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Application of the Heterogeneous Thorium Fuel Core for Enhanced Proliferation Resistance and Fuel Cycle Economy

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Abstract

A heterogeneous thorium-based seed and blanket core design is suggested for a conventional pressurized light water reactor (PWR) and evaluated to enhance the proliferation resistance potential and fuel cycle economics. In this paper, a core loaded with optimized seed and thorium blanket assembly were suggested and examined for the neutronic and thermal hydraulic characteristics. KTF core has more negative MTC value due to lower boron concentration by 200 ppm than that of reference PWR over the whole cycles. MDNBR is 1.36 at 2nd reload cycle under the 118% over-power transient condition in spite of high pin power peaking. Maximum cladding temperature is predicted to 973K in a LBLOCA simulation and guaranteed metal fuel integrity at severe accidental condition. Bare critical mass is 30.36 kg and thermal generation is 45.22 watts/kg that 1.5~2 times higher than those of the conventional PWR. Blanket has a higher radio-toxicity than seed and PWR assemblies owing to high burnup. The fuel cycle cost of KTF core is 4.96 mills/kWe-hr, which is cheaper than 5.23 mills/kWe-hr of the reference UO_2 fuel. It is noted that KTF core has good competitiveness in fuel cycle economics and proliferation resistance as well as neutronic and thermal hydraulic performances.

1. Introduction

During the several years proliferation resistance has been addressed for the future nuclear energy utilization. These trends are demanded of using thorium fuel in PWR and many international interests in proliferation resistance have been shown. Ultimate objectives of using thorium fuel are to enhance proliferation resistance potential and fuel cycle economics. Since U^{233} which was converted from Th^{232} produces smaller amount of actinide, thorium fuel has an inherent proliferation resistance characteristic compared to UO_2 fuel. There were three fuel assembly design concepts; Radkowsky Thorium Fuel (RTF)[1], Whole Assembly Seed and Blanket (WASB)[2] and Kyung-hee Thorium Fuel (KTF)[3] for a heterogeneous seed and blanket application. The RTF concept suggested by Ben-Gurion University was based on the seed and blanket units within an assembly. The seed unit in the central region of a fuel assembly contains 20% enriched uranium while the blanket unit in the outer region contains ThO_2 mixed with 10 to 20 % enriched uranium. The WASB concept based on the whole assembly size seed and blanket developed by MIT was applied to the Westinghouse 4-loop 1,150 MWe PWR.[4] The KTF design having the same geometric concept, but different fuel type and composition, with WASB was developed for 1,400MWe Korean Next Generation Reactor, APR-1400.[5] The KTF assembly design was based on combustion engineering fuel assembly which has 16 × 16 fuel rods array. U/Zr metal fuel was used for seed in RTF and KTF while UO_2 in WASB.

In the early stage of this research, the KTF design had 1 to 3 ratio of seed and blanket and was optimized for fissile economics by maximizing the fissile inventory ratio (FIR) because its inherent characteristics of proliferation resistance was guaranteed. However, large fissile amounts of discharged fuel assembly were useless in once through fuel cycle strategy. A new index of the fissile economy index (FEI) was suggested and applied to the optimization of the KTF design to enhance fuel cycle economics.[6] In case of 1 to 3 ratio of seed and blanket, the enrichment of seed assembly is nearly 20 w/o to have the 18 month fuel cycle lengths and it resulted in high power difference between seed and blanket assembly. Because of high power difference between seed and blanket, thermal hydraulic safety design limit is a technical issue for the heterogeneous thorium fuel core design. Currently the seed and blanket assembly ratio is changed 1:1 to satisfy the thermal hydraulic design limit.

The objective of this work is to suggest heterogeneous PWR core design with thorium blanket having good fuel cycle economics and proliferation resistance as well as neutronic performances compared with conventional PWR. In this paper, optimized KTF assembly design was suggested and applied to APR-1400 core geometry. A heterogeneous thorium fueled PWR core was analyzed for the neutronic and thermal hydraulic safety parameters such as reactivity coefficients and DNBR. Severe accidental condition like a LBLOCA was also simulated to confirm the thermal hydraulic safety for the U/Zr metal fuel. Fuel cycle costs were analyzed in addition to characteristics of spent fuel assembly. Toxicity index was also investigated in the aspects of environmental impacts and proliferation resistance.

2. Assembly & Core Design

2.1. Optimized Assembly Design

Original KTF assembly design was initiated from KOFA fuel assembly geometry and changed to CE fuel type in order to apply for APR-1400 core. U/Zr metal fuel was used in seed assembly and enrichment of seed fuel should be higher than conventional PWR fuel because of low reactivity of blanket assembly. There is a restriction of using Th^{232} as a fuel on account of criticality constraint because U^{233} builds up with burnup while U^{235} burns out. The amount of U^{233} in blanket assembly depends upon the hardened neutron spectrum as well as amount of Th^{232}. If the neutron spectrum was hardened that the amount of U^{233} was increased due to high resonance absorption of intermediate energy ranges of Th^{232}. It is shown that hardened neutron spectrum in blanket assembly is much better for U^{233} utilization from Th^{232} as long as satisfying the criticality safety constraint.

A lot of parametric studies were performed to investigate of proliferation resistance and fuel cycle economics. There were two progress of optimization of KTF assembly. First, the KTF assembly design was optimized in order to maximize the proliferation resistance and fissile inventory ratio. Second, to enhance the fuel cycle economics a new index of FEI was suggested and applied to optimize KTF assembly. The characteristics of parametric studies are bellows.

- Neutron spectrum in the blanket assembly should be hardened to maximize utilization of U^{233}, on the contrary in seed assembly it should be softened to utilize of U^{235} economically.
- Proliferation resistance indices, BCM, SNS and TG, are better than conventional PWR all of the parametric studies cases, especially BCM and SNS are larger as long as the neutron spectrum harder in seed assembly.
- Fuel economy in once through fuel cycle strategy depends upon the enrichment of U^{235} in seed. If the neutron spectrum in seed assembly is hardened then the fissile isotopes in the discharged fuel were remained a lot because of high enrichment of U^{235}.
- It is noted that the reactivity swing of blanket assembly should be small because blanket assembly stays up to several seed fuel cycles for an equilibrium core.

Optimized KTF assembly design was suggested based on the previous parametric studies results. However, seed fuel rod has higher linear power density than conventional PWR and departure from nucleate boiling (DNB) was occurred at the hottest seed fuel pin surface. KTF design has been changed to meet the thermal hydraulic design limit of MDNBR. To increase DNB margin, seed fuel rod size was increased in order to decrease fuel surface heat flux in seed assembly and blanket fuel rod size was increased to raise the mass flow rate in seed assemby respectively. The results showed that MDNBR is more sensitive to the mass flow rate than surface heat flux change as shown in figure 1. Fuel rod size of blanket assembly has been changed from 0.455 to 0.485 cm. Moderator to fuel volume ratio of blanket was changed from 2.17 to 1.70 and it caused higher conversion ratio of U^{233} from Th^{232} because of hardened neutron spectrum, resulting in a reduction of power difference between seed and blanket assembly. To control pin power peaking, weight percent of low enriched fuel pin was slightly decreased from 10 w/o to 9 w/o in seed assembly. Fuel enrichment of blanket assembly was increased by 2 % to compensate of low power defect in blanket assembly because conversion of U^{233} was not achieved yet at the beginning of cycle (BOC). Figure 2 shows optimized KTF assembly design configuration and Table I summaries the design parameters.

2.2. Core Design

APR-1400 core geometry has been used to verify the feasibility of thorium blanket fueled core design having same performances with APR-1400 UO_2 core. The APR-1400 core is loaded with conventional 241 fuel assemblies with 18-month fuel cycle length. KTF core has 18 month fuel cycle lengths with 3-batch seed assemblies and one batch of blanket assemblies. Figure 3 shows layout of the fuel assembly loading pattern in the KTF core. The numbers of fuel assemblies are 108 for seed and 133 for blanket. There was not enough degree of freedom in positioning the seed assemblies due to checkerboard low leakage loading pattern. Usually seed fuel assemblies have higher excess reactivity than blanket assemblies, only twice burned fuel assemblies were permitted to locate adjacent other fresh fuel assemblies in order to minimize power peaking. Blanket assemblies were loaded at periphery of the core for the reduction of neutron leakage. To enhance fuel cycle economics, blanket assemblies were remained in the core up to 11 seed fuel cycles and shuffled after early five cycles.

2.3. Analysis Tool

The HELIOS[7]/MASTER[8] code system was used to evaluate the neutronics of the APR-1400 core loaded with KTF assembly. HELIOS is a two dimensional transport code using the current coupling collision probability method for neutron transport calculations. 35-group neutron library is used to generate the group constants for the seed and the blanket assemblies. MASTER developed by the Korea Atomic Energy Research Institute (KAERI) is a three dimensional nodal code for the core physics calculations with thermal hydraulic feedback. MATRA and MARS are used for thermal hydraulic analysis for the KTF core. MARS(Multi-dimensional Analysis of Reactor Safety) code was developed by KAERI from RELAP-5/MOD/3.2.1.2 combined with COBRA-TF and used to analyze severe accident condition LBLOCA. For the DNBR analysis of KTF core MATRA code was used to calculate sub-channel thermal hydraulic. An evaluation of radio-toxicity and proliferation resistance indices such as SNS, TG and BCM is performed by ORIGEN-II[9] and MCNP-4b[10] codes.

3. Core Calculation Results

3.1. Neutronic Performance Analysis

KTF core performances were evaluated and analyzed comparing with APR-1400 UO_2 core. The excess reactivity of the blanket assembly in the KTF core has not been changed a lot during whole period of eleven seed cycles. Cycle lengths are more stable than previous core design[11] due to low reactivity swing of the blanket assembly. The variations of critical boron concentrations for eleven reload cycles of the KTF core are shown in Figure 4. The fact that the critical boron concentrations of all cycles are kept below 1,300 ppm which is lower than APR-1400 by about 200 ppm, this gives an advantage in moderator temperature coefficient (MTC) with more negative value. Average fuel cycle length desired to have 468 EPFD is 470 EFPD during eleven seed cycles and average discharged burnup of seed assemblies is 79.5 MWd/kgHM and 94.6 MWd/kgHM for blanket assemblies.

The pin peaking factor is a key design limit of nuclear safety. The design limit of pin peaking factor for the reference UO_2 core, APR-1400 is reported as 2.58. For the limit of the radial relative maximum assembly power, 1.55 is recommended for the DNBR limit. Figure 5 shows a pin peaking factor for the whole reload cycles. Because the burnable poison material in the seed assembly was rapidly burnt out during the first cycle, the maximum power peaking occurs at once-burned seed fuel assembly. Pin-wise peaking is much higher than in conventional PWR core because of high power difference between seed and blanket. Maximum pin peaking in KTF core occurs as of 2.847 at 2^{nd} reload cycle.

Figure 6 shows the assembly-wise radial relative power distribution of the KTF core. Maximum radial power peaking is too high as 2.02 at fresh fuel assembly whereas 1.55 for nominal PWR. Therefore, thermal hydraulic safety should be analyzed in order to check the thermal hydraulic safety limits for DNBR and presented in section 3.2.

Moderator Temperature Coefficient (MTC), Fuel Temperature Coefficient (FTC) and Boron Worth (BW) are evaluated for the KTF core. Calculation conditions are All control Rods Out (ARO), Hot Full Power (HFP) and Equilibrium Xenon (Eq. Xe.) condition. The reactivity coefficients calculation results are presented in Table II. KTF core has more negative MTC than reference PWR due to lower boron concentration than current PWR. The more negative MTC of the thorium-based fueled core may provide an inherent safety feature as the negative Doppler Temperature Coefficient does. The worth of soluble Boron is less than that of a reference PWR in spite of low boron concentration because the neutron spectrum of KTF core has been changed more soft than conventional PWR.

3.2. Thermal Hydraulic Safety

MATRA code was used to evaluate DNBR analysis for KTF core. A hottest color-set geometry was selected as a sub-channel analysis model with pin-wise power distribution data. CE-1 correlation was used to calculate critical heat flux (CHF) and 118 % over power condition was considered as an anticipated overpower transient. In case of using CE-1 correlation factor for CHF calculation, the MDNBR limit was 1.13, but 1.3 was recommended as a limit condition comprising uncertainty. A new design of grid that has high loss coefficient in blanket assembly was suggested to solve the DNB problems. DNBR analysis results are shown in Figure 7 for 3 burnup stages. MDNBR of KTF core is 1.36 at BOC of reload cycle 2 which has the highest pin power peaking factor through the whole cycles. In spite of high power ratio in seed assembly, MDNBR is satisfied with design limit due to the larger coolant channel area of seed assembly than blanket.

A model for MARS code has been set up based on the reference APR-1400 UO_2 core and it has been used to analyze the accidental condition of LBLOCA. Physical properties of U/Zr metal fuel have been improved. Conductivity of U/Zr metal fuel alloy is a significant factor and it would be to improve thermal hydraulic safety margin. Accidental scenario of LBLOCA has been simulated for the KTF core and the results are shown in Figure 8.

Limiting condition of LBLOCA is that peak cladding temperature should not exceed 1477.6 °K in UO_2 core. KTF core has the less peak cladding temperature compare to the APR-1400 UO_2 core and it means that the KTF core has high thermal hydraulic safety margin. Although maximum pin peaking of KTF core is higher than current PWR design limit, it is note that the KTF core has a high thermal hydraulic safety margin due to high thermal conductivity of U/Zr metal fuel.

3.3 Fuel Cycle Costs Analysis

In order to evaluate for the economic potential of heterogeneous thorium fuel core, the disposal cost of spent fuel assemblies as well as front-end fuel cycle cost were compared to those of the APR-1400 UO_2 core. For the front-end fuel cycle cost analysis, four factors related to ore purchase, conversion, enrichment and fabrication were considered. The costs of uranium purchase, thorium purchase, conversion, enrichment and fabrication are 50$/kg, 85 $/kg, 8$/kg, 110$/SWU-kg and 275$/kg, respectively[12]. 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 of the cases. Since any disposal facility for the spent fuel hasn’t existed and planned to be built in KOREA so far, the disposal cost was assumed to be 600 $/kg-spent-fuel which is saved by KHNP. The results of fuel cycle cost are shown in Table III as a fuel cycle cost in the unit of mills per kilo-watt electric power in a hour. The cost of heterogeneous thorium fuel cycle is better than the current existing PWR. It represents that the fuel cycle cost of heterogeneous thorium fuel core is more favorable as the blanket assemblies are stayed longer in the core and as the enrichment and the volume fraction in the blanket fuel assembly become lower. One of the main factors in the fuel cycle costs analysis is enrichment requirement. In this point of view, the UO_2 fuel with lower enriched U-235 has a good economic potential than that of the thorium fuel. Compared to the reference PWR with UO_2, the volumes of discharged fuel for KTF core were reduced to about 47 % compared to APR-1400 UO_2 core. Note the disposal cost depends upon the discharged volume of spent fuel per every year. In this study disposal cost is considered for the back-end fuel cycle analysis. However, the spent fuel disposal cost is not confined and this problem might be issued in near future.

3.4. Characteristics of Spent Fuel

3.4.1. Proliferation Resistance

The proliferation resistance potential is one of advantages of using the thorium-based fuel. Usually, the proliferation resistance of a fuel cycle depends upon the quantity and the quality of plutonium isotopes in the discharged fuel. Larger amount of the fertile plutonium isotopes that generate much decay heat and spontaneous neutrons becomes an intrinsic barrier to reach a critical mass of weapon. Therefore, the proliferation resistance potential is increased with increasing amount of the fertile plutonium isotopes in the discharged fuel. Even atomic number of plutonium isotopes especially such as Pu-238 produce a remarkable decay heat that may give a difficulty in handling spent fuel. For this reason, plutonium production rates are investigated to estimate the proliferation resistance of the KTF core. The results are given in Figure 9. Compared with the reference APR-1400, the total plutonium production rate of the heterogeneous thorium fuel core is much smaller than that of the current existing PWR. The composition of the fertile plutonium isotopes in the discharged fuel of KTF core is much larger than that of the reference APR-1400. It means that the KTF core has higher proliferation resistance than the reference ARP-1400 UO_2 core. Plutonium annual production rate of KTF core is about 46% of APR-1400 which is a significant decrease of plutonium quantity. Fissile plutonium (Pu-239 + Pu-241) fraction of KTF core is about 55.5% that has lower quality of plutonium to use a weapon purpose than existing PWR and may give an high bare critical mass index value. The weight fraction of actinides in the discharged seed and blanket assembly is presented in Table IV. The average discharged burnup of the seed is 94.6 MWd/kgHM and the blanket is 79.5 MWd/kgHM.

Three indices such as BCM, SNS and TG were calculated based on the Table IV data and represented in Table V. BCM and TG values are remarkably higher than APR1400 and both characteristics would make the plutonium considerably less desirable for weapons than current existing PWR. KTF core needs 1.5 times of plutonium amount to use a weapon purpose and 2 times of thermal shielding material is needed compared to APR-1400.

3.4.2. Criticality Safety Constraint

In a thorium-fueled core, U^{233} converted from Th^{232} is one of major fissile isotope. It should be noted that the definition of low enriched uranium for mixtures of U^{233} and U^{235} has not been established in law or in international agreements. In the aspect of criticality concern, an acceptable concentration of U^{235} in U^{238} is 20 %, and that for U^{233} in U^{238} is generally accepted at 12%.[13] This content is nearly criticality equivalent to 20w/o of U^{235} in UO_2. The limit of the equivalent U^{233}+U^{235} in U^{238} can be expressed by the relationship.

$$\frac{U^{233} + 0.6 * U^{235}}{U^{tot}} \leq 12 \ w/o$$

The uranium isotope content of blanket assembly in the KTF core is shown in Figure 10. Uranium fissile fraction does not reach the limit condition during burnup period of 120 MWd/kgHM. U^{233} builds up while U^{235} is consumed with burnup and amount of fissile uranium is maintained consistently through burnup. The concentration of U^{233} depends mainly upon the amount of Th^{232} as well as neutron spectrum. Th^{232} has a high resonance absorption cross section between ~eV and ~keV energy region, therefore conversion ratio of U^{233} depends on moderator to fuel volume ratio in the blanket.

3.4.3. Radio-Toxicity

The radio-activity of the KTF spent fuel has been analyzed using ORIGEN-II code. The radio-activity in Ci/MTHM is shown in Figure 11 during decay time. Blanket has a high radio-activity due to high burnup, because the blanket assemblies are stayed up to 11 seed cycles in the KTF core. There is a hump radioactivity of the blanket assembly between ten thousands and one million years, because of the decay product of U-233. It is note that KTF core is more hazardous to environment than ARP-1400, however it also means that KTF core is more difficult to handle the spent fuel for using weapon purpose due to high radio-toxicity. Therefore, KTF core has more proliferation resistance than APR-1400 in dealing with spent fuel.

4. CONCLUSIONS

In this paper heterogeneous thorium fuel core design (KTF core) is suggested and examined to verify the core performance, fuel cycle economics and proliferation resistance. The KTF core design is better than current existing PWR, APR1400, in fuel cycle economics and comparable to the core neutronic and thermal hydraulic performances. It also has high proliferation resistance owing to significant reduction of the plutonium production in the blanket assembly and all of the proliferation resistance indices are better than APR-1400 UO_2 spent fuel.

Therefore, heterogeneous thorium fueled PWR core design option is compatible with conventional UO_2 fuel.

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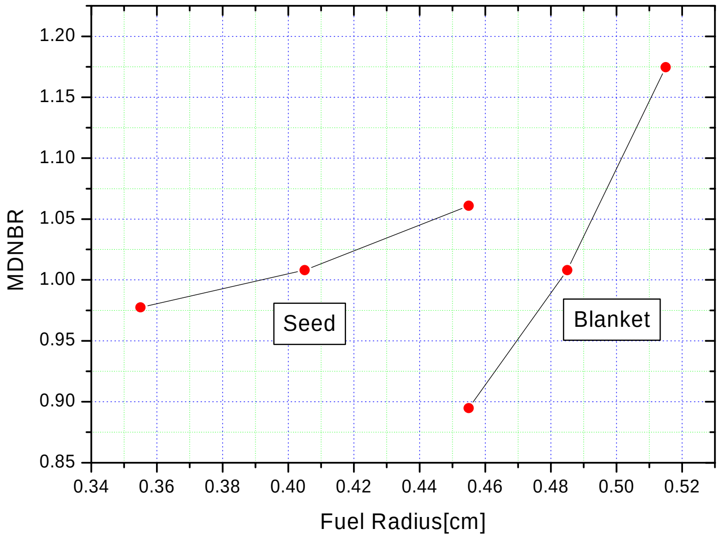


Fig. 1. DNBR vs. Fuel Rod Radius.

Table 1. Optimized 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, 12w/o 15v/o
Pellet Radius	0.325 cm	0.4195 cm
Gas Gap	-	0.0085 cm
Cladding Thickness	0.03 cm	0.0057 cm
Fuel Rod Radius	0.355 cm	0.485 cm
Burnable Poison	Gd_2O_3 ,12 w/o_20	-
V_m/V_f	3.78	1.70
Core Volume Ratio	45	55

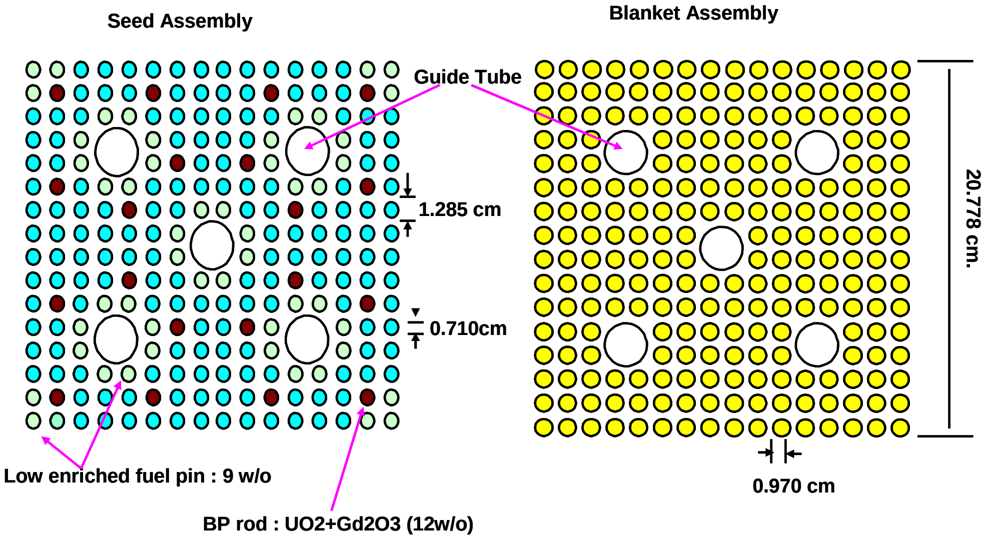
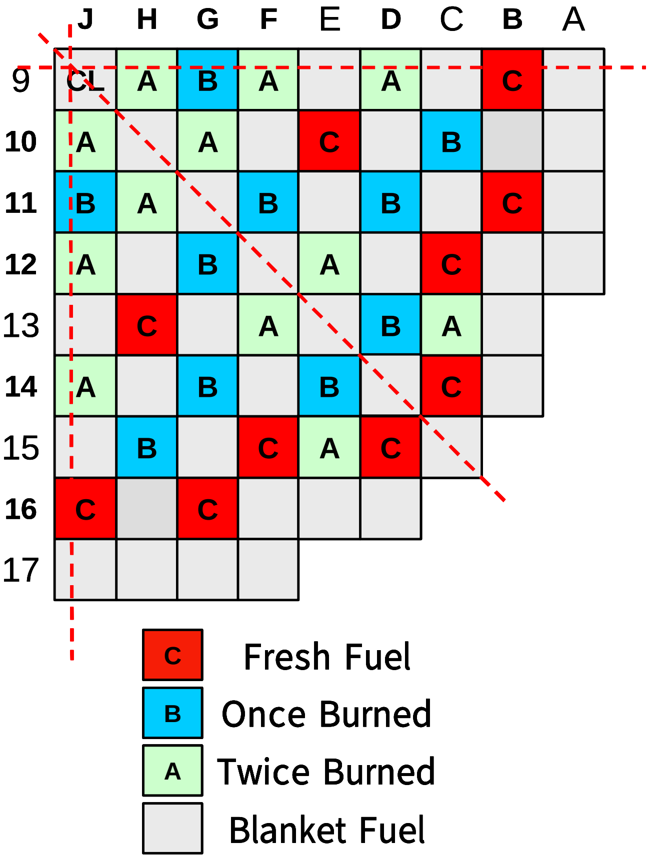


Fig. 2. Assembly Configuration.



	J	H	G	F	E	D	C	B	A
9	CL	A	B	A		A		C	
10	A		A		C		B		
11	B	A		B		B		C	
12	A		B		A		C		
13		C		A		B	A		
14	A		B		B		C		
15		B		C	A	C			
16	C		C						
17									

C Fresh Fuel
B Once Burned
A Twice Burned
Blanket Fuel

Fig. 3. 1/4 Core Loading Pattern.

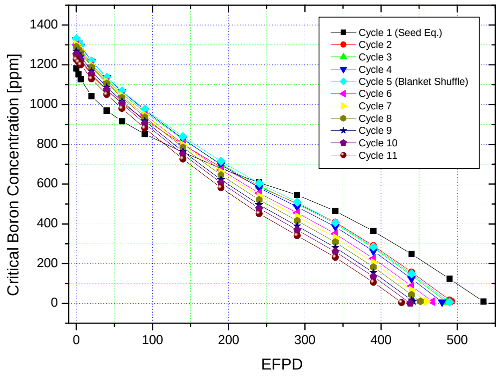


Fig. 4. Critical Boron Concentrations.

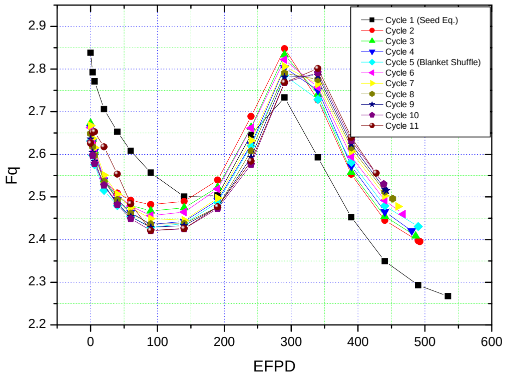
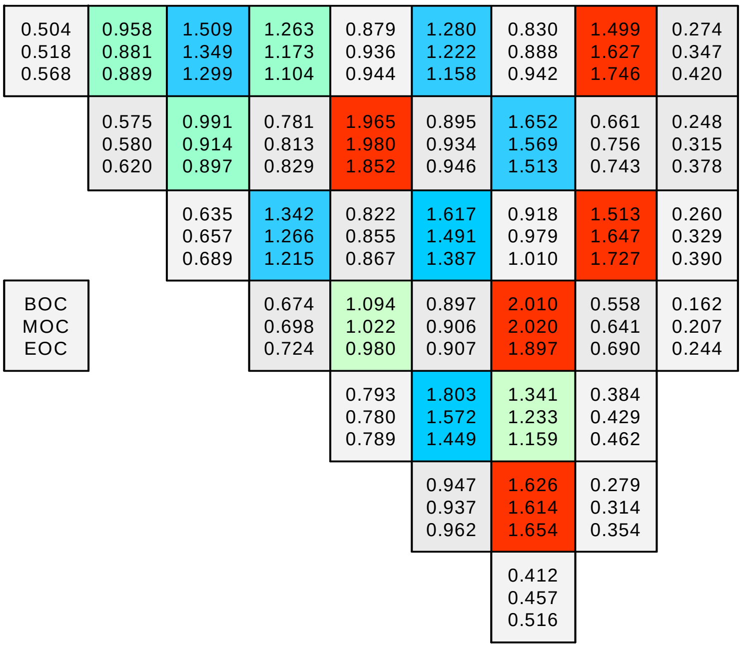


Fig. 5. Pin Peaking Factors.



0.504 0.518 0.568	0.958 0.881 0.889	1.509 1.349 1.299	1.263 1.173 1.104	0.879 0.936 0.944	1.280 1.222 1.158	0.830 0.888 0.942	1.499 1.627 1.746	0.274 0.347 0.420
	0.575 0.580 0.620	0.991 0.914 0.897	0.781 0.813 0.829	1.965 1.980 1.852	0.895 0.934 0.946	1.652 1.569 1.513	0.661 0.756 0.743	0.248 0.315 0.378
		0.635 0.657 0.689	1.342 1.266 1.215	0.822 0.855 0.867	1.617 1.491 1.387	0.918 0.979 1.010	1.513 1.647 1.727	0.260 0.329 0.390
BOC MOC EOC			0.674 0.698 0.724	1.094 1.022 0.980	0.897 0.906 0.907	2.010 2.020 1.897	0.558 0.641 0.690	0.162 0.207 0.244
				0.793 0.780 0.789	1.803 1.572 1.449	1.341 1.233 1.159	0.384 0.429 0.462	
					0.947 0.937 0.962	1.626 1.614 1.654	0.279 0.314 0.354	
						0.412 0.457 0.516		

Fig. 6. Relative Assembly-wise Power Distribution.

Table 2. Reactivity Coefficients

		MTC (pcm/℃)	DTCISO (pcm/℃)	BW (pcm/ppm)
APR-1400	BOC	-18.0	-	-6.91
	EOC	-57.6	-	-8.77
KTF core	BOC	-45.4	-1.66	-6.22
	EOC	-79.4	-1.87	-7.24

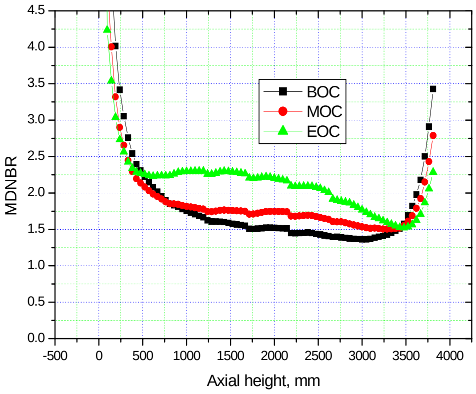


Fig. 7. DNBR of SEED in KTF Core.

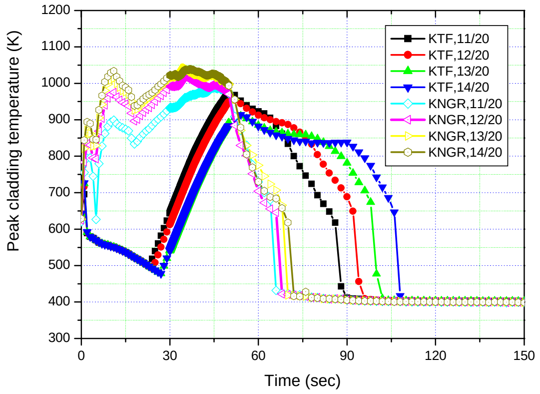


Fig. 8. Peak Cladding Temperature.

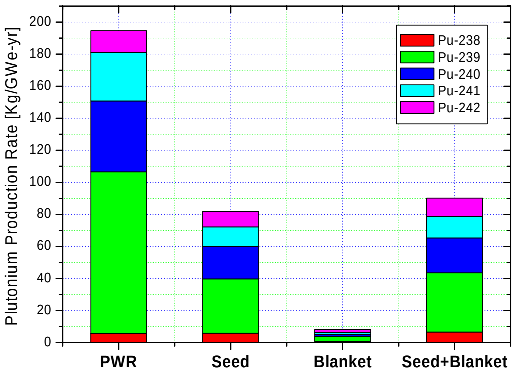


Fig. 9. Plutonium Production Rates.

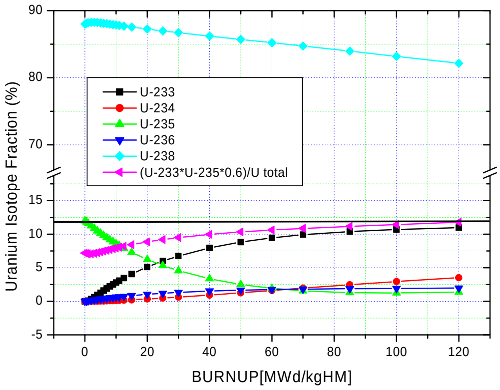


Fig. 10. Uranium Isotope Fraction.

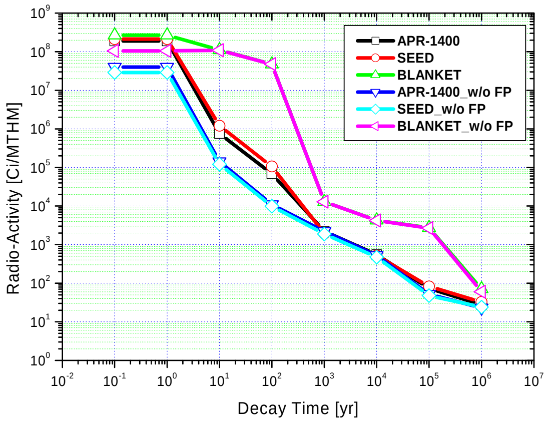


Fig. 11. Radio-Activity vs. Decay Time.

Table 3. Fuel Cycle Costs, [mills/kWe-hr]

Component	APR-1400	KTF Core (11 cycle)		
		Seed	Blanket	
			U	Th
Ore	1.14	1.17	0.07	0.03
Conversion	0.18	0.18	0.01	0
Enrichment	1.79	2.19	0.13	0
Fabrication	0.69	0.30	0.02	0.08
Front End Sum	3.78	3.84	0.34	
Spent Fuel Disposal	1.44	0.57	0.21	
Total Sum	5.23	4.96		

Table 4. Isotope Weight Fraction in the Discharged Fuel Assembly

ISOTOPE	Seed (w/o)	Blanket (w/o)	APR-1400*
Th-232	-	81.2370	-
U-233	-	1.4220	-
U-234	-	0.3929	-
U-235	0.9803	0.1514	0.8292
U-236	1.4955	0.2599	0.6066
U-238	85.5068	8.7150	91.9133
Np-237	0.1416	0.0385	0.0752
Np-239	0.0082	0.0024	0.0093
Pu-238	0.0799	0.0264	0.0343
Pu-239	0.4665	0.1164	0.6145
Pu-240	0.2907	0.0489	0.2696
Pu-241	0.1640	0.0448	0.1837
Pu-242	0.1332	0.0540	0.0832
Am-241	0.0062	0.0015	0.0061
Am-243	0.0375	0.0208	0.0217
Am-242m	0.0001	0.0	0.0001
Cm-242	0.0034	0.0010	0.0024
Cm-244	0.0223	0.0017	0.0095

* : 4.7 w/o enriched UO_2 fuel, B_d = 52.0 MWd/kgHM

Table 5. Proliferation Resistance Indices

INDEX	APR-1400	KTF		
		Seed	Blanket	Average
BCM (kg)	22.54	28.52	32.20	30.36
SNS (#/kg-sec)	4.02E5	4.21E5	3.95E5	4.08E5
TG (Watts/kg)	19.03	43.61	46.83	45.22