ONCE-THROUGH THORIUM FUEL CYCLE OPTIONS FOR THE ADVANCED PWR CORE

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ABSTRACT

The use of once-through thorium fuel cycle was investigated to improve the PWR core performance with respect to fuel utilization, proliferation resistance, and radio-toxicity reduction of spent fuels. In this paper, nuclear core design was performed mainly for thermal high conversion reactors. The concept of the core was based on the seed-blanket unit concept of Radkowsky Thorium Fuel (RTF or RTR). An extensive parametric study examined maximization of the conversion ratio for different cores including the RTF design. The choice of fuel materials included UO_2 ceramic and U-Zr alloy for seed, and $(Th,U)O_2$ MOX for blanket. Parameters in search were fuel composition, enrichment, pin pitch, fuel radius, and seed/blanket configuration.

The optimized design was found to be almost the same as RTF except for a few parameters. The size of seed/blanket unit was modified compared to the conventional PWR assembly unit for the ease of reloading. To benefit the fuel cycle economics, enrichment of uranium was reduced to 6 w/o in seed and 10 w/o in blanket, and U/Zr alloy composition was also modified. Calculation was done for a unit reactor module instead of full core reloading simulation. The conversion ratio of the optimized design showed similar value as the RTF. Potential benefits from this core are considerable from the spent fuel treatment aspect. The total amount of spent fuel could be reduced up to 55% compared to the conventional PWR once-through cycle. The amount of Pu and fissile contents in Pu could be significantly reduced too. These findings demonstrate that this core provides a better proliferation resistance than a conventional PWR. The thermal power unbalance between seed assemblies and blanket assemblies was as high as in RTF.

1. INTRODUCTION

Worldwide attention is beginning to be focused on thorium fuel as an option for the environment-friendly next-generation fuel cycle. Thorium fuel has some favorable aspects compared with uranium or plutonium fuel.[1] The first point is that thorium cycle is the best way for a converter or breeder as a thermal reactor. Thermal reactor option has a strong foundation for the next-generation reactor because of its capability of inherent safety features and its long operational experience. The second factor is related with the proliferation danger of spent fuel. Thorium cycle is not free from proliferation potential, however is much more favorable in plutonium contents in spent fuels as well as decay heat amount and radioactivity level from spent fuels. The third one is the benefit in the amount of long-lived minor actinides production from either once-through cycle option or recycling option. Radio-toxicity level of spent fuel is known to be much less in thorium cycle than the others in case of once-through cycle application for PWR. From now on, the above-mentioned points seem to be very crucial for many developing countries.

On-going R&D programs related to thorium fuel could be classified into three categories. The first active R&D programs are accelerator-driven sub-critical reactor programs in which thorium blanket core is driven by external neutron source. The second category is a program for thermal breeders. In these reactors, on-line fuel reprocessing is essential to remove the fission products and to enhance the conversion process of U-233. The third one is a development of advanced thorium fuel cycle that could be applied to an existing reactor core. One of the examples is the Radkowsky Thorium Reactor (RTR)[2]. This reactor emphasizes the thorium benefits within a bound of once-through cycle PWR applications. The concept is, therefore, to invent a fuel assembly unit (so called Radkowsky Thorium Fuel, RTF) rather than a core.

In this study, a new option for the once-through thorium fuel cycle for the existing PWR core was investigated based on seed/blanket unit concept in RTF. Contrary to RTF, it was assumed that mechanical and hydraulic design for fuel assemblies be the same with conventional PWR except a minor change in nuclear design parameters, such as enrichment of fissile, fissile/fertile volume ratio and radius of fuel pin. A parametric study was performed to find the core optimized with high conversion characteristics and high proliferation resistance. All nuclear calculations were done by the code system HELIOS3 for a unit reactor module consisted with

9 fuel assemblies; separate seed assemblies and blanket assemblies. Refueling simulation was done only for this module for the equilibrium cycle condition of core. Seed fuel assemblies within a module were replaced with fresh fuels when the burnup was reached to the pre-designed level, whereas blanket fuel assemblies stayed as long as possible. Nuclear design characteristics such as conversion ratio, proliferation resistance, spent fuel toxicity, and safety parameters were measured and compared for the optimization. Benefits of the optimized design candidate were investigated comparing with conventional PWR cycle.

2. CORE DESIGN CONCEPT

The goal of this study is the search for an advanced once-through fuel design for PWR which is improved in proliferation resistance as well as fuel cycle cost. The basic approach is to minimize the design changes from the existing PWR fuel assemblies. The core of reference is the conventional PWR core rated as 2,775 MWth and loaded with 157 assemblies.

RTR core is loaded homogeneously with heterogeneous Seed Blanket Units.[2] To enhance neutron moderation, seed fuel pins which are located at inner region are thinner than those of blanket fuel pins as shown in Figure 1. A drawback of this concept is that a fuel assembly has two different regions, which makes refueling procedure complex and tricky. In this study, on the contrary, a separation of seed and blanket was applied for the easiness of refueling and manufacturing. Therefore, reactor core is to be loaded separate seed and blanket assemblies heterogeneously. As shown in Figure 2, each fuel assemblies have the same geometry but different material composition with each other. Therefore, existing refueling procedure can be applied without any changes in hardware.

Compared with the case of uranium-238, the time to the saturation level of U-233 production from thorium-232 conversion is quite long over 5 years. In the once-through thorium fuel cycle, therefore, blanket fuel should be kept in a core for over the period of 5 to 7 seed refueling cycles. However, fresh seed fuels should be refueled to maintain the core excess reactivity as well as the capability of neutron supply to the blanket.[4] Seed fuel assemblies was designed to be replaced annually in the 3 batch cycle with about 900 EFPD discharge rate. Blanket fuel assemblies, however, should stay for about 10 years for the sufficient fissile production.

Candidate materials for seed fuel in this study were UO_2 and U/Zr metal alloy with 5 ~ 20 w/o enrichment. Candidate material for blanket fuel should also be enriched (in RTF case, 20 w/o) for the control of power generation sharing between seed and blanket for the period of initial few years. The U-235 enrichment in thorium blanket is also inevitable for the denaturing of blanket fuel. In the aspect of fuel integrity, core residence time of 10 years for blankets is quite long, however UO_2 ceramic may stand enough because of those low discharge burnup rate.

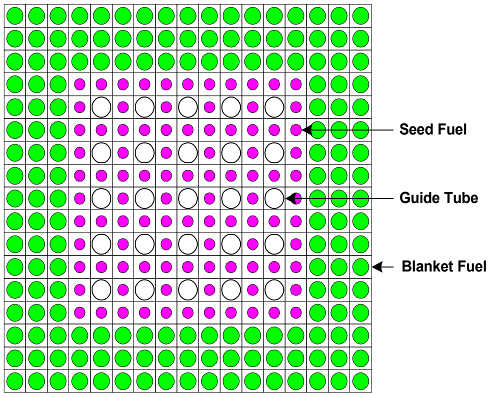

Figure 1. Seed-Blanket Unit (SBU) layout.

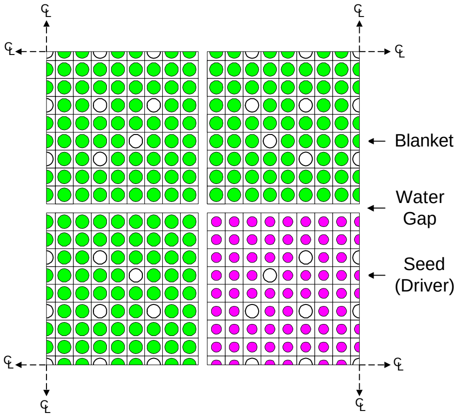

Figure 2. Designed Reactor Unit Module.
(1/4 Size of Module)

3. PARAMETRIC STUDY

A previous study[5] was done for the choice of UO_2 seed fuel. The optimized design showed a feasibility of once-through thorium PWR fuels for the high-conversion. In this study, a more extensive parametric study was performed including the option of RTF design. Reference 5 summarized the effects of each parameter to the fissile inventory ratio (FIR). The parameters in considerations are seed to blanket ratio, fissile to fertile ratio, fuel to moderator ratio, etc. The same procedures were repeated again in this study. The following discussions will be focused only for the new option, that is, U/Zr alloy case.

First of all, conversion characteristics were compared between UO_2 seed and U/Zr metal fuel seed. Table 1 shows reference design parameter in this comparison. Because of higher physical density of metal fuel, excess reactivity of a reactor module is higher in U/Zr case than in UO_2 case as shown in Figure 3. Nevertheless, there was no difference in the production rate of U-233 in blanket as shown in Figure 4, resulting in no change in FIR value in blanket as shown in Table 2. There was a slight increase in overall FIR. It seems to be caused by higher production rate of plutonium in seed region, which is due to higher uranium density in seed metal fuel. This shows that seed material choice is fairly independent to blanket conversion except a conversion effect in seed itself. The choice of U/Zr alloy is more favorable than ceramic because that has higher thermal conductivity and physical density, those are advantageous points for thermal converter.

Table 1. Reference Parameters for the Study for Seed Fuel Material

Seed			Blanket			Pin Pitch
Material	Enrichment	Pin Radius	Enrichment	UO_2 Content	Pin Radius	
UO_2	20 w/o	0.413 cm	20 w/o	10%	0.413 cm	1.285 cm
U/Zr metal						

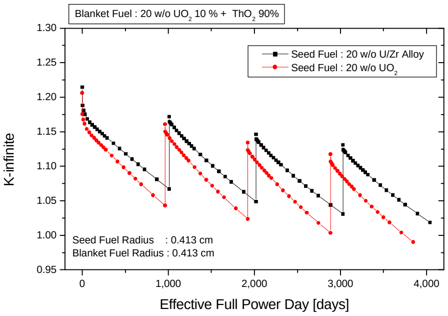

Figure 3. Impact on K-inf. from Seed Material Change

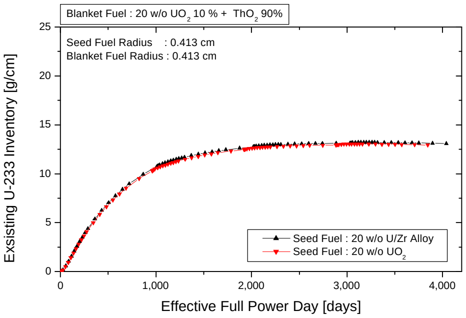

Figure 4. Impact on U-233 Inventory from Seed Material Change.

Table 2. FIR Value Comparison for Seed Material Choices

Seed Material	Blanket					Module				
	Seed Refueling Cycle #				Average FIR	Seed Refueling Cycle #				Average FIR
	1	2	3	4		1	2	3	4	
UO_2	0.901	0.962	1.003	1.002	0.96	0.737	0.743	0.743	0.741	0.74
U/Zr	0.908	0.967	1.000	1.001	0.96	0.782	0.787	0.786	0.783	0.78

Seed fuel used in RTF was known to be U/Zr metal alloy whose uranium content was 20~30% in volume. Uranium enrichment of both seed and blanket are very high up to 20 w/o. For the once-through cycle strategy, this high enrichment level is very disadvantageous in sense of front-end fuel cycle costs. The following table shows this economics. Therefore, a reduction of enrichment level was searched in this study.

Table 3. Front End Fuel Cycle Requirement for RTR and PWR

	U weight (Ton H.M).	Enrichment U-235 %	Natural U (Ton)	SWU (kg SWU)
RTR*	36.8	20	1,337	1,570,591
PWR*	256.6	3.3	1,516	1,215,243

* 2,775 MWth, 157 assemblies or SBU

For the reduction of enrichment, uranium volume content can be raised in U/Zr alloy. A parametric study for the optimum seed fuel composition was done as shown in Table 4. These five cases are fixed to have the same amount of U-235 in a fuel pin.

Table 4. Material Composition Table for U Content Change in U/Zr Metal Fuel

U to Zr volume ratio	Avg. Density [g/cm^3]	Converted Weight Percent (w/o)		
		U-235 <Fissile w/o>	U-238	Zr
10 : 90	7.70	14.81 <60 w/o>	9.88	75.31
30 : 70	10.21	11.17 < 20 w/o>	44.67	44.16
50 : 50	12.72	8.96 <12 w/o>	65.72	25.32
70 : 30	15.23	7.48 <8.57 w/o>	79.84	12.68
90 : 10	17.74	6.43 <6.67 w/o>	89.85	3.62

Figure 5 shows the effect of uranium volume ratio change. As the uranium volume increases, uranium-238 mass in a fuel pin increases resulting in drop of excess reactivity due to neutron capture. This change, however, is favorable in conversion and makes reactor critical with lower uranium enrichment. In the aspect of proliferation-resistance, however, this change is slightly unfavorable due to higher conversion to fissile plutonium. Table 5 shows the change of fuel cycle cost for the SWU. As we may expect, higher uranium volume ratio with less enrichment level case is found to be more favorable in economics.

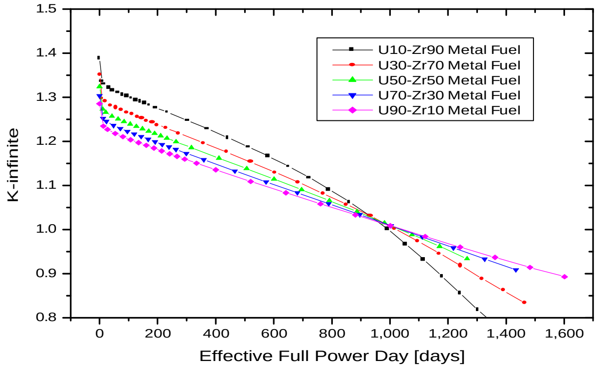

Figure 5. Impact on K-inf. from U content of U/Zr metal fuel

Table 5. Change of Natural U Requirement and SWU to the U content change

Volume Ratio	Loaded U-235 (kg)	Loaded U-238 (kg)	Loaded U (kg)	Required Nat. U (kg)	SWU (kg)
U10-Zr90	15.4	10.3	25.7	3,015	3,820
U30-Zr70		61.8	77.2	2,995	3,536
U50-Zr50		113.4	128.8	2,975	3,322
U70-Zr30		164.9	180.3	2,954	3,134
U90-Zr10		216.4	231.8	2,949	2,984

4. THE OPTIMIZED DESIGN

One of the optimized design options at this stage is as the following. Seed fuel is enriched to 6.0 w/o in U/Zr metal fuel form with fuel radius of 0.33 cm and the size of assembly is the same with conventional PWR assembly. Blanket fuel has 20 % UO_2 (10 w/o enrichment) and 80% ThO_2 MOX. Pellet radius 0.4025 cm. Seed and blanket assemblies are to be loaded in a ratio of 1 to 3 in a checkerboard pattern. The burnable poison design was applied for seed fuel assembly in order to control excess reactivity, but not in blanket fuel assembly. Table 6 shows the design parameters of optimized design.

Conversion characteristics of the core are measured by FIR values. As shown in Table 7, overall FIR value is larger than one of PWR. This value is much less than those of Table 2 where operational compatibility was not concerned. The optimized design shown above has the parameters to be matched for the real world. In Table 8, the required mass of fuel materials for the production of 8,325 GWD was compared with that of PWR. In the optimized design, the amount of uranium required was 83.17 tons that was just 31 % of amount for PWR, 264.33 tons. The heavy metal mass to be discharged after 3,000 EFPD was 111.5 tons which was 44 % of amount from PWR, 254.9 tons. By virtue of thermal conversion, consumed heavy metal mass was 11.32 tons (U-235: 4.20 tons) which was 120 % of amount for PWR, 9.46 tons (U-235: 5.56 tons)

Table 6. Design Parameter of Optimized Design

Parameter	Seed	Blanket
Fuel Assembly Size, cm	21.61	
Fuel Material Composition	U/Zr Metal Fuel U content : 75 % U enrichment : 6.0 w/o	$(Th+U)O_2$ UO_2 content : 20 % U enrichment : 10 w/o
Initial Fuel Weight (kg H.M)	U : 460	Th : 337 , U : 92
Fuel Radius (cm)	0.33	0.4025
Number of Guide Tubes	24 + 1 Central	
Reactivity Control	Control Rod + Burnable Poisons	None

Table 7. FIR Value of the Optimized Design

	Seed Refueling Cycle #				Average FIR
	1	2	3	4	
Optimized Design	0.55	0.60	0.60	0.60	0.58
PWR	0.42				

Table 8. Comparison of Fuel Mass Demand for the Energy Production of 8,325GWD

	Optimized Design	PWR
Effective Operation Day	3,000	3,000
Requirement of Th-232 (Ton)	39.64	0
Requirement of U-238 (Ton)	77.74	256.62
Requirement of U-235 (Ton)	5.43	7.71
Th-232 Mass in Spent Fuel (Ton)	35.70	0
U-238 Mass in Spent Fuel (Ton)	74.57	252.72
U-235 Mass in Spent Fuel (Ton)	1.23	2.15
Actual Consumption of Th-232 (Ton)	3.95	0
Actual Consumption of U-238 (Ton)	3.17	3.90
Actual Consumption of U-235 (Ton)	4.20	5.56

Proliferation resistance could be measured by the amount of plutonium in the spent fuel and its isotopic vector. The total production of plutonium was 0.72 tons from seed and 0.24 tons from blanket that was 51 % of that from PWR, 1.88 tons. Table 9 shows plutonium isotopic vector in the spent fuel. The plutonium fissile contents in spent fuel in both seed and blanket were less than those from PWR and the contents of fertile were larger than those from PWR. This means that proliferation resistance of the optimized design is higher than conventional PWR.

Table 9. Pu Isotopic Vector of Produced Pu in Spent Fuel

	Seed	Blanket	Seed + Blanket	PWR
Pu-238	0.03	0.09	0.07	0.01
Pu-239	0.46	0.39	0.41	0.59
Pu-240	0.28	0.17	0.21	0.21
Pu-241	0.14	0.15	0.15	0.14
Pu-242	0.09	0.20	0.16	0.05

The production amount of long-lived minor actinide was shown in Table 10. As we expected, the total amount of long-lived minor actinide production in the optimized design was much less than those from conventional PWR. Therefore, optimized design core is more environmental-friendly compared with PWR.

Table 10. Minor Actinide Buildup [kg/yr]

	Seed	Blanket	Seed + Blanket	PWR
Np-239	3.9	2.9	6.8	13.1
Am-241	0.2	0.1	0.3	0.8
Am-243	1.1	2.2	3.3	6.2
Cm-242	0.1	0.1	0.2	0.5
Cm-244	0.4	2.4	2.8	2.9
Total	5.7	7.7	13.4	23.5

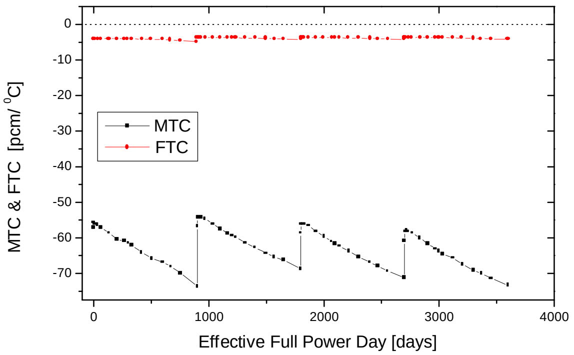

Figure 6. MTC and FTC change of Optimized Design

The loss of U-238 in the core may change the Doppler feedback characteristics, and change of fuel to moderator ration would change the value of moderator temperature coefficient. The following figure shows the inherent safety of optimized design.

One of the unresolved issues in RTF design is to overcome the high mismatch in power sharing between seed region and blanket region. The same situation was observed in this study. The large discrepancy in power generation density is high especially at the initial stage. Figure 7 shows the power distribution across the seed to blanket region at BOC. The maximum to minimum ratio in linear power density was about 5 times. This high tilt in power generation is mitigated as seed fuel is burned and blanket fuel is converted. This problem may be solved by the elaborate nuclear design as the future works. One of the applicable idea is the use of shroud for each assembly just like in BWR core. This makes each channel have different coolant mass flow rate.

Table 11. Peaking factor of optimized design

	Seed	Blanket	Seed + Blanket	PWR
BOC	1.1228	1.1025	2.4575	1.0775
EOC	1.0148	1.0564	1.5375	1.0184

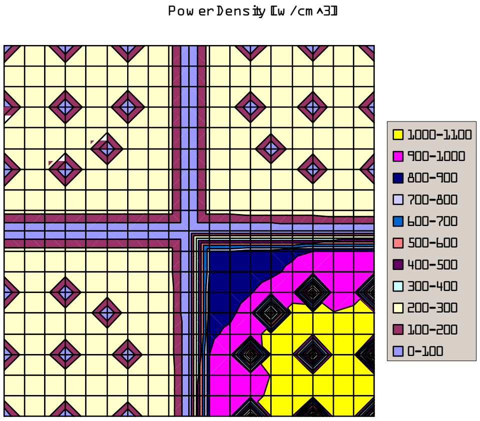

Figure 7. Power density map of optimized design (Module)

5. CONCLUSIONS

A new design concept for once-through thorium fuel assembly was introduced. The conversion characteristic of thorium fuel in PWR was investigated and the optimized designs having high conversion capability as well as proliferation resistance were searched based on results from parametric studies. Proposed designs have advantages as the follows; they

1) have higher conversion ratio than conventional PWR,
2) can reduce amount of spent fuel production evidently,
3) produce smaller amount of plutonium, so it is advantageous in proliferation resistance, and
4) is more environmentally favorable, because of less production of long-lived actinides.

Also, in the aspect of safety, the design can ensure inherent safety due to negative MTC and FTC.

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