CORE DESIGN FOR HETEROGENEOUS THORIUM FUEL ASSEMBLIES FOR PWR(I)-NUCLEAR DESIGN AND FUEL CYCLE ECONOMY

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Kyung-hee Thorium Fuel (KTF), a heterogeneous thorium-based seed and blanket design concept for pressurized light water reactors, is being studied as an alternative to enhance proliferation resistance and fuel cycle economics of PWRs. The proliferation resistance characteristics of the KTF assembly design were evaluated through parametric studies using neutronic performance indices such as Bare Critical Mass (BCM), Spontaneous Neutron Source rate (SNS), Thermal Generation rate (TG), and Radio-Toxicity. Also, Fissile Economic Index (FEI), a new index for gauging fuel cycle economy, was suggested and applied to optimize the KTF design. A core loaded with optimized KTF assemblies with a seed-to-blanket ratio of 1:1 was tested at the Korea Next Generation Reactor (KNGR), ARP-1400. Core design characteristics for cycle length, power distribution, and power peaking were evaluated by HELIOS and MASTER code systems for nine reload cycles. The core calculation results show that the KTF assembly design has nearly the same neutronic performance as those of a conventional UO_2 fuel assembly. However, the power peaking factor is relatively higher than that of conventional PWRs as the maximum Fq is 2.69 at the 9th equilibrium cycle while the design limit is 2.58. In order to assess the economic potential of a heterogeneous thorium fuel core, the front-end fuel cycle costs as well as the spent fuel disposal costs were compared with those of a reference PWR fueled with UO_2. In the case of comprising back-end fuel cycle cost, the fuel cycle cost of APR-1400 with a KTF assembly is 4.99 mills/KWe-yr, which is lower than that (5.23 mills/KWe-yr) of a conventional PWR. Proliferation resistance potential, BCM, SNS, and TG of a heterogeneous thorium-fueled core are much higher than those of the UO_2 core. The once-through fuel cycle application of heterogeneous thorium fuel assemblies demonstrated good competitiveness relative to UO_2 in terms of economics.

KEYWORDS : Thorium Fuel Cycle, Seed and Blanket Assembly, Proliferation Resistance, Core Design, Fuel Cycle Costs

1. INTRODUCTION

Global attention to proliferation resistance has increased over the past several years and as a result advanced nuclear core and fuel designs are required to possess a high level of proliferation resistance. For those concerned about nuclear weaponry proliferation, proliferation resistance is the highest priority. Thorium fuel is well recognized for its inherently high proliferation resistance potential because of the low production rates of plutonium and minor actinides as compared with uranium fuel. Thorium also displays a good breeding ratio in thermal reactors. In addition, various efforts have been expended to utilize U-233 converted from Th-232. High U-233 conversion can be achieved by using the soft neutron spectrum, because Th-232 has a higher absorption cross-section than U-238 for thermal neutron energy, as shown in figure 1.

Recently, heterogeneous thorium-based fuel assembly design concepts were suggested for conventional PWRs. There are three assembly design concepts using thorium as a blanket for PWRs. The Radkowsky Thorium Fuel[1] (RTF) concept developed at Ben-Gurion University (Israel) is based on seed and blanket units within an assembly. The seed unit in the central region of a fuel assembly contains 20% enriched uranium, which is alloyed with 10% zirconium, while the blanket unit in the outer region contains ThO_2 mixed with 10%~20% enriched uranium. This concept of a seed and blanket unit in an assembly entails a complex reloading scheme, because the seed and blanket each require different fuel reloading strategies. In this system the seed and blanket areas are physically divided into two parts in an assembly in order to allow independent movement.

The Whole Assembly Seed and Blanket[2] (WASB) concept developed at MIT (USA) is another option for thorium utilization in PWRs. WASB uses an annular fuel geometry for seed fuel that contains burnable poison

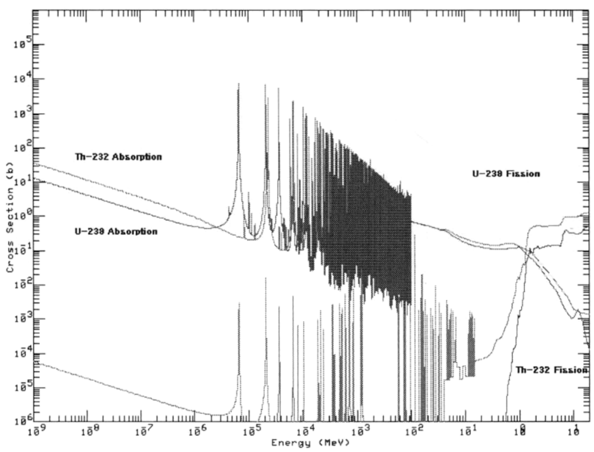

Fig. 1. Cross-section characteristice of Th-232 and U-238

material in the inner hole. An annular type of seed fuel is used to increase the thermal hydraulic safety margin. However, it is expected that the annular fuel concept will be more difficult and expensive to manufacture than conventional UO_2 fuel.

The initial Kyung-hee Thorium Fuel[3] (KTF) design concept, composed of a whole seed and blanket assembly with a 1:3 ratio, was designed to have a maximized conversion ratio. Generally, the heterogeneous seed and blanket concept leads to a high power tilt between the seed and blanket, which brings about a thermal hydraulic safety problem at a hot seed channel. U/Zr metallic fuel (having a high thermal conductivity) is used for the seed in order to increase the fuel melting margin in the KTF design. On the contrary, the blanket produces less fraction of power generation than the seed by about 30% of core power, and it requires longer discharged burnup than seed assembly due to the one batch fuel cycle strategy. The blanket should reside in the core for as long as possible for thermal conversion. For this reason, the ceramic form of UO_2-ThO_2 was considered as a blanket fuel material instead of U-Th-Zr.

Ultimately, the KTF design was changed to a 1:1 ratio of seed to blanket in order to guarantee thermal hydraulic safety and it will be tested at the 3,983 MWth Korea Next Generation Reactor (KNGR), APR-1400.

In the early stages of this study, the KTF design was optimized for fissile economics by maximizing the Fissile Inventory Ratio (FIR), because the employed thorium fuel concept was based on high conversion. FIR was used to evaluate the conversion of U-233 from Th-232 and was defined by the final fissile mass over the initial fissile mass. However, for the once-through fuel cycle strategy the high fissile inventory in the spent fuel has no use after being discharged. A new index of FEI was suggested and applied in order to optimize the KTF design for fuel cycle economy. The neutronic characteristics such as BCM, SNS, and TG of the discharge fuel were evaluated in order to assess the proliferation resistance potential. Radio-toxicity was used to investigate the environmental effects of the KTF design.

The purpose of our research is to suggest an alternative core design with thorium-based blanket fuel assemblies, which offer competitive fuel cycle economics and high proliferation resistance as well as high neutronic and thermal hydraulic performance. In this paper, the KTF assembly design was optimized and tested at the APR-1400 to verify the feasibility of the core design with regard to core neutronics. Fuel cycle costs of the thorium -based heterogeneous PWR core were analyzed including back-end fuel cycle costs.

2. OPTIMIZATION OF THE KTF ASSEMBLY DESIGN

2.1 KTF Design Concept

Since the original KTF design is basically composed of a heterogeneous seed and blanket, a higher blanket assembly volume ratio than the seed assembly is desirable for conversion[4] maximization. Thus, the original KTF design focused on high conversion and has a seed-to-blanket ratio of 1:3. However, the seed-to-blanket ratio is important for thermal hydraulic safety, because of the high power tilt between the seed and blanket assembly. Maximum pin power peaking at the hottest seed assembly exceeds the tolerable limit when the core design was composed of the original KTF design, which used a 1:3 seed-to-blanket ratio. Thus, the KTF design should be changed to a 1:1 seed-to-blanket ratio in order to reduce power peaking. Figure 2 shows the revised KTF design using a 1:1 seed-to-blanket ratio.

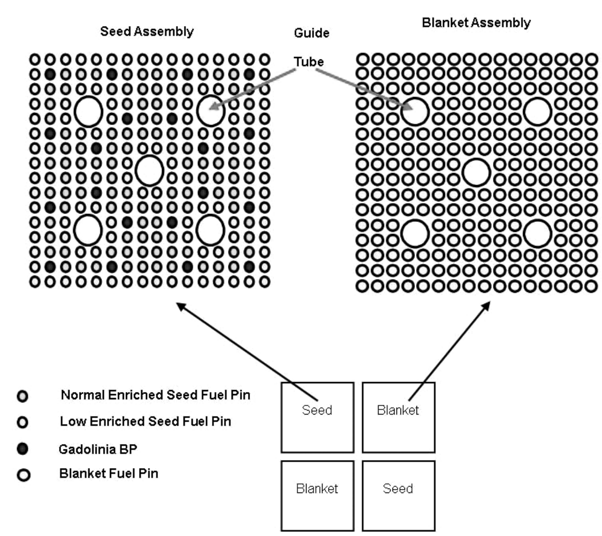

Fig. 2. KTF Color-set Geometry

Seed fuel should have a high enrichment of U-235 compared to a typical PWR UO_2 core in order to yield the same fuel cycle length, because of the low reactivity of the blanket assembly, which is sub-critical during the entire burnup period. Under the same moderator-to-fuel ratio of current PWRs, because of this fact an excessive amount of fissile materials remains in the seed assembly after they are discharged.

The blanket fuel is usually composed of a small fraction of enriched UO_2 within the ThO_2 matrix to compensate for the low reactivity at the initial burnup until saturation of U-233 by conversion. It is more favorable to make neutron spectrum harder in blanket for increasing U-233 conversion speed in the blanket assembly.

2.2 Analysis Tool

The HELIOS[5]/MASTER[6] code system was used to evaluate the neutronics of parametric studies and core calculation of the APR-1400 loaded with the KTF assembly. HELIOS is a two-dimensional transport code using the current coupling collision probability method for neutron transport calculations. The 35-group neutron library is used to generate the group constants for the seed and blanket assemblies. MASTER, developed by the Korea Atomic Energy Research Institute (KAERI), is a three-dimensional nodal code for core physics calculations with thermal hydraulic feedback. MCNP-4b[7] and ORIGEN-II[8] codes are used to evaluate proliferation resistance potential. BCM is calculated by MCNP for a homogeneous sphere model with reflective boundary condition. SNS and TG are calculated by the ORIGEN-II code with the plutonium vector from the HELIOS output.

2.3 Parametric Studies

A parametric study was conducted using the HELIOS code to analyze the effects of changes made to the geometry and composition of the KTF design with the goal of optimizing fuel cycle economics, minimizing radioactive waste, and realizing high proliferation resistance. Rod sizes varied between 0.355cm and 0.415cm for the seed fuel and 0.455cm and 0.485cm for the blanket fuel, whereas the pitch size was fixed at 1.285cm, which corresponds with that of APR-1400. The calculational model for the parametric studies was based on the original KTF seed-to-blanket design ratio of 1:3 and the results were compared with those of the 1:1 ratio of KTF, WASB, and RTF. We considered whether plutonium isotope compositions recovered from the discharged fuel could be used in a nuclear explosive. The BCM does not have the mass necessary to construct such a device, since the critical mass can be reduced by the use of a reflector. However, BCM is the most important component of evaluating weapon purpose proliferation resistance.

The SNS is regarded as an important characteristic of weapon material. Neutrons released by spontaneous fission will cause a reduction of the fissile plutonium isotopes in a weaponized device, which will render the

Table 1. Plutonium Isotopic Fractions in Total Plutonium (w/o)

Case	Isotope	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
Seed : 0.355 cm Blanket : 0.455 cm	Seed 1*	4.0916	49.8862	24.7940	14.4689	6.7592
	Seed 2**	4.1210	49.8886	24.7114	14.5295	6.7496
	Seed 3***	4.2886	49.2386	24.8619	14.5891	7.0221
	Blanket	10.5472	35.7627	16.1734	13.5039	24.0128
Seed : 0.355 cm Blanket : 0.485 cm	Seed 1	4.8641	47.2469	25.2085	14.7065	7.9739
	Seed 2	4.8423	47.4705	25.0644	14.7616	7.8612
	Seed 3	5.0262	46.8525	25.1800	14.7807	8.1606
	Blanket	11.5551	37.4578	15.1058	14.4018	21.4795
Seed : 0.415 cm Blanket : 0.485 cm	Seed 1	2.9595	60.4886	19.8993	13.7777	3.4748
	Seed 2	2.9838	60.4884	19.8320	13.2424	3.4534
	Seed 3	3.1070	59.9192	19.9931	13.3987	3.5819
	Blanket	10.9001	35.4950	15.7502	13.4663	24.3883
	Seed 1	3.4594	58.4660	20.3293	13.7713	3.9740
	Seed 2	3.4444	58.6759	20.1939	13.7889	3.8969
	Seed 3	3.5798	58.1272	20.3365	13.9239	4.0325
	Blanket	11.9313	37.2968	14.7365	14.4037	21.6318

* : Seed cycle from 1 to 3   ** : Seed cycles from 4 to 6   *** : Seed cycles from 7 to 9

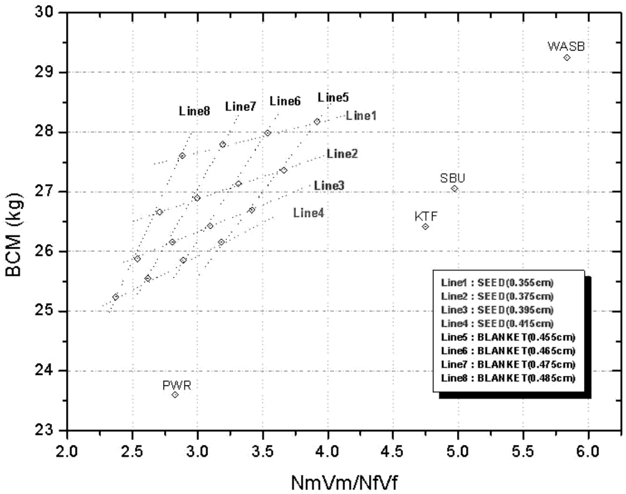

Fig. 3. BCM vs. Vm/Vf

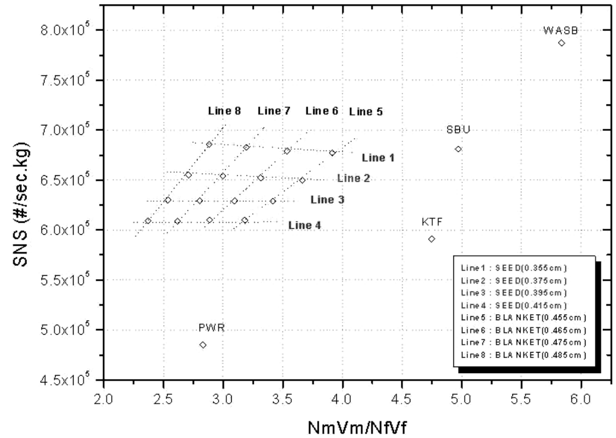

Fig. 4. SNS vs. Vm/Vf

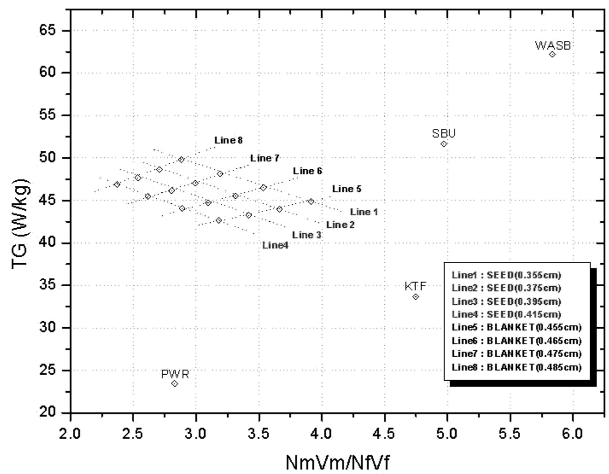

Fig. 5. TG vs. Vm/Vf

weapon material inactive. Plutonium isotopes generate a great amount of heat and radiation. The thermal generation can increase the temperature of a device, resulting in two effects: a temperature increase of metallic Pu, which undergoes a metallurgical phase transition at 115°C, and overheating of a high explosive around the Pu core, which may cause disintegration of this high explosive. Plutonium isotopic data, obtained by HELIOS code outputs of seed and blanket assemblies, are displayed in Table 1. BCM, SNS, and TG are calculated by MCNP and ORIGEN-II with Table 1 data and then averaged for 3 seed cycles. The parametric study results for proliferation resistance indices are shown in figures 3 through 5. All cases had the same burnup time during 9 seed cycles in which one-third of the fresh seed fuel was reloaded every cycle. The blanket remained unchanged for 9 seed cycles.

As shown in figure 3, BCM is sensitive to the soft neutron spectrum, because the high fission cross-section of fissile plutonium isotopes decreased rapidly at thermal neutron energies. The blanket rod size has little effect on the BCM, whereas the seed rod size has a significant effect. Due to a well thermalized neutron spectrum in line 1 as compared to line 4, the blanket rod size effect is not as great in line 1 as it is in line 4.

On the contrary, the SNS value depends upon even plutonium isotopes and has a different tendency, as shown in figure 4. The blanket rod size has a small effect on the SNS; however, the seed fuel rod size has a significant effect on the SNS, because the seed fuel assembly has a more over-moderated neutron spectrum that increases consumption of Pu-239. Therefore, the fractions of even plutonium isotopes such as Pu-238, Pu-240, and Pu-242 in plutonium are relatively higher than those of a conventional PWR.

TG is slightly different in that it depends mainly on the Pu-238 isotope. In the seed assembly, the softened neutron spectrum increases the fission reaction with Pu-239, resulting in a higher Pu-238 fraction in plutonium. However, the tendency is shown to proceed in the opposite direction in the blanket assembly, as shown in figure 5, due to the higher absorption cross-section of Th-232 compared with Pu-238. It is noted that a thinner fuel rod size, which produces a more thermalized neutron spectrum, is better for proliferation resistance potential.

Another parameter is fuel cycle economy, which is the most important consideration for industrial power generation. As we mentioned before, the fuel cycle economy of thorium fuel was simply evaluated by the FIR of the discharged spent fuel for U-233 breeding. However, FIR is not a reasonable method for evaluating the economic performance of the once-through fuel cycle. The optimization goal for fuel cycle economy is minimization of the U-235 requirement of the seed fuel assembly at the initial burnup point, because U-233 could be generated from Th-232 in the blanket fuel during the

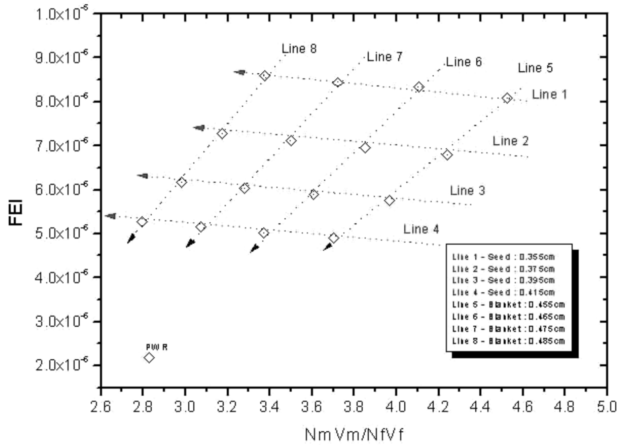

Fig. 6. FEI vs. Vm/Vf

burnup. Fuel cycle costs are mainly dependent upon the enrichment cost of U-235, and therefore a lesser U-235 requirement would result in better fuel cycle economy by reduction of the Separation Work Unit (SWU) of U-235. For this purpose, a new economic performance index, the Fissile Economic Index (FEI), is proposed in this study. FEI is defined as follows:

$$FEI = \frac{Burnup}{Initial\ Fissile\ Number\ in\ the\ Core.} \qquad (1)$$

The parametric sensitivity of FEI is opposite to that of FIR. FEI is different from FIR because it measures economic performance with regard to fuel utilization rather than breeding. We focused on effective fissile consumption with less initial fissile loading. Large fissile contents at the discharge point cannot be counted as a credit in the fuel cycle economics evaluation under the once-through cycle strategy. Figure 6 shows the FEI results of various cases. FEI is mainly dependent upon the seed fuel rod size in the KTF design, because U-235 is only used for FEI calculation. The results show that the seed fuel rod size should be smaller than that of the blanket fuel for high fuel cycle economy.

A radio-toxicity index can be defined based on the Annual Limit Intake (ALI), which was recommended by the International Commission on Radiological Protection (ICRP)[9]. The radio-toxicity index is expressed as follows:

$$R(t) = \frac{A(t)}{ALI} = \frac{\lambda N(t)}{ALI} \qquad (2)$$

where R(t) : radio-toxicity index at time t
A(t) : activity at time t
ALI : annual limit on intake
λ : decay constant
N(t) : number of nuclides at time t.

Radio-toxicity of actinides decreases with decay time from the point when they are discharged. It is not easy to compare the time-dependent variations of each isotope existing in a reactor volume. Therefore, a new index of the time-independent value is required for evaluating the overall radio-toxicity level in spent fuels[10]. Integration of time is one of the methods used to derive this time-independent index. Integration is performed for the total radio-toxicity for any time interval (i.e. t=0 to $1x10^3$ years, or $1x10^3$ to $1x10^6$ years) to obtain time-integrated values. The lifetime of vitrified waste is important. A lifetime is postulated as being several thousand years, and thus it is appropriate to consider ten thousand years as a period of time. For estimating short-time risk, we set the time interval to 0 to $1x10^3$, and for a long-term interval, we set the time to between $1x10^3$ and $1x10^6$ years. The radio-toxicity index integrated for this interval

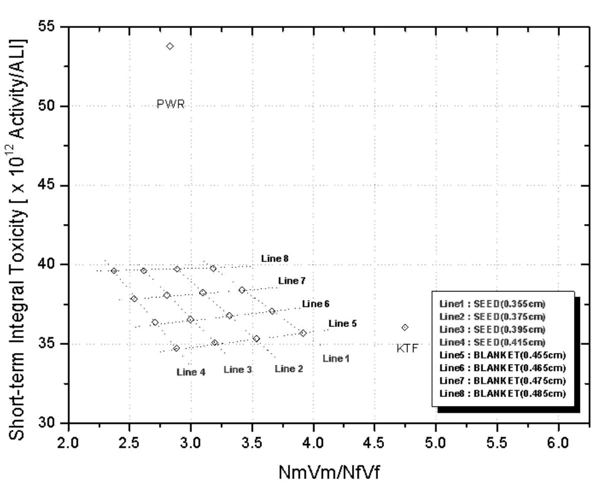

Fig. 7. Short-term Radio-Toxicity vs. Vm/Vf

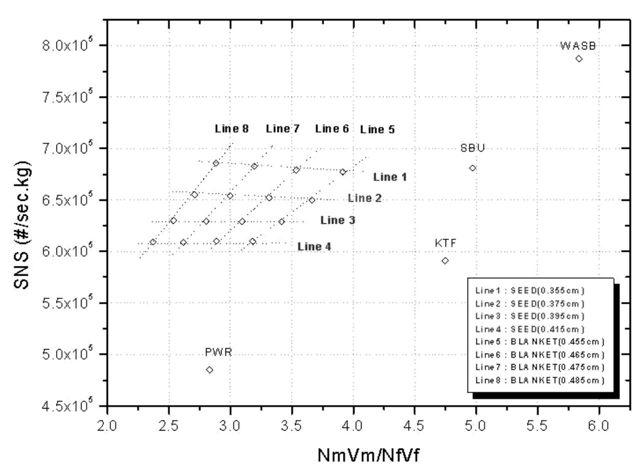

Fig. 8. Long-Term Radio-Toxicity vs. Vm/Vf

Table 2. Minor Actinides Isotopic Fractions in Total MAs(w/o) Isotope

Case \ Isotope	Np-237	Am-241	Am-243	Am-242m	Cm-242	Cm-244
Seed : 0.355 cm Blanket : 0.455 cm	56.9894	3.0202	19.6937	0.0453	1.1725	19.0789
Seed : 0.355 cm Blanket : 0.485 cm	56.1563	2.8587	20.0160	0.0450	1.2322	19.6918
Seed : 0.415 cm Blanket : 0.455 cm	58.0677	3.7878	17.6137	0.0832	1.0538	19.3939
Seed : 0.415 cm Blanket : 0.485 cm	57.9319	3.7580	17.6800	0.0782	1.1385	19.4134

is defined as below:

$$I = \int_0^t A(t)dt. \qquad (3)$$

This index gives the total radio-toxicity, which may affect humans after the vitrified waste collapses. Short-term toxicity is much less than conventional PWRs whereas long-term radio-toxicity shows little difference between the KTF design and PWRs, as illustrated in Figures 7 and 8. All cases have smaller radio-toxicity than those of conventional PWR due to the small fractions of Np-237 and Am-241, which affect short-term toxicity. On the other hand, long-term toxicity relies on Am-243, and both conventional PWR and thorium-based core have similar Am-243 fraction in their spent fuel. All isotopic fractions of MAs are presented in Table 2.

2.3 Assessment of the Proliferation Limit

U-233 converted from Th-232 was found to be a superior fissile isotope and builds up as a function of burnup. It is possible that U-233 can be used as a weapon material, and therefore a barrier is needed to prevent its diversion. With regard to proliferation, an acceptable concentration of fissile uranium content among the total uranium is reported to be less than 12w/o[11] when U-233 and U-235 coexist. This content is nearly equivalent to the 20w/o of U-235 in UO_2 fuel. The limit of the equivalent U-233 content for a mixture composed of U-233, U-235, and U-238 can be expressed as follows:

$$\frac{U^{235}+0.6\times U^{233}}{U_{\text{total}}} \le 12\ w/o. \qquad (4)$$

Results of parametric studies on blanket fuel compositions are shown in figure 9.

The results show that a high volume fraction and low enrichment of UO_2 in the thorium-based blanket fuel can allow higher burnups before exceeding the w/o limit. The volume fraction of UO_2 has a more significant effect on the critical requirement than the weight fraction of UO_2.

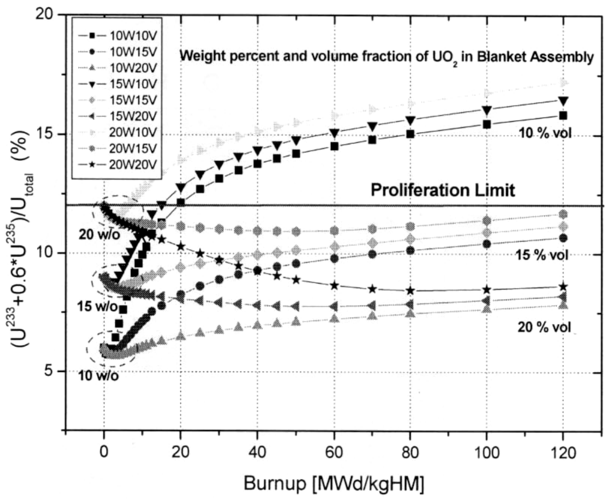

Fig. 4. SNS vs. Vm/Vf

The volume fraction of UO_2 in the blanket should be higher than 15% and the enrichment of uranium in the UO_2 should be less than 20w/o in order to satisfy the proliferation limit. U-233 builds up rapidly until the 60 MWd/kgHM burnup stage, after which the concentration is saturated at a constant level. The concentration of U-233 depends mainly upon the amount of Th-232 as well as the neutron spectrum. Th-232 has a high resonance absorption cross-section between the ~eV and ~keV energy regions, and therefore the conversion ratio of U-233 depends on the moderator-to-fuel volume ratio in the blanket.

2.4 Optimization of the KTF Design

As blanket assemblies stay in the core for up to 9 seed cycles, the reactivity swing of the blanket assembly should be small enough to have a similar fuel cycle length per reload cycle. The blanket assembly has negative reactivity during the entire burnup period due to a small amount of fissile material loading, which is necessary in order to have a periodic reload fuel cycle length.

To prevent proliferation problems of U-233, the

Table 3. Optimized KTF Assembly Design Parameters

Parameter	Optimized Assembly Design	
	Seed	Blanket
Fuel Composition	U/Zr Metal (10% Zr) U, 11/9 w/o	$(U+Th)O_2$ UO_2, 12.5w/o 15v/o
Pellet Radius	0.325 cm	0.4395 cm
Gas Gap	-	0.0085 cm
Cladding Thickness	0.03 cm	0.057 cm
Fuel Rod Radius	0.355 cm	0.505 cm
Burnable Poison	Gd_2O_3 , 8w/o_20	-
V_m/V_f	3.78	1.40
Core Volume Ratio	45	55

enrichment and portion of UO_2 are restricted in the blanket assembly along with the discharged burnup. In the case of using high enrichment and a large volume fraction of UO_2 with burnable poison material in the blanket assembly, the proliferation resistance limits are maintained, but fuel cycle economy becomes worse relative to that of the UO_2 fuel cycle. The KTF design was optimized for proliferation resistance based on the simultaneous goal of achieving optimum fuel cycle economy. In terms of fuel cycle economy, a large blanket fuel rod size relative to that of the seed is desirable; consequently, a small-sized seed fuel rod was considered to enhance fuel cycle economics.

8~10 w/o and 20 gadolinia BPs were used for the seed fuel assembly to control power peaking. Slightly low enriched U/Zr metal fuel rods were also used to control the power distribution locally in the seed assembly. Optimized assembly design parameters are summarized in Table 3.

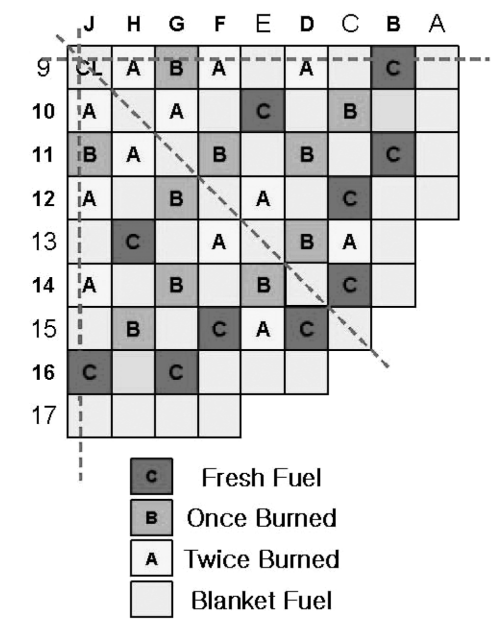

Fig. 10. 1/4 Core Loading Pattern

3. CORE DESIGN AND ANALYSIS RESULTS

3.1 Core Design Characteristics

The KTF core has 18-month fuel cycle lengths with 3-batch seed assemblies and one batch blanket assemblies. One-third of the seed fuel assemblies were replaced with fresh fuel assemblies per reload cycle and the blanket fuel assemblies were replaced entirely every nine cycles according to the one-batch reload strategy.

Figure 10 shows the layout of the fuel assembly loading pattern in the KTF core. The numbers of fuel assemblies are 108 for the seeds and 133 for the blanket. There were insufficient degrees of freedom in positioning the seed assemblies due to a checkerboard low-leakage loading pattern. Only twice-burned fuel assemblies were permitted to be located adjacent to fresh fuel assemblies in order to minimize power peaking. Blanket assemblies were loaded at the periphery of the core for reduced neutron leakage. To enhance fuel cycle economics, blanket assemblies remained in the core for up to 9 seed fuel cycles and were shuffled after five cycles.

3.2 Neutronic Performance Analysis

Excess reactivity of the blanket assembly in the KTF core did not change significantly during the entire period of nine seed cycles. The variations of critical boron

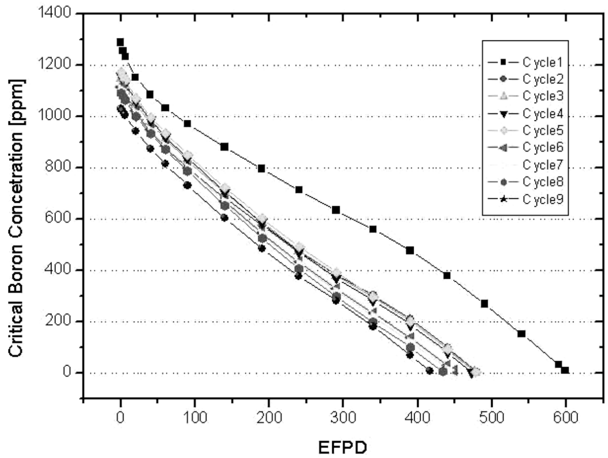

Fig. 11. CBC vs. Cycle EFPD

	J	H	G	F	E	D	C	B	A
9	0,590 0,563 0,592	1,293 1,013 0,904	1,900 1,475 1,244	1,522 1,306 1,101	0,779 0,920 0,936	1,338 1,321 1,180	0,690 0,850 0,959	1,343 1,545 1,730	0,218 0,313 0,448
10	1,293 1,013 0,904	0,661 0,629 0,641	1,285 1,050 0,919	0,767 0,835 0,840	2,000* 2,016* 1,769	0,764 0,908 0,951	1,661 1,641 1,538	0,526 0,688 0,863	0,205 0,292 0,418
11	1,900 1,475 1,244	1,285 1,050 0,919	0,671 0,706 0,728	1,614 1,459 1,285	0,748 0,858 0,886	1,713 1,595 1,416	0,749 0,894 1,011	1,347 1,510 1,697	0,207 0,289 0,413
12	1,522 1,306 1,101	0,767 0,835 0,840	1,614 1,459 1,285	0,661 0,732 0,767	1,230 1,136 1,032	0,785 0,861 0,911	1,904 1,829 1,802*	0,455 0,559 0,698	0,136 0,186 0,266
13	0,779 0,920 0,936	2,000 2,016 1,769	0,748 0,858 0,886	1,230 1,136 1,032	0,728 0,773 0,807	1,922 1,622 1,421	1,370 1,211 1,120	0,340 0,389 0,471	
14	1,338 1,321 1,180	0,764 0,908 0,951	1,713 1,595 1,416	0,785 0,861 0,911	1,922 1,622 1,421	0,825 0,875 0,933	1,573 1,502 1,535	0,246 0,281 0,348	
15	0,690 0,850 0,959	1,661 1,641 1,538	0,749 0,894 1,011	1,904 1,829 1,802	1,370 1,211 1,120	1,573 1,502 1,535	0,349 0,400 0,489		
16	1,343 1,545 1,730	0,526 0,688 0,863	1,347 1,510 1,697	0,455 0,559 0,698	0,340 0,389 0,471	0,246 0,281 0,348			
17	0,218 0,313 0,448	0,205 0,292 0,418	0,207 0,289 0,413	0,136 0,186 0,266					BOC MOC EOC

* : Maximum Pin Power Location with Burnup.

Fig. 12. Radial Assembly-wise Relative Power Distribution (Eq. Cycle #1)

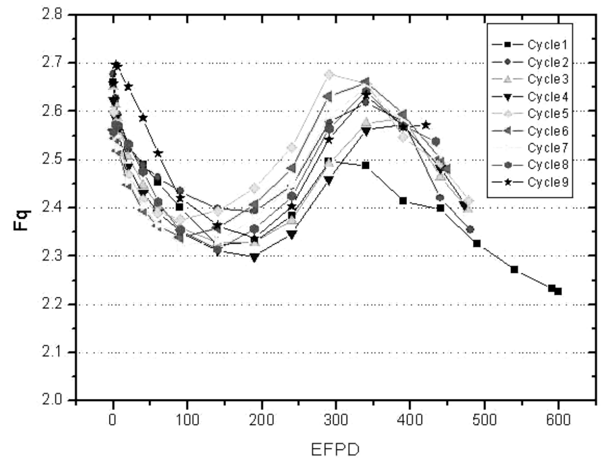

Fig. 13. Fq vs. Cycle EFPD

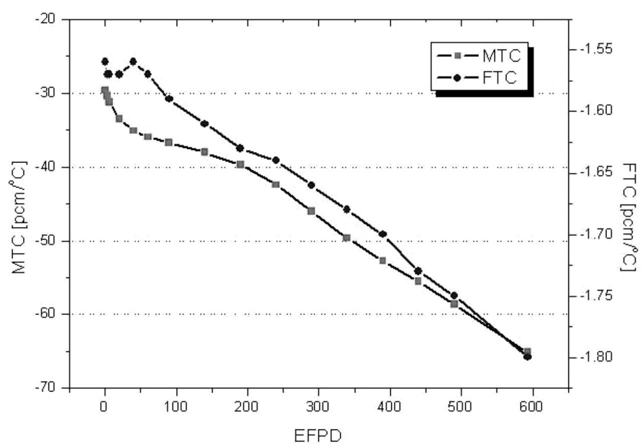

Fig. 14. Cross-section characteristice of Th-232 and U-238

concentrations for nine reload cycles of the KTF core are shown in Figure 11.

The critical boron concentrations of all cycles were maintained below 1,200 ppm, which is lower than that of the APR-1400, resulting advantageously in a moderator temperature coefficient (MTC) with a more negative value. The average fuel cycle length of nine reload cycles is 472.5 EFPD, although every cycle has a different length due to reactivity variations of the blanket fuel assembly. The first cycle is longer than average because the reactivity of the blanket fuel assembly is slightly increased at the Beginning Of Cycle (BOC) and then decreases with burnup. Average discharged burnup is 83.0 MWd/kgHM for the seed fuel assemblies and 95.9 MWd/kgHM for the blanket fuel assemblies, which show a higher burnup rate than that of conventional PWRs. The power peaking factor is a key design limit for nuclear safety. Assembly power peaking occurs at the initial burnup point of the first cycle.

Figure 12 shows the assembly-wise radial relative power distribution at the first equilibrium cycle of the KTF core. Maximum assembly-wise radial power peaking of 2.02 is too high for a fresh fuel assembly, whereas Fr is 1.55 for a nominal PWR. A DNB analysis is required for the hottest channel to guarantee a thermal hydraulic safety margin and will follow in paper II[12]. Figure 13 shows a power peaking factor (Fq) for all the reload cycles. Fq is much higher than in a conventional PWR core because of the high power density difference between the seed and blanket. The Maximum Fq is 2.69 at the 9th equilibrium cycle and is similar with other reload cycles, which exceed the limit condition slightly. The Moderator Temperature Coefficient (MTC), Fuel Temperature Coefficient (FTC), and Boron Worth (BW) are evaluated for the KTF core at the conditions of All control Rods Out (ARO), Hot Full Power (HFP), and Equilibrium Xenon (Eq. Xe.). The MTF and FTC

Table 4. Unit cost and Fuel Cycle Costs

Component	Unit Cost ($/kg)	Fuel Costs (mills/kWe-hr)			
		Ref. PWR (APR-1400)	KTF Core		
			Seed	Blanket	
		UO_2	U/Zr	U	Th
Ore	50(U)/85(Th)	1.13	1.12	0.10	0.03
Conversion	8	0.18	0.17	0.02	0
Enrichment	110	1.79	2.07	0.19	0
Fabrication	275	0.69	0.30/0.18*/0.54**	0.02	0.11
Front End Sum		3.79	3.66/3.54*/3.91**	0.47	
Spent Fuel Disposal	600	1.44	0.57	0.28	
Total Sum		5.23	4.99/4.87*/5.23**		

* : Fabrication cost is considered as 60% of UO_2
** : Fabrication cost is considered as 500 $/kg for conservative prediction.

calculation results are presented in figure 14. The KTF core has a more negative MTC than the reference PWR due to a lower boron concentration and the use of Th-232, which has a high absorption cross-section in the thermal neutron energy range. The high thermal absorption cross section of Th-232 as well as the low boron concentration contribute to the negative MTC. The more negative MTC of the thorium-based fueled core may provide an inherent safety feature like the negative Doppler Temperature Coefficient (DTC). The FTC is negative during the whole burnup period, as -1.56 pcm /°C at BOC and -1.8 pcm/°C at End Of Cycle (EOC). The soluble boron reactivity worth(BW) is higher than that of the reference PWR because of the soft neutron spectrum. The BW is -6.34 pcm/ppm at BOC and -7.24 pcm/ppm at EOC, which are slightly higher than -6.91 pcm/ppm and -8.24 pcm/ppm of the reference PWR.

4. FUEL CYCLE COSTS ANALYSIS

In order to assess the economic potential of a heterogeneous thorium fuel core, the front-end fuel cycle cost and the disposal cost of spent fuel assemblies were compared with those of current existing PWR fueled with UO_2. For the front-end fuel cycle cost analysis, four factors were considered: ore, conversion, enrichment, and fabrication. The cost of raw uranium and thorium, as well as conversion, enrichment, and fabrication are calculated to be 50$/kg, 85$/kg, 8$/kg, 110$/SWU-kg, and 275$/kg, respectively[13]. The weight fraction of U-235 in tail was assumed to be 0.25 w/o, and 5% of the discount rate was applied for all cases. Since no disposal facility for spent fuel exists, nor are any planned to be built in KOREA, the disposal cost was assumed to be 600$/kg-spent-fuel. In this fuel cycle cost comparison, the fabrication cost of U/Zr metal fuel for the KTF core is assumed to be the same as that for UO_2 fuel, because the precise fabrication cost is unknown. The fuel cycle cost analysis for the thorium-based core is compared with that of the APR-1400 UO_2 core. The reference APR-1400 UO_2 core has an 18 month fuel cycle length with a 3-batch fuel assembly. The number of seed fuel assemblies is 108 with 3 batches while the blanket assembly which resides in the core is one batch of 133 fuel assemblies for 9 cycles. Both reactors generate 3,983 MWth with 241 fuel assemblies. The availability of each core is considered to be 95% with 45 days of identical refueling periods.

The fuel cycle costs are shown in Table 4 in mills per kilo-watt per hour. The cost of a heterogeneous thorium fuel cycle is comparable with the current existing PWR. This demonstrates that the fuel cycle cost of a heterogeneous thorium fuel core improves as the cycle length increases and as the enrichment and volume fraction in the blanket fuel assembly become lower. One of the most dominant cost factors is the enrichment cost for U-235, occupying about 50% of the front end fuel cycle costs in both conventional PWR and a thorium based core. From this point of view, UO_2 fuel with lower enriched U-235 has better economic potential than U/Zr fuel in a thorium based core because more than 10% of U-235 enrichment is required even in U/Zr seed fuel. The exact fabrication cost of U/Zr metallic fuel is unknown and uncertain at this point, but if we consider the cost of fabricating U/Zr alloy fuel by extrusion to be 30-60% of that of a PWR UO_2 fuel rod, the fuel cycle costs are still less than those of the PWR. In the case of 60% cost assumption, the overall fuel cycle cost would be approximately 7% lower. Even though the fuel fabrication cost of U/Zr metallic fuel is considered to be $500/kg, the fuel cycle costs are still competitive with UO_2 fuel cycle when compared with the reference PWR. When a different discount rate was applied to the fuel cycle cost analysis, there was little difference between UO_2 and thorium fuel cycle costs. When an 8% discount rate was applied, the fuel cycle cost of reference UO_2 core was 5.36 mills/kWe-yr and that for thorium fuel cycle was 5.14 mills/kWe-yr. The cost difference between the two was 0.22 mills/kWe-yr, which is very close to the 0.24 mills/kWe-yr difference in the case of a 5% discount rate. The volume of discharged fuel assemblies from the thorium based core was reduced to about 60.5% compared with that of the APR-1400 UO_2 core during 9 reload cycles. It should be noted that the disposal cost depends upon the discharged volume of spent fuel per year. It is important that the reduction of the discharged fuel volume not only decreases fuel cycle costs but also relieves concerns for nuclear weapon proliferation and future hazardous effects. In this study, the disposal cost is considered for the back-end fuel cycle analysis. However, spent fuel disposal cost is not confined, and hence this problem could potentially become an issue in the near future.

5. CONCLUSION AND CONTINUING WORK

In this paper, the KTF thorium-based seed and blanket concept is studied for optimization by using various indices such as BCM, SNS, TG, Radio-Toxicity, and FEI, and tested at the APR-1400 reference core to enhance proliferation resistance and fuel cycle economics. Core design results during 9 reload cycles show compatible neutronic performance with more negative MTC; however, they also reveal a smaller thermal hydraulic safety margin than that of conventional PWRs due to high power peaking in the seed assembly. The maximum Fq is 2.69 at the 9th equilibrium cycle which is much lower value than those from the previous studies. In this study, the thorium fuel cycle cost, particularly the heterogeneous KTF concept with once-through fuel cycle, is 4.99 mills/KWe-yr, whereas a value of 5.23 mills/KWe-yr of UO_2 fuel cycle is attainable in the case of comprising back-end fuel cycle costs, because the blanket assembly can reside in the core during 9 reload cycles. However, these cost analysis results are based on two assumptions: that the blanket oxide fuel can resist up to 96 MWd/kgHM and that the seed U/Zr metal fuel has high performance grids favorable to the thermal margin.

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