TRU transmutation in Light Water Cooled SMR cores loaded with Fuel Assemblies composed of MOX and FCM fuel rods

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1. Introduction

Nuclear power plants (NPP) have contributed significantly to the supply of reliable and cost-effective electricity for decades. At the same time, spent fuel assemblies including radioactive nuclides with long half-lives have been generated, and nowadays the safe management of them became one of most important issue in nuclear industry. Currently, 24 NPPs (i.e., 20 PWR, 4 PHWR) are in operation in Republic of Korea and it is expected that the capacities of the spent fuel storage pools inside NPPs will be saturated in the near future within decades, in spite of the installation of dense racks and inter-transportation between different NPP units. Recently, national Public Engagement Commission on Spent Nuclear Fuel Management has recommended that the geological repository for spent nuclear fuel should be constructed and operated by 2051.

In this work, the use of TRU nuclides in light water cooled SMR core was considered as one of the option for reducing the inventory and radiotoxicity of nuclear spent fuel sent to repository. The fuel assemblies loaded in the core are composed of MOX rods (UO_2-$TRUO_2$) [1-3] and FCM rods (only $TRUO_2$). The objectives of this work are 1) to evaluate the core performance and neutronic characteristics and 2) to analyze the mass flows of TRU nuclides.

2. Methods and Results

2.1 Computational Method

Typical two step procedure for LWR core calculation was used in this study. Fuel assembly calculations were performed by using DeCART2D (Deterministic Core Analysis based on Ray Tracing for 2-Dimensional core) [4] code which has been developed at Korea Atomic Energy Research Institute (KAERI) in order to generate few group homogenized neutron cross section data. DeCART2D code solves transport equation by using MOC with the 47 group flux-weighted neutron cross section library based on ENDF.B-VII.r1. Then, the two group microscopic neutron cross section is edited for three-dimensional neutron diffusion theory code by using PROLOG [5] program. The calculation for core analysis was performed by MASTER (Multi-purpose Analyzer for Static and Transient Effects of Reactors) [6] code which have been developed at KAERI for nuclear analysis and core design. MASTER code can simulate the PWR or BWR cores in 1-, 2-, or 3-dimensional Cartesian or hexagonal geometry with the advanced nodal diffusion methods. The feed TRU composition from PWR spent fuel having burnup of 50 MWD/kgHM (4.5 wt% initial uranium enrichment) with 10 years cooling was evaluated with ORIGEN-2 [7, 8].

2.2 Fuel Assembly Design and Analysis

Table I shows the design features of fuel assemblies loaded in the core. The new fuel assemblies were designed based on WH 17×17 fuel assembly with small difference. The TRU nuclides are loaded into the fuel assembly in forms of MOX rods and FCM rods. In case of MOX rods, the fuel pellets are composed of 4.95 wt% enriched UO_2 with 7.5 wt% $TRUO_2$ and 2.5 wt% Mo. The Mo is used to derive more negative MTC which tends to be a less negative or a positive when the TRU is multi-recycled, which is considered in our future work. In case of FCM TRISO rods, the kernel having 400 μm radius consists of only $TRUO_2$ and the packing fraction of TRISO particle in SiC matrix is 40 %. In order to reduce the excess reactivity at BOC and to flatten the radial power distribution of core, FCM BISO rods were used as burnable absorber (BA) rods except for B0 fuel assembly. The BISO kernel having 250 μm radius consists of Gd_2O_3 and the packing fraction of BISO particle in SiC matrix is different for each fuel assembly. B0 fuel assembly has 212 MOX rods and 52 FCM TRISO rods, and other fuel assemblies have 180 MOX rods, 52 FCM TRISO rods and 32 FCM BISO rods. The packing fractions of BISO particle vary from 2 % in B1 to 20% in B3. The dimension of FCM particle structure is given in the table in detail. The configuration of 17×17 fuel assemblies are depicted in Figure 1.

Table I: Design data of fuel assembly composed of MOX and FCM rods

Parameter	B0	B1	B2	B3
Rod array	17×17			
Pellet radius (cm)	0.4095			
Clad. Thickness (cm)	0.0655			
Rod diameter (cm)	0.95			
Clad. Material	Zircaloy-4			
Pin pitch (cm)	1.2234			
Assembly pitch (cm)	20.879			
Pitch to Diameter ratio	1.288			
MOX rod	-			
The number of rods	212	180	180	180
Pellet material	4.95 wt% enriched UO_2 with 7.5 wt%			

	TRUO$_2$ (+2.5 wt% Mo)			
Density (g/cm^3)	10.392			
FCM TRISO rod	-			
The number of rods	52	52	52	52
Kernel material	TRUO$_2$			
Density (g/cm^3)	10.430			
Kernel diameter (μm)	800			
Buffer thickness (μm)	80			
IPyC thickness (μm)	20			
SiC thickness (μm)	35			
OPyC thickness (μm)	20			
Packing fraction (%)	40			
FCM BISO rod	-			
The number of rods	0	32		
Kernel material	-	Gd$_2$O$_3$		
Kernel diameter (μm)	-	500		
Buffer thickness (μm)	-	18		
OPyC thickness (μm)	-	23		
Packing fraction (%)	-	2	18	20

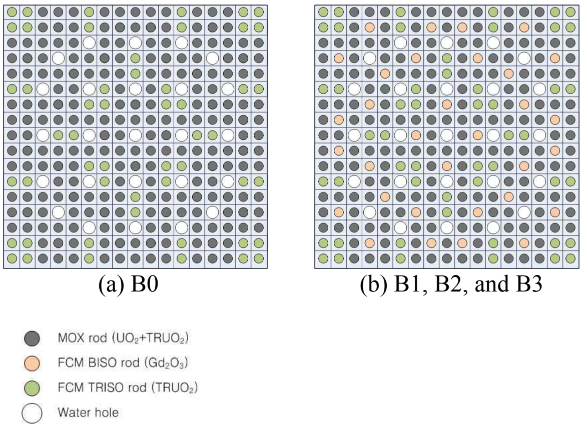

(a) B0 (b) B1, B2, and B3

Fig. 1. Configuration of 17×17 fuel assemblies composed of MOX and FCM rods

Figure 2 shows the comparison of the evolution of infinite multiplication factors for each fuel assembly. The critical boron concentration is fixed to 500 ppm in assembly calculation. Cutback region which has no BISO particle in FCM BISO rods (i.e., corresponding to B1, B2 and B3 fuel assembly)is used to flatten axial power distribution. B2 and B3 fuel assembly were designed to have considerably low excess reactivity. Especially, B2 fuel assembly has negative multiplication factor around 800 EFPDs, but the degradation in cycle length is minimized by loading the fuel assembly into appropriate position in the core. Figure 3 shows the moderator temperature coefficient (MTC) and fuel temperature coefficient (FTC) for each fuel assembly. In case of MTCs, B2 and B3 fuel assemblies have least negative MTCs, and the axial cutback has most negative MTC. In comparison of axial cutback and B1 fuel assembly, it can be seen that the MTC become less negative as the burnable absorber is used. When comparing the axial cutback and B0 fuel assembly, despite the B0 fuel assembly having a large amount of initial heavy metal typically should has more negative MTC, the B0 fuel assembly has less negative MTC. The sensitivity analysis is being conducted for this part. In comparison of FTCs, B0 fuel assembly having no BA rods has most negative FTC. When comparing B1, B2, B3 and axial cutback, the FTC becomes more negative as the burnable absorber is increased. However, the difference between them is considerably small.

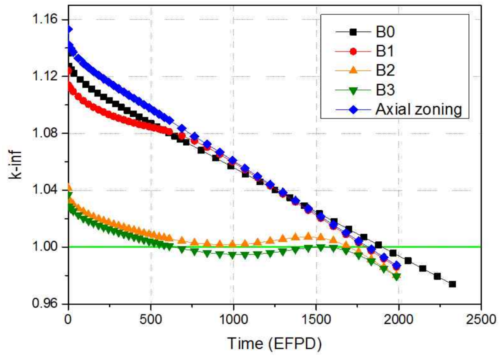
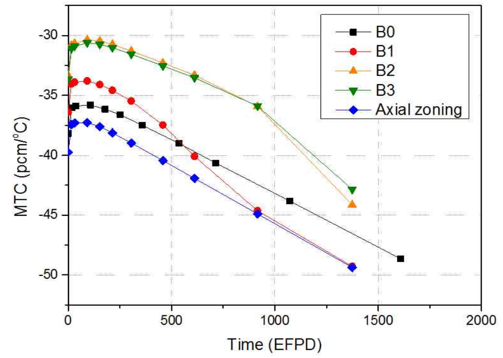
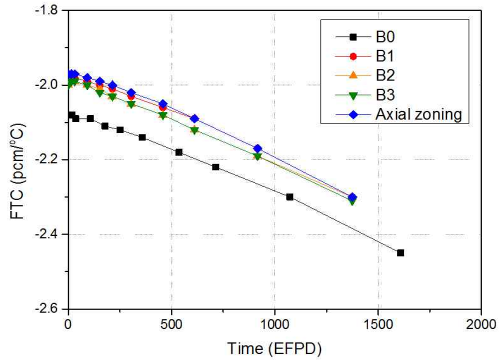


Fig. 2. Comparison of infinite multiplication factors (k-inf) for each fuel assembly



(a) Moderator temperature coefficients

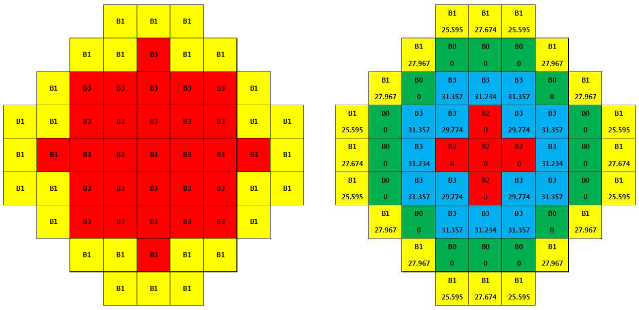


(b) Fuel temperature coefficients

Fig. 3. Comparison of (a) moderator temperature coefficients (MTC) and (b) fuel temperature coefficients (FTC) for each fuel assembly

2.3 Core Design and Analysis

Designed fuel assemblies are loaded in the light water cooled SMR core which has power rate of 330 MWt (100 MWe) with 57 fuel assemblies. The active core height is 200 cm and all of fuel assemblies except for B0 have axial cutback region in their FCM BISO rods, which has no BISO particles. Three batch refueling scheme was used to increase average discharge burnup resulted in the increase of TRU consumption rate. The reflector consists of 90 % graphite + 10 % SS-303. Figure 4 shows the core loading pattern and burnup at BOC for each core from initial to forth cycle. The core loading pattern and burnup at BOC and EOC for equilibrium cycle (i.e., 5th cycle) are shown in Figure 5. The core loading patterns from initial to equilibrium cycle were determined to have sufficiently long cycle length with the satisfaction of design limit.

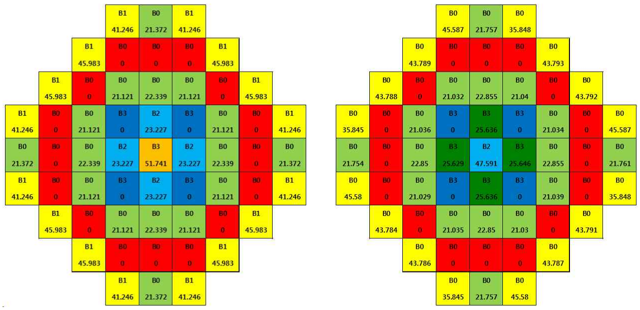


			B1	B1	B1			
		B1	B1	B3	B1	B1		
	B1	B3	B3	B3	B3	B3	B1	
B1	B1	B3	B3	B3	B3	B3	B1	B1
B1	B3	B3	B3	B3	B3	B3	B3	B1
B1	B1	B3	B3	B3	B3	B3	B1	B1
	B1	B3	B3	B3	B3	B3	B1	
		B1	B1	B3	B1	B1		
			B1	B1	B1			

(a) Cycle 1

			B1 25.595	B1 27.674	B1 25.595			
		B1 27.967	B0 0	B0 0	B0 0	B1 27.967		
	B1 27.967	B0 0	B3 31.357	B3 31.234	B3 31.357	B0 0	B1 27.967	
B1 25.595	B0 0	B3 31.357	B3 29.774	B2 0	B3 29.774	B3 31.357	B0 0	B1 25.595
B1 27.674	B0 0	B3 31.234	B2 0	B2 0	B2 0	B3 31.234	B0 0	B1 27.674
B1 25.595	B0 0	B3 31.357	B3 29.774	B2 0	B3 29.774	B3 31.357	B0 0	B1 25.595
	B1 27.967	B0 0	B3 31.357	B3 31.234	B3 31.357	B0 0	B1 27.967	
		B1 27.967	B0 0	B0 0	B0 0	B1 27.967		
			B1 25.595	B1 27.674	B1 25.595			

(c) Cycle 2



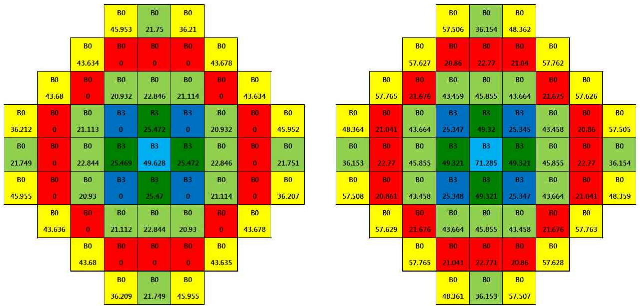
			B1 41.246	B0 21.372	B1 41.246			
		B1 45.983	B0 0	B0 0	B0 0	B1 45.983		
	B1 45.983	B0 0	B0 21.121	B0 22.339	B0 21.121	B0 0	B1 45.983	
B1 41.246	B0 0	B0 21.121	B3 0	B2 23.227	B3 0	B0 21.121	B0 0	B1 41.246
B0 21.372	B0 0	B0 22.339	B2 23.227	B3 51.741	B2 23.227	B0 22.339	B0 0	B0 21.372
B1 41.246	B0 0	B0 21.121	B3 0	B2 23.227	B3 0	B0 21.121	B0 0	B1 41.246
	B1 45.983	B0 0	B0 21.121	B0 22.339	B0 21.121	B0 0	B1 45.983	
		B1 45.983	B0 0	B0 0	B0 0	B1 45.983		
			B1 41.246	B0 21.372	B1 41.246			

(a) Cycle 3

			B0 45.587	B0 21.757	B0 35.848			
		B0 43.789	B0 0	B0 0	B0 0	B0 43.793		
	B0 43.788	B0 0	B0 21.032	B0 22.855	B0 21.04	B0 0	B0 43.792	
B0 35.845	B0 0	B0 21.036	B3 0	B3 25.636	B3 0	B0 21.034	B0 0	B0 45.587
B0 21.754	B0 0	B0 22.85	B3 25.629	B2 47.591	B3 25.646	B0 22.855	B0 0	B0 21.761
B0 45.58	B0 0	B0 21.029	B3 0	B3 25.636	B3 0	B0 21.039	B0 0	B0 35.848
	B0 43.784	B0 0	B0 21.035	B0 22.85	B0 21.03	B0 0	B0 43.791	
		B0 43.786	B0 0	B0 0	B0 0	B0 43.787		
			B0 35.845	B0 21.757	B0 45.58			

(d) Cycle 4

Fig. 4. Core loading patterns and burnup at BOC for each core from 1st to 4th cycle



			B0 45.953	B0 21.75	B0 36.21			
		B0 43.634	B0 0	B0 0	B0 0	B0 43.678		
	B0 43.68	B0 0	B0 20.932	B0 22.846	B0 21.114	B0 0	B0 43.634	
B0 36.212	B0 0	B0 21.113	B3 0	B3 25.472	B3 0	B0 20.932	B0 0	B0 45.952
B0 21.749	B0 0	B0 22.844	B3 25.469	B3 49.628	B3 25.472	B0 22.846	B0 0	B0 21.751
B0 45.955	B0 0	B0 20.93	B3 0	B3 25.47	B3 0	B0 21.114	B0 0	B0 36.207
	B0 43.636	B0 0	B0 21.112	B0 22.844	B0 20.93	B0 0	B0 43.678	
		B0 43.68	B0 0	B0 0	B0 0	B0 43.635		
			B0 36.209	B0 21.749	B0 45.955			

(a) BOC at 5th cycle

			B0 57.506	B0 36.154	B0 48.362			
		B0 57.627	B0 20.86	B0 22.77	B0 21.04	B0 57.762		
	B0 57.765	B0 21.676	B0 43.459	B0 45.855	B0 43.664	B0 21.675	B0 57.626	
B0 48.364	B0 21.041	B0 43.664	B3 25.347	B3 49.32	B3 25.345	B0 43.458	B0 20.86	B0 57.505
B0 36.153	B0 22.77	B0 45.855	B3 49.321	B3 71.285	B3 49.321	B0 45.855	B0 22.77	B0 36.154
B0 57.508	B0 20.861	B0 43.458	B3 25.348	B3 49.321	B3 25.347	B0 43.664	B0 21.041	B0 48.359
	B0 57.629	B0 21.676	B0 43.664	B0 45.855	B0 43.458	B0 21.676	B0 57.763	
		B0 57.765	B0 21.041	B0 22.771	B0 20.86	B0 57.628		
			B0 48.361	B0 36.153	B0 57.507			

(b) EOC of 5th cycle

Fig. 5. Comparison of core loading patterns and burnup at BOC and EOC for 5th cycle (equilibrium cycle)

Table II shows the number of fuel assembly loaded in each core from initial to equilibrium cycle. The numbers in brackets indicate the number of fresh, once-burnt, twice-brunt fuel assemblies. As shown in this table, 20 fresh, 20 once-brunt, 17 twice-burnt fuel assemblies are loaded in the core at BOC, and 17 twice-burnt, 3 once-burnt fuel assemblies are discharged from the core at EOC.

Table II: The number of fuel assembly loaded in each cycle

FA type	CY 1	CY 2	CY 3	CY 4	CY 5
B0		16 (16/0/0)	32 (16/16/0)	48 (16/16/16)	48 (16/16/16)
B1	28 *(28/0/0)	20 (0/20/0)	16 (0/0/16)		
B2		5 (5/0/0)	4 (0/4/0)	1 (0/0/1)	
B3	29 (29/0/0)	16 (0/16/0)	5 (4/0/1)	8 (4/4/0)	9(4/4/1)
Total	57 (57/0/0)	57 (21/36/0)	57 (20/20/17)	57 (20/20/17)	57 (20/20/17)

*(fresh/once-brunt/twice-burnt)

Figure 6 shows the critical boron concentration for each cycle from initial to equilibrium core. The cycle length of initial core is about 913 EFPD and it converges to about 670 EFPDs at equilibrium core. Any other core performance parameters of cycle-by-cycle reload cores from initial to equilibrium cycle are summarized in Table III. All of performance parameters satisfy the typical design limit of PWR core. The critical boron concentrations for all cycles are less than design target of 2000 ppm. The axial power distribution is somewhat downward biased, but the AOs are in the range of -1.0 %~-5.0 %. The 3-dimensional and radial power peaking factors have the maximum values 2.04 and 1.55 respectively. Regarding reactivity coefficient, MTC and FTC are sufficiently negative resulted from the use of Mo in MOX rods. In the analysis of shutdown margin, all cores have sufficient margin more than design target of 6000 pcm.

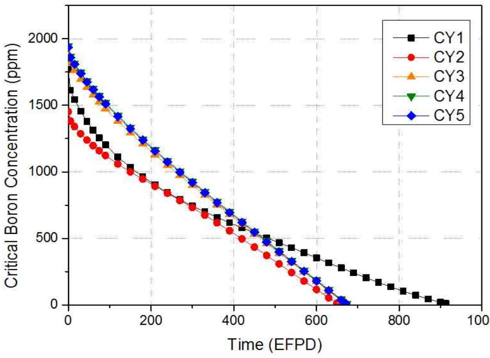


Fig. 6. Comparison of critical boron concentration for each cycle

Table III: Summary of core performance and characteristics for each cycle

Parameters	CY1	CY2	CY3	CY4	CY5
Cycle length (EFPD)	913.0	650.2	669.7	673.5	670.8
Max. CBC	1767.6	1451.2	1888.8	1944.9	1936.2
Max. AO (%)	-1.09	-2.72	-3.80	-3.52	-3.64
Min. AO (%)	-2.66	-4.53	-4.48	-3.91	-4.12
Max. Fq	2.04	2.02	2.02	2.02	2.02
Max. Fr	1.49	1.50	1.55	1.54	1.54
MTC (pcm/°C) BOC/EOC at HFP	-34.53 /-61.27	-43.9 /-67.35	-41.57 /-68.38	-41.06 /-67.84	-41.18 /-67.83
FTC (pcm/°C) BOC/EOC at HFP	-2.65 /-2.93	-3.01 /-3.10	-3.18 /-3.28	-3.17 /-3.28	-3.18 /-3.28
Shutdown margin (%Δρ) BOC/EOC at HFP	7.25 /7.94	7.40 /8.12	7.88 /8.25	7.79 /8.21	7.79 /8.21
Avg. discharge burnup (MWD/kg)	31.85	50.10	57.35	55.12	55.21

Table IV shows the analysis of assembly-wise mass flow for Pu, MA and TRU. The analysis on the mass flow of TRU (Pu, MA) nuclides for the equilibrium cycle core was performed by using DeCART2D code because MASTER code does not provide the pin-by-pin mass data for each nuclide. At the BOC of equilibrium cycle, 20 fresh fuel assemblies (16 B0, 4 B3) are loaded in the core. On the other hand, at the EOC, 17 three times-brunt fuel assembly (16 B0, 1 B3) and 3 twice-burnt fuel assembly (3 B3) are discharged. As a result of the depletion calculation up to corresponding discharge burnup at EOC for each fuel assembly, the amount of Pu is reduced by 52.5 kg compared to the total amount of Pu in fresh fuel assemblies, which corresponds to a consumption rate of about 14.13 %. In case of dividing by the type of fuel rod, MOX rod is loaded with 240.2 kg at BOC, and 223.4 kg (-16.8 kg consumed) is discharged at EOC, which corresponds to a consumption rate of about 7.0 %. In the FCM rods, 129.0 kg which is slightly more than half of that of MOX rods, are loaded. However, 93.4 kg (-35.6 kg consumed) is discharged at the EOC, which has more than twice higher consumption mass compared to MOX rods. The FCM rod has considerably high consumption rate of 27.6 %. In case of MA nuclides, the amount of MA is reduced by 12.4 kg (i.e., 17.7 %) compared to the amount loaded by fresh fuel assemblies at BOC. In MOX rods, 45.2 kg is loaded and 38.3 kg (-6.6 kg) is discharged at EOC, which corresponds to a consumption rate of about 15.4 %. In FCM rods, 24.3 kg is loaded at BOC and 5.4 kg is consumed, which has a high consumption rate of about 22.1 %, but the difference in consumption rate with MOX rods is considerably smaller than that of Pu nuclides. That is, the MOX rods have high consumption rate of MA nuclides, while the FCM rods have high consumption rate of Pu nuclides.

Regarding the total TRU nuclides, 441.4 kg is loaded by fresh fuel assemblies at BOC, and 64.9 kg is consumed, which corresponds to a consumption rate of 14.7 %. In case of dividing by the type of fuel rod, despite the FCM rods in fresh fuel assemblies have 120.8 kg TRU, which is considerably smaller than that of MOX rods (235.1 kg), the consumption mass in FCM rods (40.9 kg) is significantly higher than that of MOX rods (23.7 kg) at EOC. Considering a 1000 MWe PWR core with an assumption of proportional relation between power rate and TRU consumption capability, it will consume about 649 kilograms of TRU, which is comparable to the amount that can be consumed in a sodium cooled TRU transmutation reactor having same power rate.

Table IV: Analysis of assembly-wise mass flow for Pu, MA and TRU

Charged FA type	Number of FAs	Pu mass (kg)			MA mass (kg)			TRU mass (kg)		
		MOX	FCM	Total	MOX	FCM	Total	MOX	FCM	Total
B0	16	197.83	101.65	303.30	37.24	19.13	57.10	235.08	120.78	360.39
B3	4	42.32	27.31	68.20	7.97	5.14	12.84	50.29	32.46	81.04
Total	20	240.15	128.96	371.50	45.21	24.27	69.93	285.37	153.24	441.43
Discharged FA type	Discharge burnup (MWD/kg)	Pu mass (kg)			MA mass (kg)			TRU mass (kg)		
		MOX	FCM	Total	MOX	FCM	Total	MOX	FCM	Total
B0-1	57.51	11.48	4.50	16.20	1.96	0.92	2.92	13.45	5.42	19.12
B0-2	48.36	11.65	4.78	16.65	2.00	0.96	3.00	13.65	5.74	19.65
B0-3	57.63	11.48	4.50	16.19	1.96	0.92	2.92	13.45	5.41	19.11
B0-4	57.76	11.48	4.49	16.19	1.96	0.92	2.92	13.44	5.41	19.11
B0-5	57.77	11.48	4.49	16.19	1.96	0.92	2.92	13.44	5.41	19.10
B0-6	57.63	11.48	4.50	16.19	1.96	0.92	2.92	13.45	5.41	19.11
B0-7	48.36	11.65	4.78	16.65	2.00	0.96	3.00	13.65	5.74	19.65
B0-8	57.51	11.48	4.50	16.20	1.96	0.92	2.92	13.45	5.42	19.12
B0-9	57.51	11.48	4.50	16.20	1.96	0.92	2.92	13.45	5.42	19.12
B0-10	48.36	11.65	4.78	16.65	2.00	0.96	3.00	13.65	5.74	19.65
B0-11	57.63	11.48	4.50	16.19	1.96	0.92	2.92	13.45	5.41	19.11
B0-12	57.76	11.48	4.49	16.19	1.96	0.92	2.92	13.44	5.41	19.11
B0-13	57.77	11.48	4.49	16.19	1.96	0.92	2.92	13.44	5.41	19.10
B0-14	57.63	11.48	4.50	16.19	1.96	0.92	2.92	13.45	5.41	19.11
B0-15	48.36	11.65	4.78	16.65	2.00	0.96	3.00	13.65	5.74	19.65
B0-16	57.51	11.48	4.50	16.20	1.96	0.92	2.92	13.45	5.42	19.12
B3-1	49.32	9.87	5.25	14.80	1.69	1.04	2.68	11.57	6.28	17.47
B3-2	71.29	9.38	4.60	13.67	1.63	0.94	2.52	11.01	5.54	16.19
B3-3	49.32	9.87	5.25	14.80	1.69	1.04	2.68	11.57	6.28	17.47
B3-4	49.32	9.87	5.25	14.80	1.69	1.04	2.68	11.57	6.28	17.47
Sum or Average	55.21	223.40	93.40	318.99	38.26	18.92	57.56	261.66	112.32	376.55
Consumed mass (kg)	-	16.76	35.56	52.50	6.95	5.36	12.37	23.71	40.92	64.88
Consumpti-on rate (%)		6.98	27.57	14.13	15.37	22.07	17.69	8.31	26.70	14.70

3. Conclusions

In this work, fuel assemblies and the light water cooled SMR core for TRU transmutation were designed and various core performance parameters and TRU mass flow were evaluated. The TRU nuclides are loaded into the 17×17fuel assembly in forms of MOX rods and FCM rods. The FCM BISO rods (Gd_2O_3) were used as burnable absorber rods, which have been determined by comparing various forms and materials. The equilibrium core has the cycle length of 670.8 EFPD with average discharge burnup of 55.21 MWD/kg and any other core performance parameters satisfy the typical design limit of PWR core. For the equilibrium core, the amount of Pu is reduced by 52.5 kg compared to the total amount of Pu in fresh fuel assemblies, which corresponds to a consumption rate of about 14.3 %. In case of MA nuclides, the amount of MA is reduced by 12.4 kg (i.e., 17.8 %) compared to the amount loaded by fresh fuel assemblies at BOC. When comparing the type of fuel rod, the MOX rods have high consumption rate of MA nuclides, while the FCM rods have high consumption rate of Pu nuclides. Regarding the total TRU nuclides, 64.9 kg is consumed, which corresponds to a consumption rate of 14.7 %. In case of dividing by the type of fuel rod, despite the FCM rods in fresh fuel assemblies have 120.8 kg TRU, which is considerably smaller than that of MOX rods (235.1 kg), the consumption mass in FCM rods (40.9 kg) is significantly higher than that of MOX rods (23.7 kg). From this analysis, in the aspect of mass flow, it is notable that the TRU transmutation in PWR core using the MOX+FCM fuel assembly is comparable to that in a sodium cooled TRU transmutation reactor having same power rate.

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