A Comparative Study of Recycling Options for High Consumption of TRU using PWR Fuel Assemblies

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1. Introduction

The management of spent fuel has become an important issue due to the continuous operation of light water reactors without the preparation of spent fuel repositories. The use of MOX fuel in light water reactors has been internationally used and many studies [1-3] have been conducted on this topic. Also, it will take a considerable time period at which the recycling of actinides in sodium cooled fast reactors is technically realized in our country even if it is very promising option from view point of reactor physics. Under this situation, recycling of TRU or actinides in PWRs using MOX fuel would be an attractive alternative. However, it has been known that the recycling of TRU in PWR has technical issues such as the void reactivity coefficients, the limitations on the number of recycling due to high radioactivity and heat generations from recycled fuels, and the TRU consumption rates. The second issue should be resolved with the advancements in fuel processing and fabrication technologies and so we do not address this issue in this work. In this work, our goal is to neutronically explore the possible options which can significantly improve the amount of TRU consumption with negative void coefficient up to high level of coolant voiding.

In this work, we extend our previous work on this topic by introducing a PWR fuel assembly design concept having the reduced fuel rods with external TRU feeding to reduce the void reactivity coefficient with the softened spectra and by inter-comparing its performances with the previous fuel assembly concepts.

2. Methods and Results

In this work, the neutronic analyses were done only in the fuel assembly level with the DeCART2D [3] code which was developed at KAERI and the reprocessing modeling of spent fuel was conducted with ORIGEN-2 [4]. The multi-group cross section library is 47 group cross section (DML-E71N047G018-PV01-cr08) which was generated at KAERI based on ENDF/B-VII.r1. The feed TRU composition corresponds to the one of the PWR spent fuel which is discharged with 50 MWD/kg followed by 10 years cooling (4.5 % initial uranium enrichment). This TRU composition was evaluated with ORIGEN-2.

2.1 Assembly Design and Recycling Methods

We considered the 17×17 standard fuel assembly which has 210 MOX rods (UO_2-$TRUO_2$) and 54 FCM rods ($TRUO_2$) (see the configuration given in Fig. 1). In particular, the FCM fuel rods were considered to enhance TRU consumption rate. The fuel assembly dimensions are summarized in Table I. We considered four different fuel assemblies. The first two cases were studied in our previous works and they have exactly the same dimensions as each other but they use different recycling options. The Case 1 assembly recycle all TRUs but the remaining uranium is disposed and the reduced amount of heavy metal is supplemented by 4.95% enriched uranium while the Case 2 fuel assembly supplements the reduced amount of heavy metal by feeding external TRUs to maximize the TRU consumption. The third fuel assembly (i.e., Case 3 fuel assembly) is the same as the Case 2 one except for one thing that it uses the reduced-size fuel rods to reduce the void reactivity coefficient by making the neutron spectrum softer than the Case 2 assembly. We reduced the pellet radius from 0.4095 cm to 0.3795 cm and also accordingly reduced the fuel rod outer diameter from 0.4750 cm to 0.4450 cm without changes in cladding and gap thicknesses. The last case (i.e., Case 4) has further reduced size of fuel rods of which pellet radius is 0.3595 cm, and its feed composition is made of 70% external TRU and 30% enriched uranium.

Table I: Comparison of fuel assembly design parameters.

Design parameter	Case 1 (UO_2 feed)	Case 2 ($TRUO_2$ feed)	Case 3 ($TRUO_2$ feed)	Case 4 (UO_2-$TRUO_2$ feed)
Assembly array	17×17	17×17	17×17	17×17
Number of MOX rods (UO_2-$TRUO_2$)	210	210	210	210
Number of FCM rods ($TRUO_2$)	54	54	54	54
U enrichment in UO_2 pin (wt%)	4.95	4.95	4.95	4.95
U enrichment in MOX pin (wt%)	7.5	7.5	7.5	7.5
Pellet density (g/cm^3)	10.392	10.392	10.392	10.392
Pellet radius (cm)	0.4095	0.4095	0.3795	0.3595
Cladding material	Zircaloy-4	Zircaloy-4	Zircaloy-4	Zircaloy-4
Cladding thickness (cm)	0.0570	0.0570	0.0570	0.0570
Gap thickness (cm)	0.0085	0.0085	0.0085	0.0085
Rod radius (cm)	0.4750	0.4750	0.4450	0.4250
Pin pitch (cm)	1.2234	1.2234	1.2234	1.2234
Assembly pitch (cm)	20.879	20.879	20.879	20.879
TRISO buffer layer thickness (cm)	0.0080	0.0080	0.0080	0.0080
TRISO IPyC layer thickness (cm)	0.0020	0.0020	0.0020	0.0020

TRISO SiC layer thickness (cm)	0.0035	0.0035	0.0035	0.0035
TRISO OPyC layer thickness (cm)	0.0020	0.0020	0.0020	0.0020
TRISO packing fraction (%)	24	24	24	24

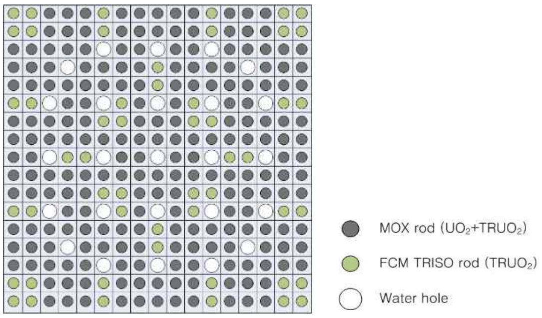
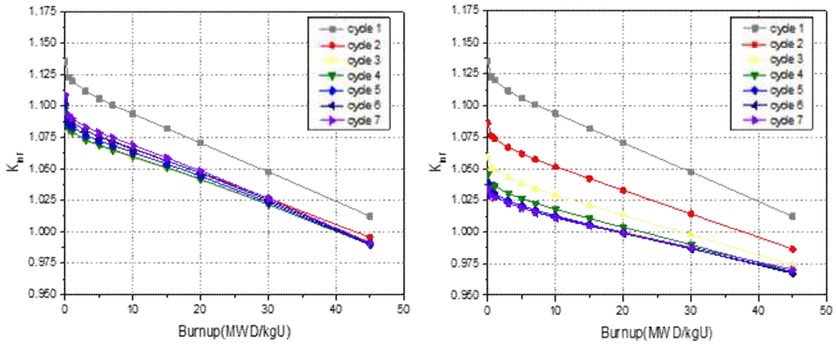


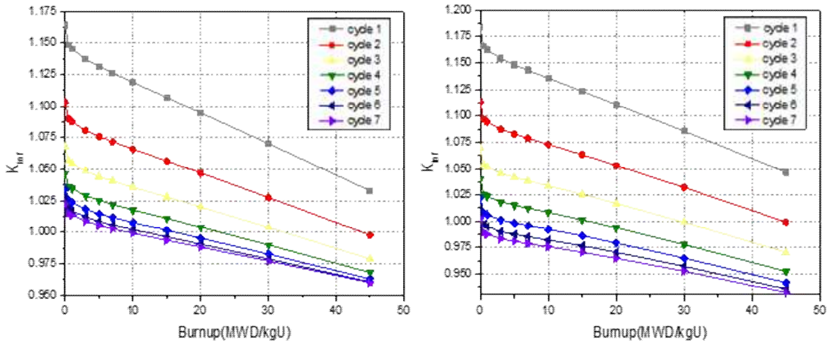
Fig. 1. Configurations of the fuel assemblies

2.2 Neutronic Analysis Results with TRU Recycling

In this section, the physics characteristics such as the evolutions of k_{inf} over recycling cycles, TRU consumptions, and void reactivity coefficients are analyzed and inter-compared for three different fuel assemblies having different recycling methods. First, the evolutions of k_{inf} up to 7th cycle are inter-compared in Fig. 2. It is shown in Fig. 2 that the k_{inf} values of Case 1 decrease as the cycle proceeds and they fast approach the equilibrium state. For the Case 2, there are significant drop in k_{inf} values from 1st cycle to 2nd cycle and from 2nd cycle to 3rd cycle because of the replacement of enriched uranium feed with TRU feed. The comparison of the Case 2 and 3 assemblies shows that the Case 3 assembly has higher initial k_{inf} values up to 3rd cycle but they become smaller over subsequent cycles than the Case 2 one. The initially higher k_{inf} values of the Case 2 assembly up to 3rd cycle are due to the enhanced fission resulted from the enhanced moderation while the smaller k_{inf} values after 3rd cycle are due to the higher neutron absorption by increased amount of minor actinides.



(a) Case 1 (b) Case 2



(c) Case 3 (d) Case 4

Fig. 2. Comparison of k_{inf} value for each cycle of Cases.

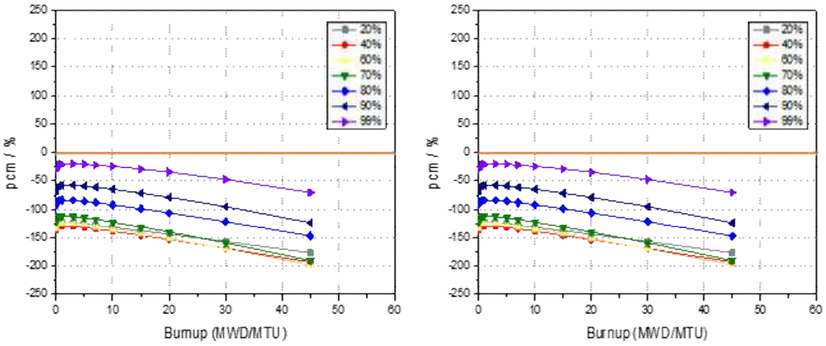
Next, we analyzed the mass flow of TRU nuclides over the cycles and their results are inter-compared in Table II. For the Case 1, the TRU consumption rate of FCM fuel rods for the 1st cycle is estimated to be 27.59% and it gradually increases to 31.00% for the 7th cycle due to the power shifting resulted from the decrease of fissile contents in MOX fuels as recycling. The total consumption rate over all the rods gradually decreases and approaches to ~10%. On the other hand, the Case 2 with $TRUO_2$ supplement shows opposite tendency in TRU consumption rate of FCM fuel rods in comparison with Case 1. That is to say, the TRU consumption rate of FCM fuel rods gradually decreases as recycling and it becomes ~23.9% for 7th cycle but the

TRU consumption rates for MOX fuel pins are higher than the Case 1 and the total TRU consumptions rates are overly higher than the Case 1. The higher TRU consumption rates in MOX pins as recycling for the Case 2 than the Case 1 is due to the external TRU feeding having high fissile contents. But it should be noted that the external feeding of TRU for the Case 2 means the additional consumption of the TRU stocks accumulated and so the Case 2 has superior performances in TRU consumption to the Case 1. This case has very large external TRU consumption of 13.6kg for 7th cycle. Table II shows that the Case 3 assembly has higher TRU consumption rates over all the cycles than Case 2 both for the FCM and TRU fuel pins. This option of Case 3 has the total TRU consumption rates of 15.27% and 10.91 % for the 1st and 7th cycles, respectively. Also, this option uses the TRU feeding of 12.1 kg for 7th cycle. The last option has higher total TRU consumption rates than the Case 3 and external TRU feed of 8.17 kg for 7th cycle.

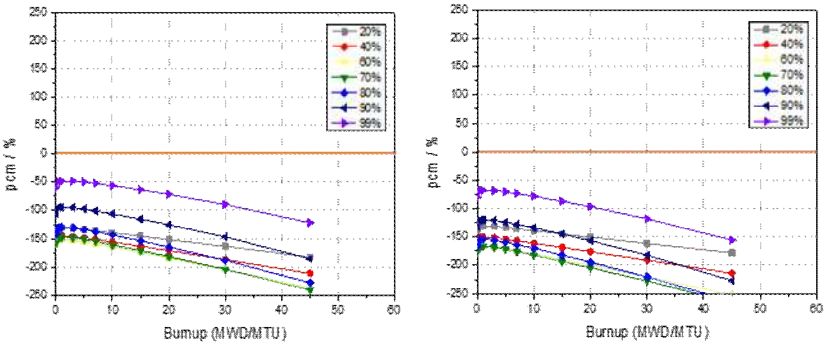
Table II: Comparison of TRU mass flows (kg) for three different fuel assemblies

Cycle		Cycle 1		Cycle 2		Cycle 3		Cycle 4		Cycle 5		Cycle 6		Cycle 7	
Rod type		FCM	MOX	FCM	MOX	FCM	MOX	FCM	MOX	FCM	MOX	FCM	MOX	FCM	MOX
Case1	Charge (kg)	8.63	28.53	8.63	26.15	8.63	24.56	8.63	23.41	8.63	22.53	8.63	21.81	8.63	21.22
	Discharge (kg)	6.25	26.28	6.12	24.73	6.05	23.60	6.01	22.73	5.98	22.01	5.97	21.41	5.95	20.92
	Net increase (kg)	-2.38	-2.25	-2.51	-1.42	-2.58	-0.96	-2.62	-0.69	-2.64	-0.52	-2.66	-0.40	-2.67	-0.31
	TRU consumption rate(%)	27.59	7.88	29.04	5.44	29.87	3.90	30.35	2.93	30.65	2.30	30.85	1.82	31.00	1.45
	Total TRU consumption rate (%)	12.46		11.29		10.65		10.32		10.15		10.05		9.99	
Case 2	Charge (kg)	8.63	28.53	8.63	43.22	8.63	55.55	8.63	66.34	8.63	76.13	8.63	85.23	8.63	93.68
	Discharge (kg)	6.25	26.28	6.31	39.05	6.36	50.14	6.41	60.03	6.47	69.11	6.52	77.64	6.56	85.62
	Net increase (kg)	-2.38	-2.25	-2.32	-4.17	-2.27	-5.41	-2.22	-6.32	-2.16	-7.01	-2.11	-7.59	-2.06	-8.07
	TRU consumption rate(%)	27.59	7.88	26.91	9.65	26.29	9.75	25.68	9.52	25.07	9.21	24.47	8.90	23.92	8.61
	Total TRU consumption rate (%)	12.46		12.53		11.97		11.38		10.83		10.33		9.90	
	TRU feeding (kg)	28.53		14.49		14.10		13.75		13.70		13.60		13.58	
Case 3	Charge (kg)	7.41	24.50	7.41	36.19	7.41	45.99	7.41	54.51	7.41	62.27	7.41	69.41	7.41	76.11
	Discharge (kg)	5.34	21.70	5.36	31.89	5.39	40.76	5.42	48.57	5.46	55.80	5.49	62.53	5.53	68.87
	Net increase (kg)	-2.07	-2.80	-2.05	-4.29	-2.02	-5.24	-1.99	-5.94	-1.95	-6.46	-1.92	-6.88	-1.88	-7.23
	TRU consumption rate(%)	27.97	11.43	27.63	11.87	27.26	11.38	26.84	10.89	26.36	10.38	25.87	9.91	25.39	9.50
	Total TRU consumption rate (%)	15.27		14.55		13.59		12.80		12.08		11.45		10.91	
	TRU feeding (kg)	24.50		12.99		12.53		12.29		12.19		12.21		12.14	
Case 4	Charge (kg)	6.65	21.99	6.65	28.07	6.65	33.05	6.65	37.11	6.65	40.67	6.65	43.77	6.65	46.53
	Discharge (kg)	4.78	19.01	4.71	24.31	4.67	28.67	4.64	32.29	4.63	35.50	4.65	38.36	4.90	40.95
	Net increase (kg)	-1.87	-2.98	-1.94	-3.77	-1.98	-4.38	-2.01	-4.82	-2.02	-5.16	-2.01	-5.41	-1.75	-5.58
	TRU consumption rate(%)	28.13	13.55	29.17	13.42	29.74	13.25	30.21	13.00	30.30	12.69	30.15	12.35	26.27	12.00
	Total TRU consumption rate (%)	16.94		16.44		16.02		15.61		15.17		14.70		13.78	
	TRU feeding (kg)	21.99		9.07		8.74		8.44		8.38		8.26		8.17	

Next, the void reactivity coefficients of four assemblies are analyzed and inter-compared. For example, the void reactivity coefficients for 1st cycle and 7th cycle are compared in Figs. 3 and 4, respectively. For the 1st cycle, the Cases 1 and 2 have the same void reactivity coefficients because they have the same compositions while the Case 3 has more negative void reactivity coefficients than the Cases 1 and 2 due to the soft neutron spectrum resulted from the enhanced neutron moderation. For the 7th cycle, the Case 1 with UO_2 supplement has more negative void coefficients in than the 1st cycle and they are all negative. On the other hand, the Case 2 has positive void reactivity coefficients for all the void fractions higher than 40% even if the 40% voiding of the coolant is impossible except for the accidents while the Cases 3 and 4 also have positive void reactivity coefficients only for higher void fractions than 70% and 90%, respectively, due to the softer neutron spectrum, which means that the softening of spectrum is helpful to mitigate the positive MTC.

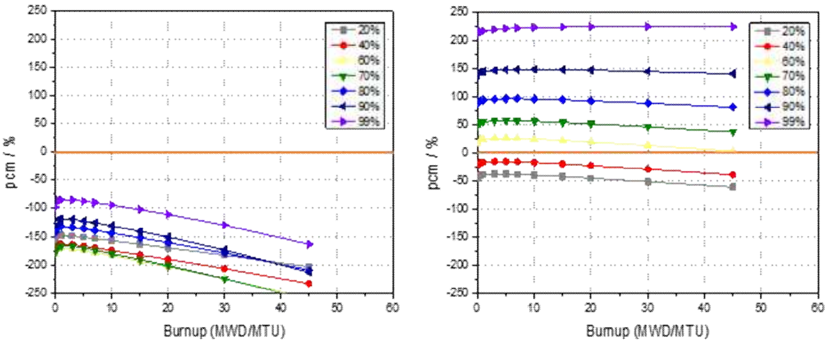


(a) Case 1 (b) Case 2

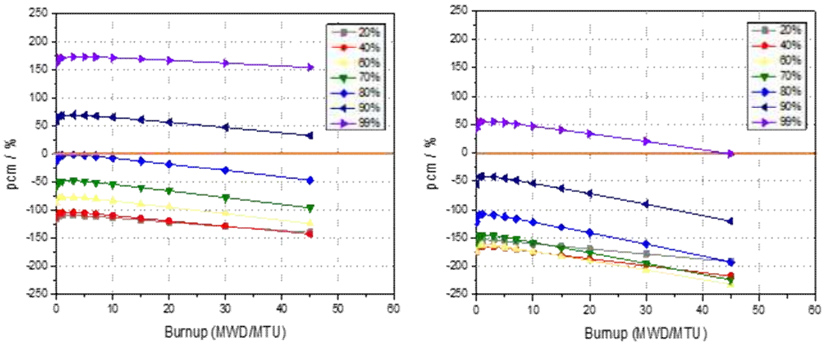


(c) Case 3 (d) Case 4

Fig. 3. Comparison of void coefficients for each cycle of Cases (1st cycle).



(a) Case 1 (b) Case 2



(c) Case 3 (d) Case 4

Fig. 4. Comparison of void coefficients for each cycle of Cases (7th cycle)

3. Conclusions

In this work, the core physics characteristics of three different PWR fuel assemblies with different TRU recycling methods were analyzed and inter-compared. In particular, we considered the TRU recycling with supplement of TRU feeds and reduced size of fuel rods in order to enhance TRU consumption and to mitigate the void reactivity coefficient. The analyzed core physics characteristics include TRU consumption rates, evolutions of k_{inf} over recycles and void reactivity coefficients. The results showed that three assemblies with TRU recycling gives considerable net TRU consumptions over the recycles up to 7th cycle. The TRU recycling with external TRU feed instead of the enriched uranium feeding improves the TRU consumption rates but this option was shown to be problematic in terms of the positive void reactivity coefficients for high level of void fractions. Finally, it was shown that the TRU recycling with TRU feeding and reduced fuel rods mitigates the positive void reactivity coefficients with improved TRU consumption rates. In the future, we are planning to another option of TRU feeding to mitigate the reduction of fuel cycle length and to perform the core-level analysis.

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