakage loading pattern is designed to obtain minimum pin peaking in the core. Seed assemblies in peripheral of the core are moved to inner core to reduce the neutron leakage as low as possible. Axial blanket concept could not be applied in the seed assembly because of U/Zr metal fuel limitation. Integral burnable poison materials of UO_2-Gd_2O_3 are used to reduce the excess reactivity in seed assembly. Burnable poisons are partially loaded also in blanket assembly in order to reduce the reactivity control burden of soluble boron. However, the use of integral BP in blanket assembly gives a disadvantage in utilizing thorium fuel. It is unfavorable to conversion of Th-232 to U-233 in an aspect of neutron economy.

3.2 Loading Pattern Search

Figure 4 shows the layout of the core and reloading scheme. Due to the 1 to 3 ratios of seed and blanket assembly there is no enough degree of freedom in loading pattern search for seed assemblies. It also may bring about of high power density difference between seed and blanket assembly. Even though the seed assembly has high thermal power density, U/Zr metal fuel would compensate pin peaking because of thermal margin due to high thermal conductivity in seed pins. It is observed that high power peaking pins are located around guide tubes. Local fuel enrichment zoning is applied to solve this problem with success. Core 3-D calculation is carried out HELIOS-MASTER system.[7]

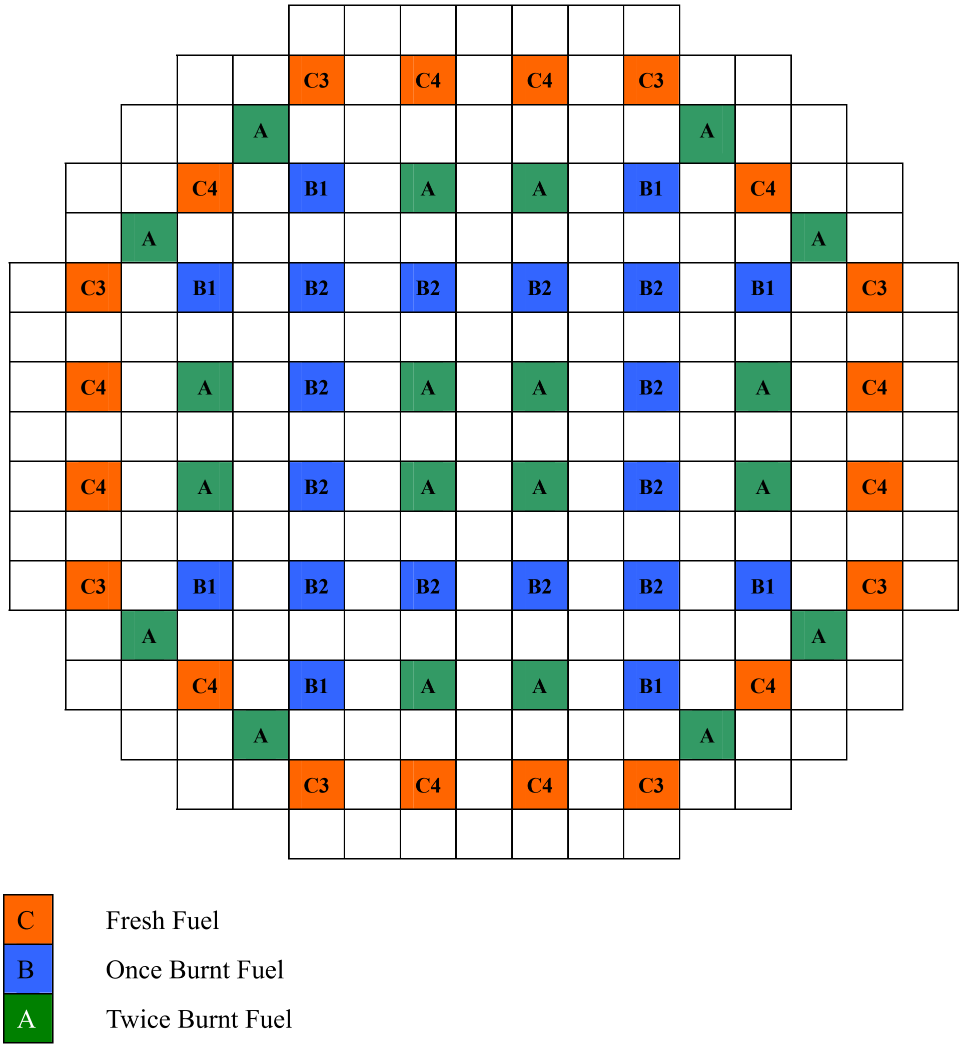


Figure 4. Core Loading Pattern.

Three batches of seed and one batch of blanket assemblies are loaded in APR-1400. Figure 5 shows the critical boron concentration as a function of burnup, which has less excess reactivity than that of APR-1400 due to more BP pins. The reactivity swing is also low because of the high conversion rate of thorium in blanket assembly.

Moderator temperature coefficient is sensitive to fuel material compositions as well as boron concentration because of spectrum change across the seed and blanket zone. MTC was calculated to be negative throughout cycle. Soluble boron worth was higher than that of APR-1400 by about -3 [pcm/ppm] due to the softer neutron spectrum in the optimized KTF core.

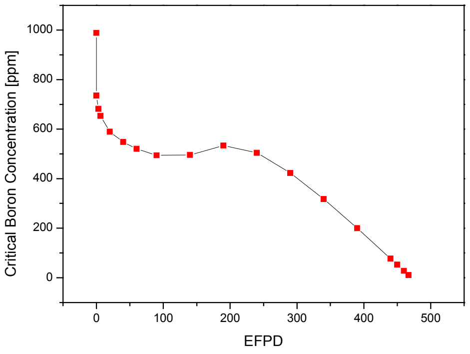


Figure 5. Critical Boron Concentration

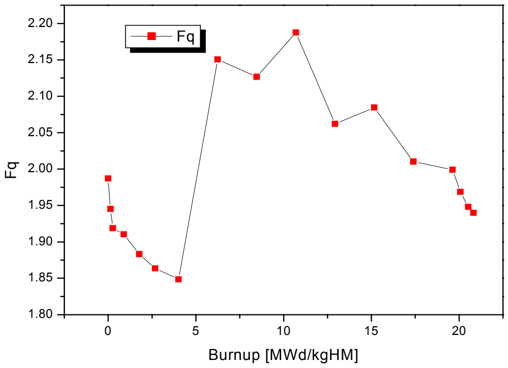


Figure 6. Maximum Pin Peaking Factor

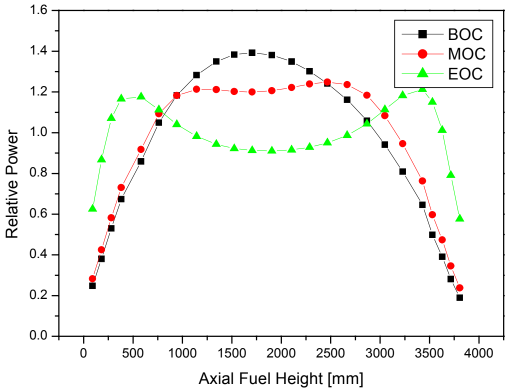


Figure 7. Axial Power Distributions

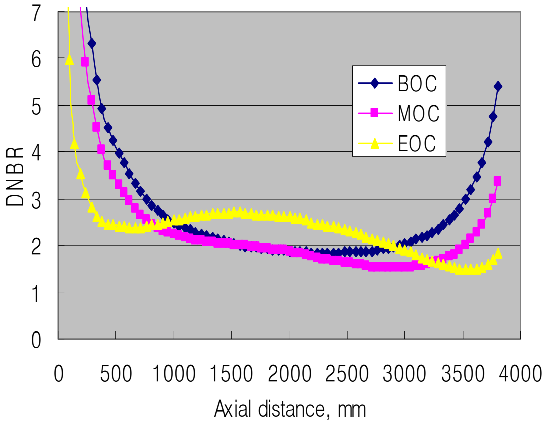
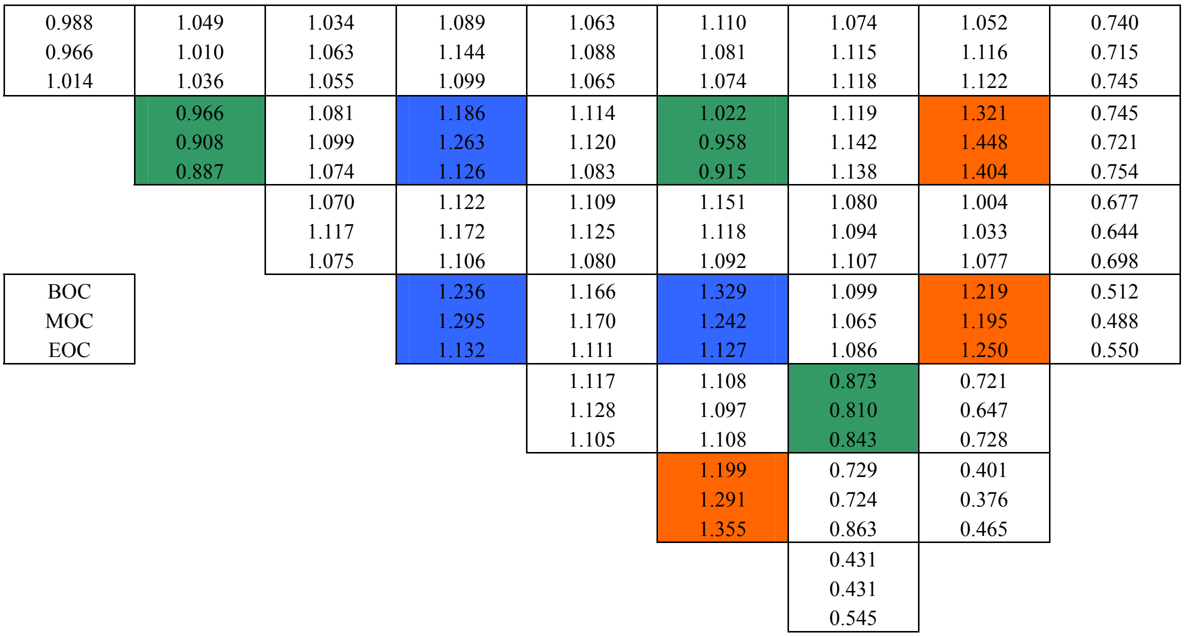


Figure 8. Minimum DNBR Prediction

3.3 Power Distributions and Thermal-Hydraulic Calculation Results

Figure 6 shows the maximum pin peaking factors in core with modified KTF fuels during cycle burnup, which are well below the design limit. Radial relative power distributions in Fig.9 shows acceptable distribution, although the power density differences between seed and blanket are still high. Axial relative power distributions shown in Fig.7 are comparable with current PWRs.

3-D thermal hydraulic calculation was done for a color set geometry consisting of seed and blanket assemblies for DNBR. Conservative assumptions were applied in pin peaking and thermal properties. It was shown in Fig. 8 that MDNBR is higher than 1.3 with overpower uncertainty of 10%.



0.988 0.966 1.014	1.049 1.010 1.036	1.034 1.063 1.055	1.089 1.144 1.099	1.063 1.088 1.065	1.110 1.081 1.074	1.074 1.115 1.118	1.052 1.116 1.122	0.740 0.715 0.745
	0.966 0.908 0.887	1.081 1.099 1.074	1.186 1.263 1.126	1.114 1.120 1.083	1.022 0.958 0.915	1.119 1.142 1.138	1.321 1.448 1.404	0.745 0.721 0.754
		1.070 1.117 1.075	1.122 1.172 1.106	1.109 1.125 1.080	1.151 1.118 1.092	1.080 1.094 1.107	1.004 1.033 1.077	0.677 0.644 0.698
BOC MOC EOC			1.236 1.295 1.132	1.166 1.170 1.111	1.329 1.242 1.127	1.099 1.065 1.086	1.219 1.195 1.250	0.512 0.488 0.550
				1.117 1.128 1.105	1.108 1.097 1.108	0.873 0.810 0.843	0.721 0.647 0.728	
					1.199 1.291 1.355	0.729 0.724 0.863	0.401 0.376 0.465	
						0.431 0.431 0.545		

Figure 9. Radial Relative Power Distribution.

4. CONCLUSIONS

A new optimized KTF design for once-through thorium fuel cycle was introduced. Optimization was done for both higher fuel utilization and higher proliferation resistance based on parametric sensitivity analysis. A new index, Fissile Economic Index is suggested and applied to the optimization of KTF design. Compatibility of this index was checked to fuel cycle cost analysis and its validity was shown. Proliferation resistance of KTF was measured and compared with PWR fuels. All aspects of proliferation resistance of the optimized design concept of KTF showed higher values than conventional PWR.

Pin peaking values at the seed fuel of KTF core were acceptable. Moderator temperature coefficient has all negative value throughout cycle and MDNBR values of high power zone was calculated higher than the design limit. Full core detail evaluation will be carried out as future works. Core with thorium fuel showed a nuclear feasibility in the aspect of cycle length, critical boron concentration, pin peaking, axial and radial relative power distributions in the 1,400 MWe plant, APR-1400.

As future works design concept of 1 to 1 ratio in seed and blanket assembly will be examined for the better reactor safety and design flexibility. Equilibrium cycle core analysis including transition cores will be studied as a next step. Finally, detailed economics analysis will be also performed for the assurance of feasibility in thorium fuel utilization to existing PWR core.

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