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Original Article

Physics analysis of new TRU recycling options using FCM and MOX fueled PWR assemblies

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ABSTRACT

In this work, new multi-recycling options of TRU nuclides using PWR fuel assemblies comprised of MOX and FCM (Fully Ceramic Micro Encapsulated) fuels are suggested and neutronically analyzed. These options do not use a fully recycling of TRU but a partial recycling where TRUs from MOX fuels are recycled while the ones from FCM fuels are not recycled due to their high consumption rate resulted from high burnup. In particular, additional external TRU feed in MOX fuels for each cycle was considered to significantly increase the TRU consumption rate and the finally selected option is to use external TRU and enriched uranium feed as a makeup for the heavy metal consumption in MOX fuels. This hybrid external feeding of TRU and enriched uranium in MOX fuel was shown to be very effective in significantly increasing TRU consumption rate, maintaining long cycle length, and achieving negative void reactivity worth during recycling.

1. Introduction

The safe management of spent fuel generated from PWRs is one of the most important issues in nuclear industry. In particular, in spite of their small amount in PWR spent fuel, TRU (Transuranics) nuclides have significantly contribution to the long-term waste radiotoxicity and heat load on the repository. Therefore, many options to transmutate TRUs have been proposed to reduce the radiotoxicities and decay heat of the waste going to repository. In particular, the fast spectrum reactors such as SFR (Sodium-cooled Fast Reactor) and LFR (Lead-cooled Fast Reactor) coupled with closed fuel cycle have been considered as the promising way for TRU burning due to the good neutron economy and higher fission-to-capture ratio which are resulted from hard neutron spectrum [1–7]. In particular, the important feature of fast spectrum reactors in transmuting TRU is the fact that they can steadily consume TRU fed from the existing PWR spent fuel stocks with closed fuel cycle in which only a quite small amount of TRU (~0.1%) loss during reprocessing go to the repository. The transmutation rate can be maximized with uranium-free fuels by reducing conversion ratio in fast spectrum critical [2,7] or subcritical reactors [1,3]. Also, TRUs recovered from PWR spent fuels can be effectively utilized in ultra-long-cycle fast reactors [8]. However, a fully implementation of TRU burning in fast reactor needs technical maturity to achieve the economic competitiveness and full commercialization. In this situation, recycling in PWRs using MOX fuel would be an attractive alternative because it can be achieved with most of the current PWR technologies. Therefore, the use of MOX fuel in light water reactors also has been internationally researched for TRU burning. However, the core physical characteristics are significantly affected by the multi-recycling of TRUs nuclides due to the reduction of fissile contents in the recycled fuel and spectrum hardening. In particular, the reduction of fissile content leads to a shortening of cycle length which is an important parameter determining economy of the cycle and also the increase of TRU content in the recycled MOX fuels can cause positive void coefficient which could increase power under some accidents related to coolant loss in the core. The usual limit of Pu contents in MOX fuel is ~12 wt% due to the positive void coefficient. The previous works on the recycling of plutonium or TRU include APA (Advanced Plutonium Assembly), CORAIL (Combustible Recyclable A ILot), and CONFU (COmbined NonFertile and Uranium) concepts [10] for stabilizing plutonium or TRU inventories [9–11]. The CORAIL concept [9,11] uses MOX and UO_2 in each assembly giving an advantage that it uses only existing UO_2 and MOX fabrication technologies. The previous works showed that the CORAIL concept has nearly net zero plutonium mass balance (i.e., the consumption of plutonium in MOX fuels are nearly the same as the production in UO_2 fuels). The APA concept [11] uses

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UO_2 fuel rods and large annular rods made up with an IMF (Inert Matrix Fuel) loaded with plutonium and it has high plutonium burning capability of ~60%. However, the implementation of APA requires advanced fabrication technology for large annular fuel rods. The CONFU concept [10] which is similar to a variation of CORAIL using IMF fuels instead of MOX fuels uses UO_2 fuel rods and fertile free fuel (FFF) rods occupying ~20% of the total fuels is suggested to obtain zero net generation of TRU with all neutronic characteristics similar to the standard PWR fuel assemblies. Also, various recycling hypotheses with both full and partial TRU recycling were investigated by Taiwo et al. for plutonium and minor actinide multi-recycling in PWR to analyze various impacts such as proliferation resistance, fuel handling, and repository performance [12]. This study showed that at least seven recycles of TRU can be performed if remote handling of fuel is feasible.

Another option for TRU stabilization was studied using FCM and UO_2 fuel rods in PWR without recycling [13,14]. In this concept, a zero net or small TRU consumption rate was achieved and a very high TRU consumption rate of ~60% was achieved in FCM fuel rods due to the small amount of TRU loading [13]. The high burnup of FCM fuel rods is considered to be acceptable due to their high irradiation performances due to multiple barriers for fission product retention [13–16].

In this work, we suggest new TRU burning strategy using a special PWR fuel comprised of MOX and FCM fuel rods. In this strategy, multi-recycling is applied only for the TRUs discharged from MOX fuel rods while the ones from FCM fuel rods are disposed without recycling. With this strategy, we pursued not only the significant net consumption rate of TRU loading in fuel assembly but also the one of accumulated existing PWR TRU stocks. In Section 2, the computational method for neutronic characteristics coupled with recycling is described and Section 3 describes the detailed analysis and results of recycling options. Finally, the summary and conclusions are given in Section 4.

2. Computational method

The DeCART2D code which was developed at KAERI is used to perform the depletion calculations in the fuel assembly level and to analyze the reactivity coefficients [17]. The mass flows of actinides are analyzed by coupling DeCART2D with ORIGEN-2 [18] for considering the radioactive decays during cooling time. DeCART2D solves the multi-group neutron transport equation using MOC (Method of Characteristics) and it uses the subgroup method for resonance self-shielding treatment. In particular, DeCART2D has a special resonance shielding treatment method based on the Sanchez's method for the FCM fuel pins having double heterogeneities. We used the 47 multi-group cross section library (DML-E71N047G018-PV01-cr08) which was generated by 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. The discharged MOX fuels are assumed to be cooled for 7 years before loading into core. This cooling time includes reprocessing and fuel fabrication times. All fission products are assumed to be removed while TRUs are assumed to be completely recovered during reprocessing even if the reprocessing such as PUREX process is involved with small loss fractions for actinides (e.g., 0.1%). However, it is considered that the neglect of the small loss fractions of TRUs during reprocessing gives only a minor effect on the neutronic analysis. The TRUEX process can be used for our purpose and this process uses centrifugal contactor to mix radioactive tank waste with a solvent containing an extractant.called CMPO which is dissolved in organic solvent [19]. The transuranic elements are extracted into the organic phase and the other waste components remain in the aqueous phase. The transuranic elements are subsequently stripped from the organic phase. The cooling after discharge, and during reprocessing and fuel fabrication are processed using an in-house program and ORIGEN-2 to calculate the composition of the recycled fuel.

3. Recycling analysis and results

3.1. Reference assembly design and recycling method

Before going to the detailed analysis of new recycling strategy using FCM and MOX fuels, two reference fuel assemblies using a reference recycling method are considered to be used as a comparison purpose [20]. The 17 × 17 standard Westinghouse type fuel assembly is considered in this work. The configurations of the reference fuel assemblies are shown in Fig. 1. We assumed that the fuel assemblies are loaded into a 330 MWt SMR (Small Modular Reactor) which consists of 57 fuel assemblies. With this thermal output and 200 cm active fuel height, the average fuel assembly thermal power per 1 cm height is 0.0285 MWt/cm which was used in the fuel assembly depletion calculations using DeCART2D. The first reference fuel assembly (REF-I) consists of 156 UO_2 and 108 MOX (i.e., UO_2-$TRUO_2$) rods while the second one (REF-II) is loaded with all MOX fuel rods. The $TRUO_2$ content in MOX fuels is 9.5 wt% for these two cases. For REF-I, the uranium enrichments in UO_2 and MOX fuels are 4.5 wt% and 0.2 wt%, respectively while the one for MOX fuels in REF-II is 4.5 wt%. Table I summarizes the main design parameters of the reference fuel assembly. The cladding is Zircaloy-4 and fuel pin pitch is 1.2234 cm.

After discharge, we assumed seven years cooling time which includes reprocessing and fuel fabrication and only TRUs are recovered from reprocessing. These recovered TRUs are used in MOX fuel fabrication after mixed with depleted uranium for REF-I or enriched uranium for REF-II to compensate the heavy metal consumption. It should be noted that the TRUs discharged from UO_2 fuels for REF-I are recovered and used in MOX fuels. In MOX fuels, small amount of molybdenum (i.e., 2.5 wt%) is included to improve thermal conductivity [21]. In this scoping calculations, the depletion calculation for each cycle is performed up to 45 MWD/kg even if the infinite multiplication factors (k_{inf}) are below 1.0 over some burnup range lower than 45 MWD/kg. The k_{inf} values for all the cycles up to 7th cycle of REF-I and -II are compared in Fig. 2. As shown in Fig. 2, the k_{inf} values for these assemblies decrease as recycling proceeds and they converge. The decreases in k_{inf} are resulted from the reduction of fissile content in recycled TRUs and from the makeup of TRU with depleted uranium instead of enriched uranium. In particular, the k_{inf} values for the second cycle are significantly reduced in comparison with those of the first cycle. For REF-I, k_{inf} values for 7th cycle are kept above 1.0 up to 22.5 MWD/kg. For the full MOX case (i.e., REF-II), it is noted in comparison with REF-I that longer cycle lengths with lower reactivity swings are achieved due to the enrichment uranium feeding and that the k_{inf} values of 7th cycle over the initial low burnup range are higher than those of the previous cycles. In particular, for REF-II, k_{inf} values for 7th cycle are kept above 1.0 up to 37.5MWD/kg.

Table 2 analyzes the changes of TRU inventories up to 7th cycle for the reference assemblies. In this table, we also considered an additional reference fuel assembly which consists of all UO_2 fuel rods having 4.5 wt% uranium enrichment for comparison. This additional case generates 6.63 kg of TRUs over 45 MWD/kg burnup. On the other hand, REF-I consumes a small amount of TRU (i.e., 0.05 kg) for the first cycle but generates 0.41–0.52 kg TRU for the other cycles while REF-II consumes 1.18–4.28 kg TRU corresponding to 3.78–9.25% TRU consumption rates. It is noted for REF-II that the TRU consumption rate monotonically decreases as recycling

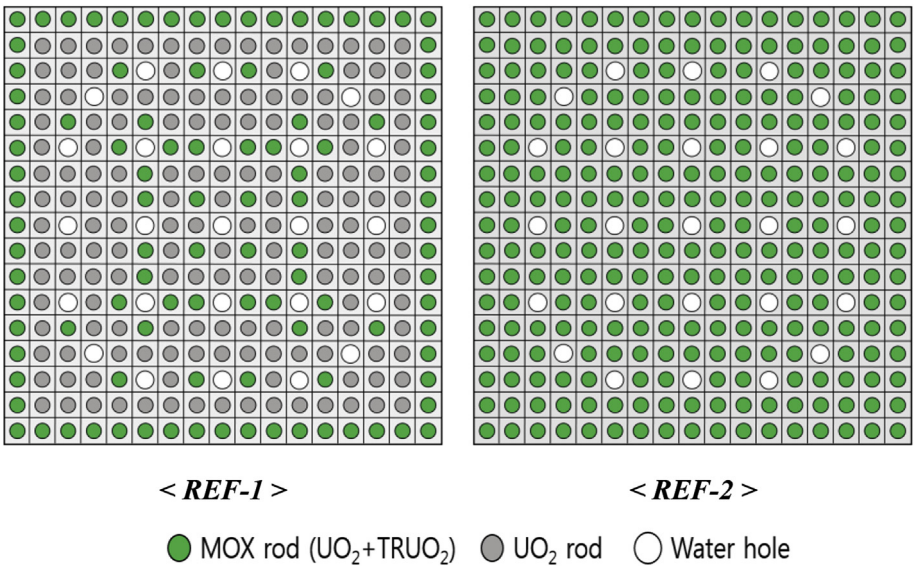


Fig. 1. Configurations of the reference fuel assemblies having no FCM fuel rods.

Table 1
Main design parameters of the reference assemblies.

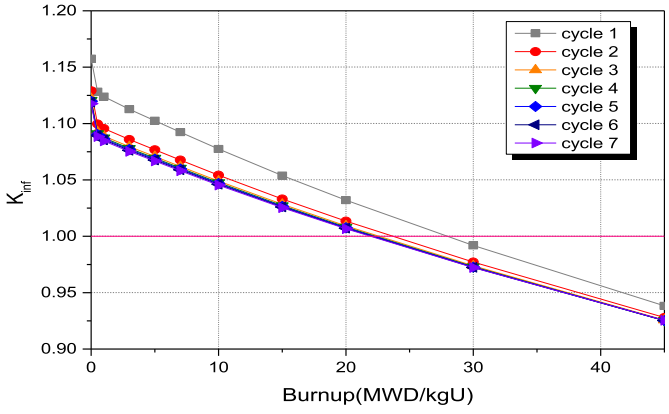
Design parameter	REF-I (Partial MOX)	REF-II (Full MOX)
Assembly array	17 × 17	
Number of UO_2 rods	156	0
Number of MOX rods (UO_2-$TRUO_2$)	108	264
U enrichment in UO_2 pin (wt%)	4.50	-
U enrichment in MOX pin (wt%)	0.20	4.95
$TRUO_2$ content (wt%) in MOX	9.5	
Pellet density (g/cm^3)	10.430	
Pellet radius (cm)	0.4095	
Cladding material	Zircaloy-4	
Cladding thickness (cm)	0.0570	
Gap thickness (cm)	0.0085	
Rod radius (cm)	0.4750	
Pin pitch (cm)	1.2234	
Assembly pitch (cm)	20.879	

due to the reduction of the fissile TRU contents.

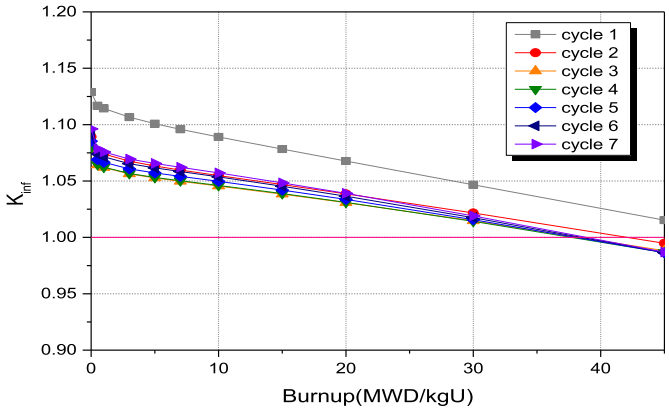
Table 3 compares the minimum and maximum values of void reactivity worth for various void fractions for these reference assemblies during a cycle over which the least negative (or most positive) void reactivity worth occur. The minimum and maximum void reactivity worth represent the minimum and maximum values of void reactivity worth, respectively, over burnup range (i.e., 0–45 MWD/kg) for each void fraction. That is to say, these minimum and maximum void reactivity worth were estimated by comparing the void reactivity worth at various burnup values for a fixed void fraction. This table shows that REF-I has all strong negative void reactivity for all the void fractions up to 99% for 7th cycle while REF-II has positive ones for void fractions higher than 85% for 1st cycle. However, it should be noted that these void reactivity worth will be more negative in the core configuration due to neutron leakage because the present assembly level calculations do not consider neutron leakage.

3.2. Analysis of assembly design with FCM fuel

In this section, new fuel assembly comprised of MOX and FCM fuel rods (MOX-FCM) is introduced and analyzed to increase TRU consumption [20,22,23]. The configurations of this fuel assembly is shown in Fig. 3. The basic dimensions of the fuel rods and assembly



(A) REF-I



(B) REF-II

Fig. 2. Comparison of k_{inf} values up to 7th cycle for the reference cases.

are the same as those of the previous reference assembly. However, the initial composition of MOX fuel is different from that of the previous designs in that the TRU content in MOX fuels is reduced

Table 2
TRU mass changes for each cycle of the reference assemblies.

Cycle		Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6	Cycle 7	All UO_2
REF-I	Charge (kg)	18.94	18.90	19.31	19.83	20.33	20.80	21.26	0.00
	Net decrease (kg)	0.05	−0.41	−0.52	−0.50	−0.47	−0.44	−0.52	−6.63
	Net TRU consumption rate (%)	−0.26	2.17	2.69	2.52	2.31	2.21	−2.45	NA
REF-II	Charge (kg)	46.33	42.04	38.86	36.38	34.36	32.68	31.27	0.00
	Net decrease (kg)	4.28	3.18	2.49	2.02	1.68	1.41	1.18	−6.63
	Net TRU consumption rate (%)	9.25	7.57	6.40	5.55	4.89	4.30	3.78	NA

Table 3
Comparison of void reactivity worth (pcm) at the cycles having least negative void reactivity for the reference assemblies.

Void fraction (%)	*REF-I (7th cycle)*		*REF-II (1st cycle)*	
	Max. void reactivity (pcm)	Min. void reactivity (pcm)	Max. void reactivity (pcm)	Min. void reactivity (pcm)
10	−1526	−2258	−932	−1375
30	−5520	−8145	−2959	−4304
50	−11234	−16531	−5026	−7867
60	−14912	−21889	−4129	−7468
80	−23658	−34063	−1952	−5446
85	−26665	−36246	−784	−4274
90	−27968	−38817	722	−2361
99	−33098	−43146	4825	2934

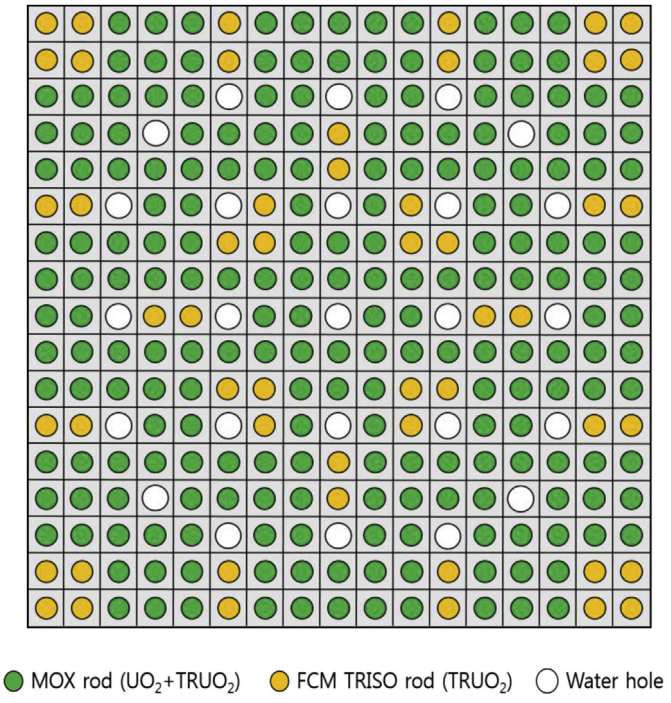


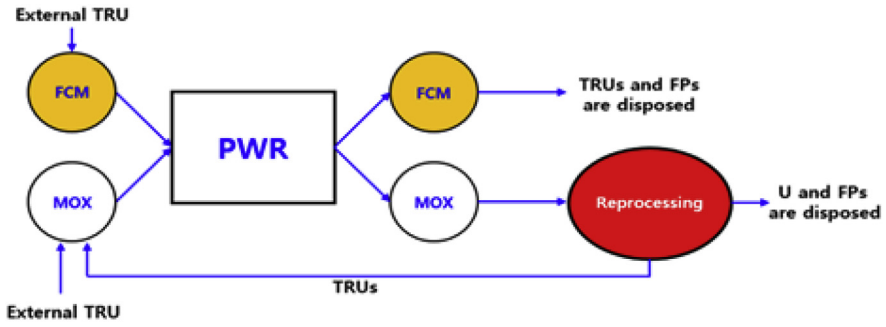
Fig. 3. Configuration of the MOX-FCM assembly.

from 9.5 wt% to 7.5 wt% in order to mitigate the degradation of the reactivity coefficients due to large TRU loading. The number of FCM rods is 52 and the remaining rods (212 rods) are MOX fuel ones. The FCM fuel rod is comprised of fuel clad and fuel compact [13–16]. In the fuel compact of FCM fuel, the TRISO fuel particles are randomly distributed in SiC matrix and TRUs are loaded as the oxide form (i.e., $TRUO_2$) into the kernels of the TRISO particles. The kernel of TRISO particle fuel is successively surrounded by 80 μm thick buffer, 20 μm thick inner PyC, 35 μm thick SiC, and 20 μm thick outer PyC layers. This feature of FCM fuel leads to the superior safety characteristics to the UO_2 fuel such as the high mechanical stability, good thermal conductivity, and high fission gas retention. The much higher thermal conductivity of FCM fuel due to higher thermal conductivity of SiC matrix than UO_2 fuel significantly lowers fuel centerline temperature. With the small amount loading of TRUs without uranium in FCM fuel, it will lead to a very high burnup, which will be effective in increasing the consumption rate of TRU, if the similar power level to the MOX fuel is kept in the FCM rods. In this work, a large kernel size of 800 μm diameter for TRISO particle fuels and 40% PF (Packing Fraction: volume fraction of TRISO fuel particles in SiC compact) in FCM fuels are considered based on recommendation as a reference design data with consideration of fabrication aspects by ORNL [24,25].

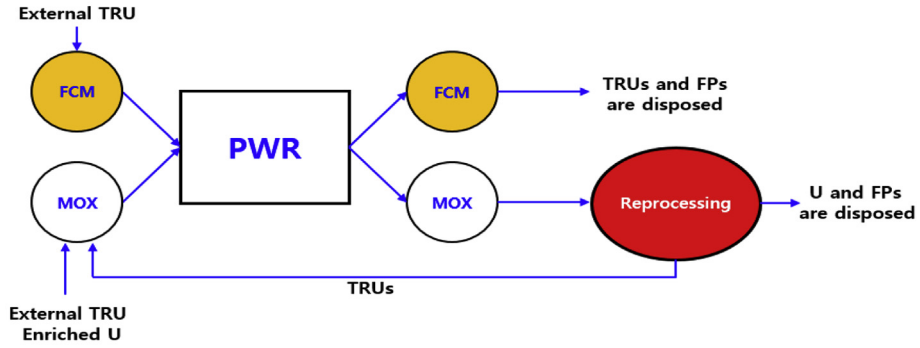
In this section, two different recycling options are considered for new fuel assemblies with MOX and FCM fuels. Fig. 4 schematically explains these recycling options. In the both options, MOX fuels are cooled down for 7 years and then all TRUs are recovered through reprocessing and loaded into new MOX fuels mixed with the additional external feed materials in the next cycle while FCM fuels are disposed into repository after cooling and new FCM fuels are loaded for each cycle. For both options, the spent uranium is not recycled. The difference between these two options is in the composition of the additional external feed composition. The first option (MOX-FCM-R1) uses only TRUs from the existing PWR spent fuel stocks as the additional external feed in MOX fuels while the second one (MOX-FCM-R2) uses not only TRUs from the existing PWR spent fuel stocks but also enriched uranium.

The goal of MOX-FCM-R1 is to increase TRU consumption by increasing TRU loading in MOX fuels. For this option using pure TRU external feed in MOX fuels, we considered two different sub-options having different rod diameters to analyze the effects of moderation on the neutronic parameters including TRU consumption rate. Table 4 summarizes the main design parameters of the MOX-FCM-R1 fuel assemblies. The first sub-option (MOX-FCM-R1-1) uses the reference design data of 0.4095 cm pellet radius and 0.4750 cm rod radius described above while the second one uses thin fuel rods of 0.3922 cm pellet radius and 0.4577 cm rod radius.

Fig. 5 compares the evolutions of k_{inf} values for these cases and Table 5 compares TRU mass changes up to 7th cycle. The slightly higher initial reactivity for 1st cycle than the full MOX fuel case (i.e., REF-II) is due to the higher TRU inventory and the fact that TRU has higher reactivity worth than the UO_2 fuel. It is noted that the k_{inf}



(A) MOX-FCM-R1



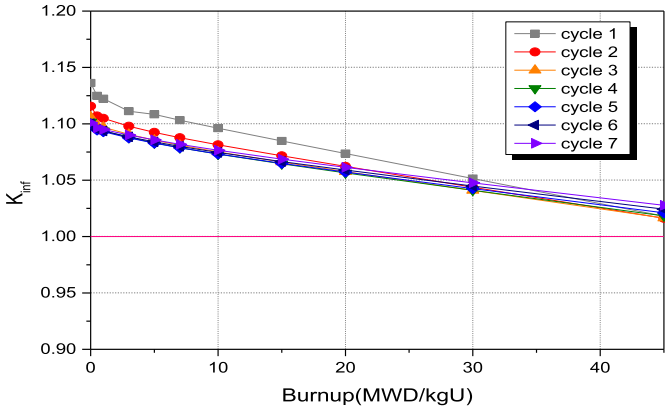
(B) MOX-FCM-R2

Fig. 4. Schematic view of the recycling methods for MOX-FCM options.

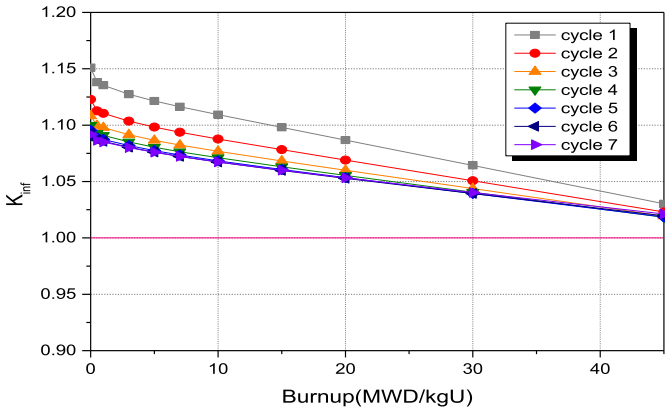
Table 4
Comparison of design parameters for the MOX-FCM-R1 option fuel assemblies.

Design parameter	MOX-FCM-R1-1	MOX-FCM-R1-2
Assembly array	17 × 17	
Number of MOX rods (UO_2-$TRUO_2$)	212	
Number of FCM rods ($TRUO_2$)	52	
U enrichment in UO_2 pin (wt%)	4.95	
$TRUO_2$ content in MOX pin (wt%)	7.5	
Pellet density (g/cm^3)	10.392	
Pellet radius (cm)	0.4095	0.3922
Cladding material	Zircaloy-4	
Cladding thickness (cm)	0.0570	
Gap thickness (cm)	0.0085	
Rod radius (cm)	0.4750	0.4577
Pin pitch (cm)	1.2234	
Assembly pitch (cm)	20.879	
TRISO buffer layer thickness (cm)	0.0080	
TRISO IPyC layer thickness (cm)	0.0020	
TRISO SiC layer thickness (cm)	0.0035	
TRISO OPyC layer thickness (cm)	0.0020	
TRISO packing fraction (%)	40	

values for both cases are maintained above 1.0 over a burnup range higher than 40MWD/kg for all the cycles up to 7th cycle. The longer cycle lengths of MOX-FCM-R1 for the subsequent cycles are also due to the external TRU feed to makeup the actinide consumption in MOX fuel and in FCM fuels. The comparison of these two sub-options shows that the reduced rod size case has higher initial reactivity for 1st cycle than the original rod size one due to higher moderation but they have lower reactivity for the other cycles. Table 5 shows these new options have significantly higher total TRU consumption rates ranging from 8.4% to 13.3% depending on the number of recycling than the previous full MOX option. Similar to the full MOX option, the total TRU consumption rate monotonically decreases as recycling. The total TRU consumption rate means the net consumption rate of TRU over a cycle in all the fuel rods and it is calculated as the ratio of the difference between the charged and discharged TRU inventories to the charged TRU inventory. It is also noted in Table 5 that FCM fuel rods have higher TRU consumption rate ranging 17.3%–22.4% than MOX ones having 6.6%–8.9% TRU consumption rates while TRU consumption in MOX fuel rods gradually increases as recycling due to the external feeding and TRU consumptions in MOX fuel rods are higher than those in the FCM fuel rods. The comparison of MOX-FCM-R1-1 and −2 shows that the use of the reduced rod size gives higher TRU consumption rates both in MOX and FCM fuel rods. These higher TRU consumption rates of the reduced rod size option are resulted from the initially lower TRU loading and soft neutron spectrum by higher moderation. From this comparison, it is also noted that the amounts of external TRU feeding for the reduced rod size case except for the first cycles are higher than those for the reference rod size one. So, the reduced rod size option gives favorable features such as higher TRU consumption rate, higher TRU consumption of existing PWR spent fuel stocks (i.e., higher external TRU feeding), and a lower amount of TRU wastes from FCM fuel rods going to repository without reprocessing. In this work, we used this reduced rod size option in the further study even if the rod size should be determined with consideration of many different aspects such as fuel integrity and thermal hydraulics performances. This reduced rod size option (i.e., MOX-FCM-R1-2) has TRU consumption rates of



(A) Original rod size (r_{rod}=0.4750 cm)



(B) Reduced rod size (r_{rod}=0.4450 cm)

Fig. 5. Comparison of k_{inf} values up to 7th cycle for the MOX-FCM-R1 options.

17.8% and 7.4% for FCM and MOX rods, respectively, which correspond to 2.35 and 6.65 kg TRU consumptions over 7th cycle. In addition, this option consumes 17.6 kg of external TRU over 7th cycle.

Table 6 summarizes the void reactivity worth for these two options for 7th cycle over which the void reactivity worths are least negative. Table 6 shows that the positive void reactivity worth occurs even at a low void fraction of 30% for the reference rod size case while they are all negative even up to 85% void fraction for the previous full MOX case. On the other hand, the reduced rod size option has slightly better void reactivity worth because it has negative void reactivity worth for 30% void fraction. From our previous work [20,22,23], it was shown that the positive void worth for higher void fraction is mainly contributed from the reduction of capture rate in ^{238}U, ^{240}Pu, ^{242}Pu, and minor actinides, which is resulted from spectrum hardening.

We also analyzed the effect of the reduced rod size on the reactivity coefficients (i.e., MTC (Moderator Temperature Coefficient) and FTC (Fuel Temperature Coefficient)) which are given in Fig. 6. The reactivity coefficients are evaluated only for 1st and 7th cycles. As shown in Fig. 6., the new design option having reduced rod diameter (i.e., MOX-FCM-R1-2) has more negative MTC at 1st and 7th cycles, more negative FTC at 7th cycle, but slightly less negative FTC at 1st cycle than the reference one (i.e., MOX-FCM-R1-1). Also, it is noted that the differences in the reactivity coefficients are significantly large for 7th cycle in comparison with those for 1st cycle.

The MOX-FCM-R2 recycling option using a mixture of TRU and enriched uranium as an external feed is considered to improve void reactivity worth. We considered three different sub-options having different external feed compositions: 1) 70% TRU and 30% enriched uranium (MOX-FCM-R2-1), 2) 50% TRU and 50% enriched uranium (MOX-FCM-R2-2), and 3) 30% TRU and 70% enriched uranium (MOX-FCM-R2-3). These cases use the reduced rod size considered above. Uranium enrichment for external feed is also 4.95%. Fig. 7 compares the evolutions of k_{inf} values up to 7th cycle for the MOX-FCM-R2-1 case having external feed of 70% TRU and 30% enriched uranium. The comparison of this case with the previous full TRU external feed case (i.e., MOX-FCM-R1-1) shows that k_{inf} values for this case more rapidly decrease as recycling than the full TRU external feed case due to its reduced TRU feeding. Fig. 8 compares the evolutions of k_{inf} values for the sub-options of MOX-FCM-R2 over 7th cycle. From this figure, it is noted that there are no significant differences in k_{inf} values except for the observation that the slopes of k_{inf} evolution curves increases as enriched uranium content increases. In all the cases, k_{inf} values are maintained above 1.0 up to burnups larger than 40MWD/kg.

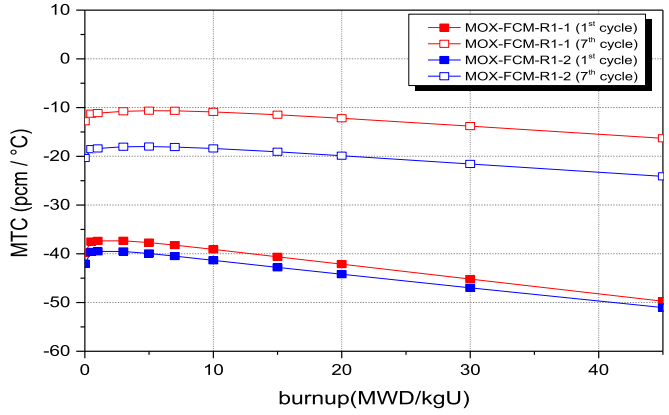
Table 7 summarizes the TRU inventories in the charged and discharged fuels and TRU consumption rates for these cases. From this table, it is noted that the cases having higher enriched uranium content in external feed show higher total TRU consumption rate and higher TRU consumption rate in FCM fuels due to the lower fissile contents in MOX fuels. For example, the last case having 30% TRU and 70% enriched uranium in external feed has 22.3% and 7.2% TRU consumption rates in FCM and MOX fuel rods, respectively, which corresponds to 11.1% total TRU consumption rate for 7th cycle, and this case consumes 7.2 kg TRU through external feeding of TRU from the existing PWR spent fuel stocks.

Table 5
Comparison of mass change (kg) for each cycle of the MOX-FCM-R1 options.

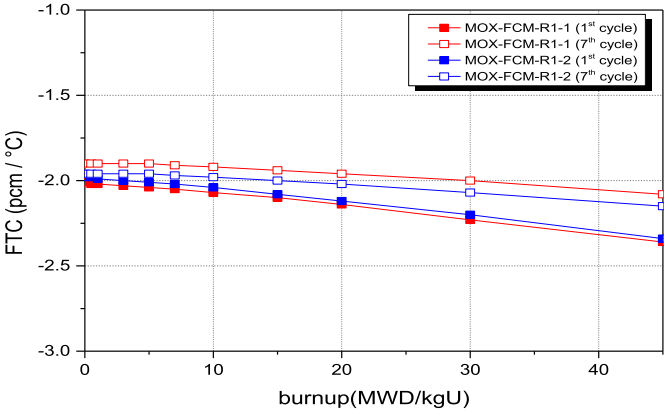
Cycle		Cycle 1		Cycle 2		Cycle 3		Cycle 4		Cycle 5		Cycle 6		Cycle 7	
Rod type		FCM	MOX	FCM	MOX	FCM	MOX	FCM	MOX	FCM	MOX	FCM	MOX	FCM	MOX
MOX-FCM-R1-1	Charge (kg)	14.38	28.53	14.38	43.02	14.38	56.11	14.38	68.22	14.38	79.52	14.38	90.25	14.38	100.4
	Net decrease (kg)	3.22	1.88	2.98	3.33	2.83	4.39	2.72	5.23	2.62	5.95	2.55	6.58	2.48	7.13
	TRU consumption rate (%)	22.38	6.61	20.74	7.74	19.68	7.82	18.88	7.66	18.25	7.48	17.72	7.29	17.27	7.10
	Total consumption rate (%)	11.89		10.99		10.24		9.62		9.13		8.72		8.37	
	External TRU feed (kg)	42.91		27.68		26.28		25.3		24.49		23.92		23.34	
MOX-FCM-R1-2	Charge (kg)	13.19	26.17	13.19	38.83	13.19	50.42	13.19	61.14	13.19	71.20	13.19	80.68	13.19	89.73
	Net decrease (kg)	2.97	2.26	2.78	3.45	2.65	4.34	2.55	5.05	2.47	5.66	2.40	6.18	2.35	6.65
	TRU consumption rate (%)	22.48	8.64	21.04	8.89	20.06	8.60	19.31	8.25	18.71	7.94	18.22	7.66	17.78	7.41
	Total consumption rate (%)	13.28		11.97		10.98		10.22		9.63		9.15		8.74	
	External TRU feed (kg)	39.36		25.85		24.78		23.91		23.25		22.67		22.24	

Table 6
Comparison of void reactivity worth (pcm) at the cycles having least negative void reactivity for the MOX-FCM-R1 options (7th cycle).

Void fraction (%)	*MOX-FCM-R1-1 (7th cycle)*		*MOX-FCM-R1-2(7th cycle)*	
	Max. void reactivity (pcm)	Min. void reactivity (pcm)	Max. void reactivity (pcm)	Min. void reactivity (pcm)
10	−21	−176	−242	−435
30	570	115	−172	−779
50	2626	1976	1326	364
60	4545	3895	3022	1975
80	11,219	10,480	9612	8863
90	16,906	15,725	15,450	14,521
99	25,952	23,716	25,062	23,233



(A) MTC



(B) FTC

Fig. 6. Comparison of reactivity coefficients for the MOX-FCM-R1 options (1st and 7th cycles).

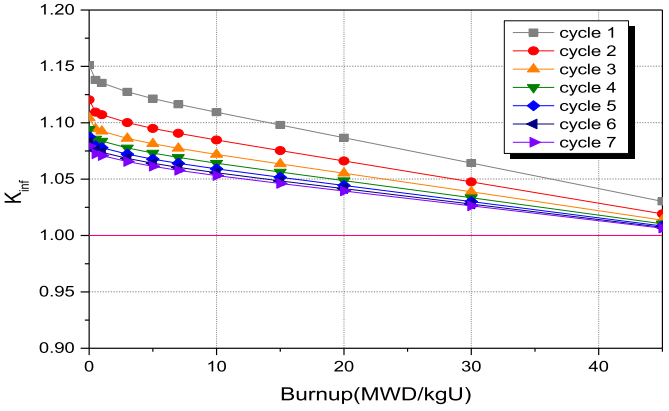


Fig. 7. Comparison of k_{inf} values for each cycle for the MOX-FCM-R2-1 option.

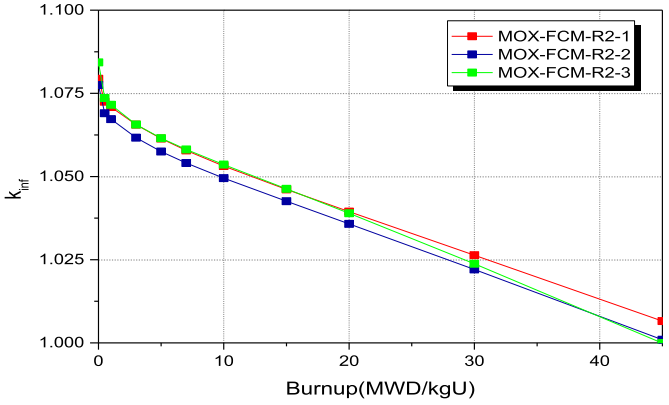


Fig. 8. Comparison of k_{inf} values for each cycle of the MOX-FCM-R2 options (7th cycle).

Table 8 summarizes void reactivity worth for these sub-options for various void fractions ranging from 10 to 99% for 7th cycle over which the least negative void reactivity worth occur. This table shows that the void reactivity worth can be improved by reducing TRU content in the external feed. For example, the last case having 30% TRU and 70% enriched uranium in external feed shows negative void reactivity worth even for 85% voiding. From these analysis, we consider this case (i.e., MOX-FCM-R2-3) as the final candidate because it has high TRU consumption rate (in particular, higher TRU consumption rate in FCM rods) and it can keep negative void reactivity up to high void fraction.

Finally, we analyzed the last case (i.e., MOX-FCM-R2-3) with the cycle-dependent cycle lengths which are determined to maintain k_{inf} above 1.02 for consideration of reactivity loss with neutron leakage and calculation uncertainties in 3D core situation. Fig. 9 compares the evolutions of k_{inf} values up to 7th cycle. As expected, the cycle length decreases from 1049 (32 MWD/kg) to 984 EFPDs (Effective Full Power Days) (30 MWD/kg) as recycling proceeds and the cycle length is almost converged at 7th cycle.

Fig. 10 compares the evolutions of two reactivity coefficients (i.e., MTC and FTC) for 1st and 7th cycles. As shown in Fig. 10., MTCs are all negative over all the considered burnup ranges for both cycles and 7th cycle has less negative MTCs than 1st cycle. The MTC values range from ~50 pcm/°C to ~ −35.9 pcm/°C. FTCs are also all negative and 7th cycle has more negative FTCs than 1st cycle.

The void reactivity worth as function of burnup is analyzed and given in Fig. 11 for various void fractions for 7th cycle. As shown in

Table 7
Comparison of mass change (kg) for each cycle of the MOX-FCM-R2 options.

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
MOX-FCM-R2-1	Charge (kg)	13.19	26.17	13.19	34.32	13.19	41.83	13.19	48.80	13.19	55.23	13.19	61.23	13.19	66.79
	Net decrease (kg)	2.97	2.26	2.87	2.93	2.78	3.52	2.71	4.02	2.65	4.46	2.60	4.85	2.56	5.18
	TRU consumption rate (%)	22.48	8.64	21.73	8.55	21.08	8.41	20.54	8.25	20.10	8.08	19.71	7.92	19.39	7.75
	Total consumption rate (%)	13.28		12.21		11.45		10.86		10.40		10.01		9.67	
	External TRU feed (kg)	39.36		21.34		20.70		20.16		19.62		19.19		18.75	
MOX-FCM-R2-2	Charge (kg)	13.19	26.17	13.19	31.31	13.19	36.15	13.19	40.58	13.19	44.67	13.19	48.47	13.19	51.97
	Net decrease (kg)	2.97	2.26	2.93	2.55	2.89	2.90	2.84	3.23	2.80	3.53	2.76	3.80	2.73	4.04
	TRU consumption rate (%)	22.48	8.64	22.23	8.15	21.87	8.01	21.53	7.96	21.22	7.90	20.95	7.85	20.70	7.77
	Total consumption rate (%)	13.28		12.33		11.72		11.29		10.94		10.65		10.39	
	External TRU feed (kg)	39.36		18.33		18.03		17.62		17.28		16.99		16.69	
MOX-FCM-R2-3	Charge (kg)	13.19	26.17	13.19	28.30	13.19	30.53	13.19	32.66	13.19	34.64	13.19	36.45	13.19	38.10
	Net decrease (kg)	2.97	2.26	3.01	2.14	3.01	2.21	2.99	2.34	2.97	2.49	2.95	2.63	2.94	2.76
	TRU consumption rate (%)	22.48	8.64	22.78	7.55	22.79	7.23	22.68	7.17	22.54	7.18	22.39	7.22	22.27	7.24
	Total consumption rate (%)	13.28		12.39		11.92		11.63		11.42		11.25		11.11	
	External TRU feed (kg)	39.36		15.32		15.42		15.32		15.17		15.00		14.84	

Table 8
Comparison of void reactivity worth (pcm) at the cycles having least negative void reactivity for the MOX-FCM-R2 options.

Void fraction (%)	*MOX-FCM-R2-1 (7th cycle)*		*MOX-FCM-R2-2 (7th cycle)*		*MOX-FCM-R2-3 (7th cycle)*	
	Max. void reactivity (pcm)	Min. void reactivity (pcm)	Max. void reactivity (pcm)	Min. void reactivity (pcm)	Max. void reactivity (pcm)	Min. void reactivity (pcm)
10	−567	−840	−809	−1141	−1055	−1441
30	−1329	−2240	−2233	−3386	−3200	−4593
50	−901	−2500	−2746	−4898	−4848	−7605
60	202	−1673	−2200	−4843	−5045	−8570
80	5730	5066	2198	−857	−2274	−6897
85	9647	7298	4328	1448	−516	−5093
90	11,066	10,238	7030	4495	1804	−2481
99	23,509	21,766	14,631	13,195	8246	5123

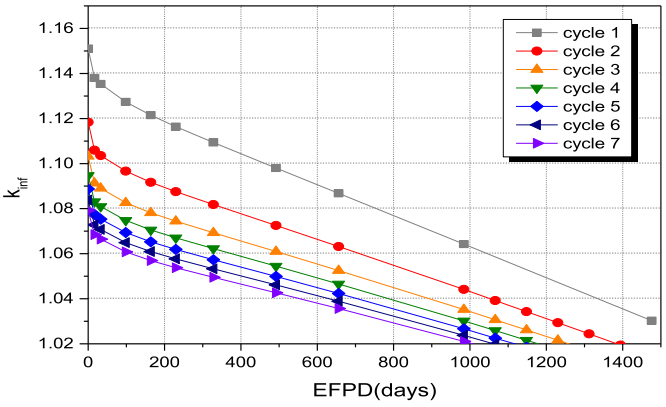


Fig. 9. Comparison of k_{inf} values for each cycle of the MOX-FCM-R2-3 with different cycle lengths.

Fig. 11., the void reactivity worth becomes more negative as burnup except for the very initial burnup stages and void reactivity worths are negative over all the considered burnup range except for 90% and 99% void fractions.

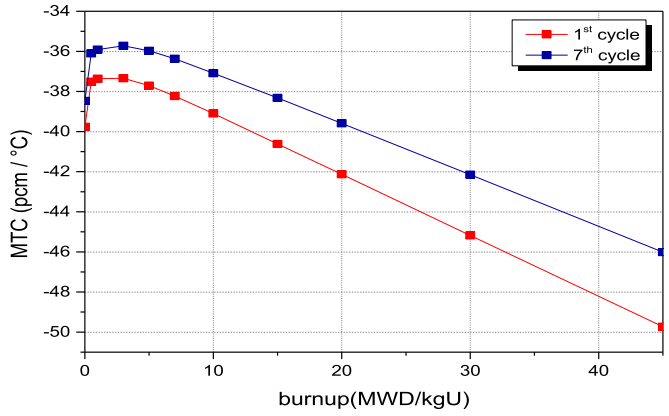
Fig. 12 compares the evolutions of void reactivity worth (pcm) with 80% void fraction as depletion for all the cycles up to 7th cycle. This figure is given to show how the void reactivity changes as recycling proceeds. This figure shows that the void reactivity worth with 80% void fraction becomes less negative as recycling proceeds and the void reactivity worth are negative for all the cycles over the considered burnup range.

Next, we analyzed the evolutions of the pin power peaking factors which are directly related with the MDNBR (Minimum Departure from Nucleate Boiling Ratio). Large pin power peaking factors reduce MDNBR, which reduces thermal margins. In particular, pin power peaking factor can be large in comparison with the typical UO_2 fuel assemblies due to the heterogeneous loading of FCM and MOX fuel rods in our concept. Fig. 13 compares the evolution of the pin power peaking factors for 1st and 7th cycles. As shown in Fig. 13., the pin power peaking factors are less than 1.112 for 1st cycle while they are less than 1.104 for 7th cycle. The levels of pin power peaking factors are considered not to be significantly higher than those of the typical UO_2 fuel assemblies.

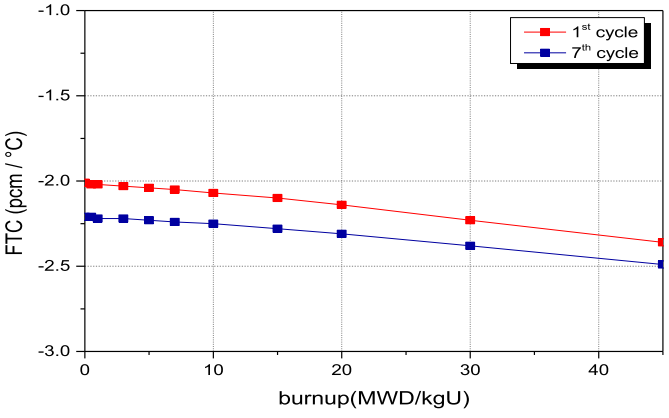
Next, the TRU inventories of charged and discharged fuels and TRU consumption rates are analyzed and summarized in Table 9. The total TRU consumption rate decreases from 13.3% to 8.0% as recycling proceeds. FCM and MOX fuel rods have 22.45% and 8.6% TRU consumption rates for 1st cycle while they have 16.5% and 4.9% for 7th cycle. The amount of external TRU feeding monotonically decreases from 39.36 kg for 1st cycle to 16.22 kg for 7th cycle.

Table 10 summarizes the overall mass balances of TRU and U through 1st to 7th cycles. Total 2217.3 kg enriched uranium is externally fed through MOX fuels and 88.4 kg uranium is consumed. The consumptions of TRU through MOX and FCM fuels are 13.5 kg and 17.8 kg, respectively, which leads to 22.3% overall TRU consumption rate while 74.6 kg TRU are discharged through FCM fuels through 1st to 7th cycles and 34.9 kg TRU is discharged through MOX fuels after 7th cycle. These discharged TRU (i.e., 109.5 kg) should be disposed to a final geological repository.

Table 11 shows the change of the TRU composition of discharged MOX fuels as recycle proceeds. As shown in this table, the contents of ^{237}Np, ^{239}Pu, and ^{241}Pu decrease as recycling (i.e., fissile content in TRU decreases as recycling) while those of ^{238}Pu, ^{242}Pu,



(A) MTC



(B) FTC

Fig. 10. Comparison of reactivity coefficients for the MOX-FCM-R2-3 option with different cycle lengths (1st and 7th cycles).

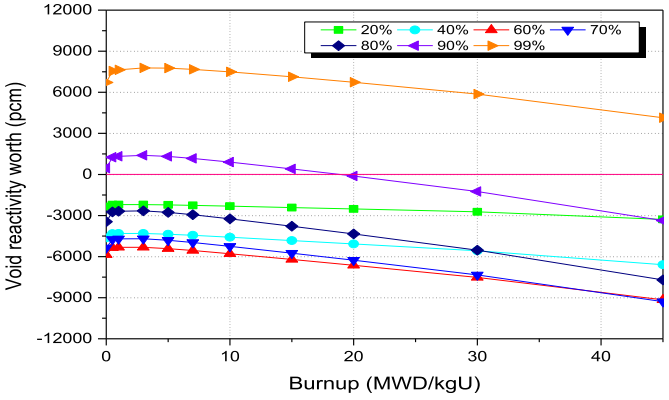


Fig. 11. Comparison of void reactivity worth (pcm) for the MOX-FCM-R2-3 option with different cycle lengths (7th cycle).

^{241,242m,243}Am, and ^{244,242,244,245,246}Cm increases as recycling. On the other hand, it is noted that the content of ^{240}Pu very slightly changes as recycling.

Finally, we analyzed the radioactivity and decay heat of 1 kg TRU in the FCM fuels discharged from each cycle and they are compared in Figs. 14 and 15, respectively. As shown in these figures, recycled

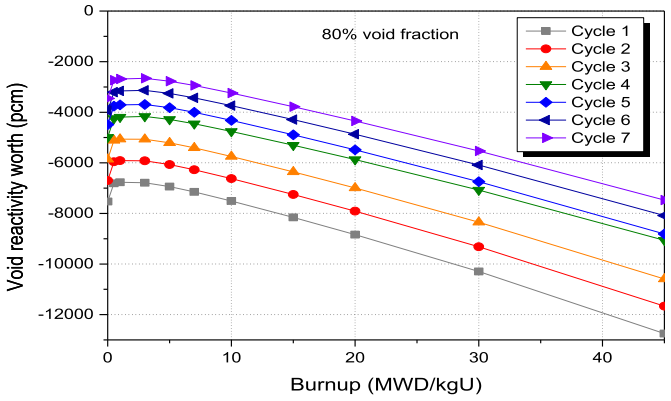


Fig. 12. Comparison of void reactivity evolutions of the MOX-FCM-R2-3 option with different cycle lengths as recycling (80% void fraction).

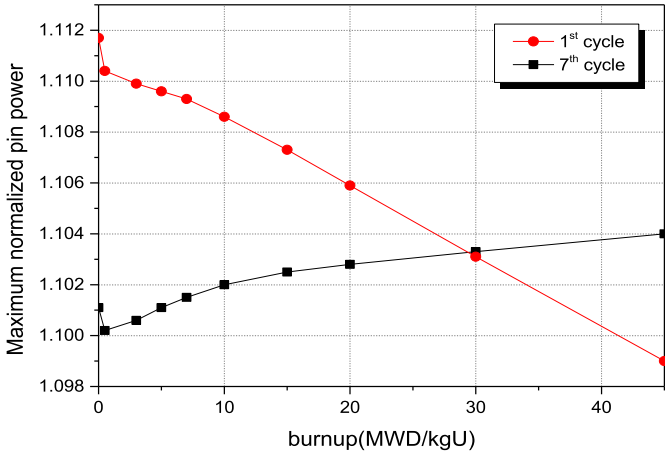


Fig. 13. Comparison of pin power peaking factors for the MOX-FCM-R2-3 option with different cycle lengths as depletion (1st and 7th cycles).

TRU has much higher initial radioactivity and decay heat by a factor of 1.70–1.60 and 3.87–3.30, respectively, than the reference 1 kg TRU of the typical PWR spent fuel having 45MWD/kg. In particular, it is noted that the decay heat of 1 kg TRU of recycled MOX fuel considerably increases as recycling. The decay heats of 1 kg TRUs discharged from 1st and 7th cycles after 3 years cooling are still higher by factors of 6.77–3.47, respectively than those of 1 kg TRU of the typical PWR spent fuel. On the other hand, the decay heat and radioactivity of 1 kg recycled TRU more rapidly decrease after 1–2 years cooling than those of the reference 1 kg TRU of the typical PWR spent fuel. These higher decay heat and radioactivity of recycled TRUs make it difficult to fabricate new fuel using recycled TRUs, which have been well known from the literatures [12].

4. Summary and conclusion

New TRU recycling options using PWR fuel assembly are suggested and their physics characteristics are analyzed in detail to show their potentials from neutronic aspects in effectively consuming TRUs from the current PWR spent fuel stocks. The PWR fuel assemblies are comprised of MOX and FCM fuel rods. Both type fuel rods contain TRU in oxide form. In the suggested recycling options, TRUs only from MOX fuel rods are recycled through reprocessing while the ones from FCM fuel rods are disposed without reprocessing after deep burning and all uranium from MOX fuel rods are also not recycled to achieve a reasonable level of

Table 9
Comparison of mass change (kg) for each cycle of the MOX-FCM-R2-3 option with different cycle lengths.

Cycle	Cycle 1		Cycle 2		Cycle 3		Cycle 4		Cycle 5		Cycle 6		Cycle 7	
Cycle length (EFPD)	1476		1310		1230		1148		1066		1049		984	
Burnup (MWD/kgU)	45		40		37		35		32		32		30	
Rod type	FCM	MOX	FCM	MOX	FCM	MOX	FCM	MOX	FCM	MOX	FCM	MOX	FCM	MOX
Charge (kg)	13.19	26.17	13.19	28.30	13.19	30.40	13.19	32.27	13.19	33.95	13.19	35.43	13.19	36.69
Net increase (kg)	−2.97	−2.26	−2.85	−2.02	−2.69	−1.94	−2.53	−1.88	−2.36	−1.84	−2.19	−1.76	−2.18	−1.82
TRU consumption rate (%)	22.48	8.64	21.60	7.13	20.42	6.37	19.15	5.84	17.86	5.41	16.57	4.98	16.52	4.97
Total consumption rate (%)	13.28		11.73		10.62		9.70		8.89		8.13		8.02	
External TRU feed (kg)	39.36		17.58		17.30		17.01		16.74		16.50		16.22	

Table 10
Overall mass balance (kg) of TRU and U through 1st ~7th cycle for the MOX-FCM-R2-3 option with different cycle lengths.

Items	Values
Uranium external feed through MOX fuels (A)	2217.3
Uranium consumption through MOX fuels (B)	88.4
Discharged uranium from MOX fuels (C = A-B)	2128.9
TRU external feed through MOX fuels (D)	48.4
Discharged TRU from MOX fuels at EOC of 7th cycle (E)	34.9
TRU consumption through MOX fuels (F = D-E)	13.5
TRU external feed through FCM fuels (G)	92.3
TRU consumption through FCM fuels (H)	17.8
Discharged TRU through FCM fuels (I = G-H)	74.6
Total TRU external feed (J = D + G)	140.7
Total TRU consumption (K = F + H)	31.3
Total TRU to be disposed (L = J-K) after 7th cycle	109.4
Total TRU consumption rate (%, M = K/Jx100)	22.3

Table 11
Discharged TRU compositions (wt%) from MOX fuels of the MOX-FCM-R2-3 option with different cycle lengths.

	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6	Cycle 7
Np237	5.325	4.400	3.834	3.476	3.240	3.081	2.940
Pu238	7.560	10.723	12.556	13.632	14.278	14.668	15.042
Pu239	36.933	32.410	30.096	28.808	28.033	27.536	27.027
Pu240	19.773	19.922	19.740	19.579	19.500	19.498	19.495
Pu241	11.943	11.158	10.601	10.135	9.736	9.381	9.165
Pu242	8.893	9.971	10.703	11.219	11.586	11.853	12.102
Am241	3.966	4.178	4.279	4.398	4.549	4.730	4.787
Am242 m	0.169	0.183	0.188	0.194	0.202	0.210	0.213
Am243	2.685	3.140	3.385	3.531	3.626	3.693	3.760
Cm242	0.518	0.550	0.549	0.546	0.547	0.551	0.549
Cm243	0.034	0.042	0.043	0.043	0.042	0.041	0.041
Cm244	1.902	2.737	3.205	3.442	3.538	3.545	3.581
Cm245	0.277	0.524	0.705	0.825	0.899	0.941	0.975
Cm246	0.021	0.062	0.115	0.171	0.225	0.273	0.321

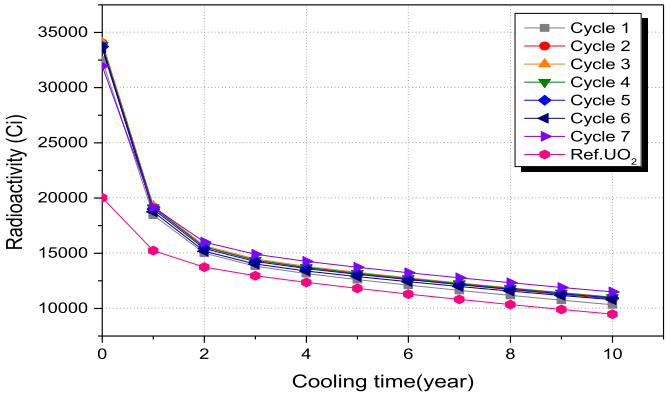


Fig. 14. Comparison of radioactivity of 1 kg TRU in discharged MOX fuels of the MOX-FCM-R2-3 option with different cycle lengths as recycling.

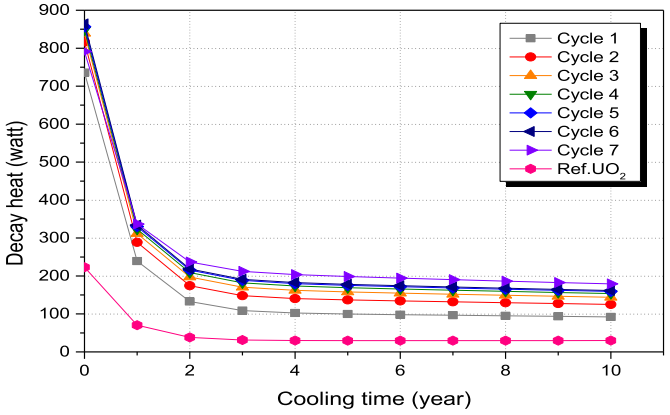


Fig. 15. Comparison of decay heat of 1 kg TRU in discharged MOX fuels of MOX-FCM-R2-3 with different cycle lengths as recycling.

cycle length. In particular, we considered external TRU feed to make up the consumption of actinides in MOX fuels in order to reduce TRUs in the existing accumulated PWR spent fuel stocks. From the assembly-level neutronic analysis with a fixed cycle length of 45MWD/kg, it was shown that the full TRU external feeding option has sufficient cycle length (or reactivity), 13.3–8.4% total TRU consumption rates, and 17.3–22.5% and 6.6–8.9% TRU consumption rates in FCM and MOX fuels, respectively. Also, the reduced rod size option (4.22% reduced pellet radius) was shown to have higher TRU consumption rate and external TRU feeding for most recycling cycles, and more negative void reactivity worth than the reference rod size one. On the other hand, the full TRU external feed option has positive void reactivity worth for voiding fractions higher than ~30%. To mitigate the positive void reactivity worth, mixing of TRU and enriched uranium in external feed was considered. The option using 30% TRU and 70% enriched uranium in external feed was shown to have negative void reactivity worth up to ~80% voiding over the considered burnup range and 13.3–8.02% total TRU consumption rates depending on recycling number, and sufficient cycle lengths up to 7th cycle even if the equilibrium cycle has a significantly reduced cycle length than the first cycle. Finally, the analysis of this option with cycle-dependent cycle lengths which are determined to maintain k_{inf} above 1.02 was performed to reflect more realistic considerations such as neutron leakage, calculation uncertainties, and variable cycle lengths. The results of analysis showed that the cycle length significantly decreases as recycling but 7th cycle still has reasonably long cycle length of 984 EFPDs (30 MWD/kg). The last option with cycle-dependent cycle length has negative reactivity coefficients (FTC and MTC) and negative void reactivity worth up to 80% void fraction over 7th cycle, 8.02–13.3%

total TRU consumption rate, and 22.3% overall TRU consumption rate (corresponding to 31.3 kg) through 1st to 7th cycles. From the analysis of recycled TRU characteristics, the decay heat and radioactivity of recycled TRU increase as recycling and they are significantly higher than those of the typical PWR spent fuel TRU, which makes it difficult to fabricate new fuels for the next cycles. In conclusion, the new recycling option using MOX and FCM fuels is feasible from view point of neutronics (i.e., reasonably long cycle length, negative reactivity coefficient and negative void reactivity worth up to high void fractions) and it has considerable TRU consumption.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2019.10.006.

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