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Effects of Radial Reflector Material on the Performances of Small LWR Core Using ThO_2-UO_2 and FCM Fuels

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1. Introduction

Recently, a 308MWth LWR core [1] using new fuel assembly designs has been studied to efficiently destroy TRU (transuranics) nuclide without degradation of safety aspects by using ThO_2-UO_2 fuel pins and FCM (Fully Ceramic Micro-encapsulated) fuel pins containing TRU fuel particles [2,3,4,5]. The previous results have shown that new core has 1400 EFPD (Effective Full Power Day) cycle length and the TRU destruction rates of ~21% per cycle.

This paper is to analyze the effects of different radial reflector materials on the performances of the small LWR core using ThO_2-UO_2fuel pins and FCM fuels. In this work, a 2D whole core modeling using DeCART2D [6] was used to accurately generate the radial reflector cross sections because the accuracy of the reflector cross sections is important in small reactor core design. We considered several candidate materials for solid reflector such as lead, SS303, beryllium metal, and graphite. The results of analysis show that all the solid reflectors considered here except for beryllium metal lead to longer cycles lengths, lower power peaking, and less negative MTCs (Moderator Temperature Coefficient) than the core having water reflector.

2. Computational Methods

The fuel assembly calculations were performed with the DeCART2D (Deterministic Core Analysis based on Ray Tracing for 2-Dimensional core) code which has been recently developed by KAERI to model 2D geometries and with a 47 group cross section library that was generated based on ENDF/B-VII.r0. In the 47 group cross section library, the resonance integrals of Th-232, U-235 and U-238 in ThO_2-UO_2fuel pins are adjusted so as to preserve the one-group cross sections over resonance energy range for the reference ThO_2-UO_2fuel pins. In particular, in this work, a whole core modeling with DeCART2D was used to accurately produce the homogenized two group cross sections and the discontinuity factors of the reflector assemblies for core analysis using nodal diffusion calculation. The final table set for core calculations were prepared by using the PROLOG program. The core calculations were performed by using the MASTER (Multi-purpose Analyzer for Static and Transient Effects of Reactors) [7] code which is a 3D core depletion code developed by KAERI.

3. Core Design and Performance Analysis

In this study, the reference fuel assembly is the ABB/CE 16x16 type fuel assembly which has four water holes for control rods and one central water hole for in-core instrumentation. We have designed four types of new fuel assemblies having TRU FCM pins and UO_2-ThO_2 pins that are to be used in the core. These fuel assemblies were designed to flatten the core power distribution by adjusting the packing fractions of TRISO and BISO particles, arrangements of FCM pins, and enrichment zoning. Table I summarizes the compositions of the fuel pins and main design parameter for these fuel assemblies.

Table I Composition of fuel pins for the new assemblies

Type	A	B	C	D
FCM TRU pin				
Kernel diameter	600μm			
Matrix	SiC			
Packing fraction (TRISO/BISO)	44/ 4.0	45/ 3.5	47/ 1.5+1.5	48/ 1.0
BP material	Gd_2O_3	Gd_2O_3	Gd_2O_3, Er_2O_3	Gd_2O_3
UO_2-ThO_2 pin				
Uranium enrichment	11% 8.5%	12.5% 10%	16%	17%
Wt% of ThO_2	50 wt%			

Fig. 1 shows how the UO_2-ThO_2 pins and FCM TRU pins are arranged in 1/4 fuel assembly. The new assemblies of A and B types apply to the left side configuration which have separated enrichment uranium fuel pins, while C and D types have the arrangement of fuel pins shown in the right side configuration of Fig. 1. In the fuel assemblies of type C and D, the uranium enrichments are the same for all the UO_2-ThO_2 pins while the enrichment zoning was used to reduce pin power peaking in the type A and B assemblies. For all the UO_2-ThO_2 pins, the weight percent of ThO_2 is 50wt%. Also, it is noted that the type C assembly uses two types of BISO particles of Gd_2O_3 and Er_2O_3 to reduce fluctuation in the reactivity change as burnable poison materials deplete and to reduce the initial excess reactivity. Each of BISO particles has 1.5% packing fraction. Also, all the FCM fuel rods have axial cutbacks of 21.5cm height both in the top and bottom where BISO burnable poison particles are not used to optimize the axial power distribution.

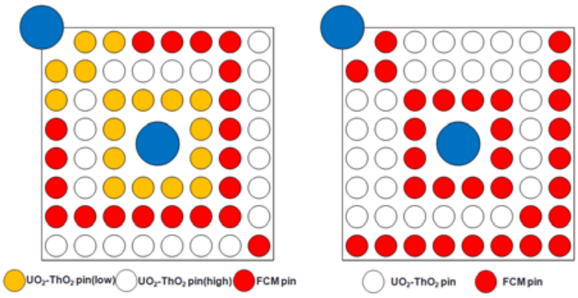

Fig. 1 Configuration of the new fuel assembly (1/4)

The core rates 308MWth and its active fuel height is 210cm. This core has been designed to have relatively small power density whose the average linear heat generation rate is 109.1W/cm, so as to have large thermal margin and long cycle length. This core uses one batch refueling scheme and so every fuel assembly is discharged at EOC and new fresh assemblies are re-loaded together. Our minimum target cycle length is 3years. Fig. 2 shows the loading pattern of core. The core consists of 57 fuel assemblies. On the outside region of core, the assemblies with the highest enrichment were placed to achieve the power flattening. In Fig. 2, R2 and R3 indicate radial reflectors. Specifically, R2 means the corner reflector which faces two adjacent fuel assemblies while R3 indicates the reflectors facing only one adjacent fuel assembly.

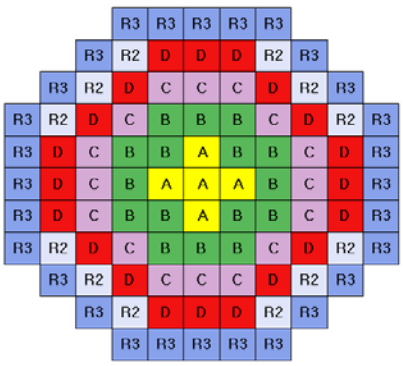

Fig. 2 Radial configuration of the new core

In this study, we considered four different materials of radial reflector: graphite, SS303, lead and metallic beryllium. Although realistic fabrications of the reflectors using pure graphite, pure lead, and pure beryllium may be not practical, we believe that the combinations of these pure materials and structural material such as SS303 are possible and the performances for the cores using the combinations of these pure materials and SS303 can be inferred from the results given in this work. Fig. 3 compares the evolutions of CBC (Critical Boron Concentration) over time for the different four cases using the different radial reflector compositions. All the cases have longer cycle length than the water reflected core. This figure shows that beryllium is most effective as reflector in terms of cycle length. And it is found that the core having the graphite reflector also has much larger cycle length by 400 EFPD than the core having the water reflector. The cores having lead and SS303 reflectors have smaller cycle lengths of 1600 and1500 EFPDs, respectively but these values of cycle length are larger by ~200EFPD than the core using water reflector.

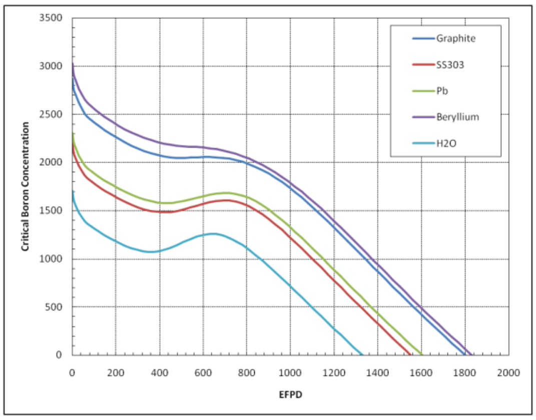

Fig. 3 Comparison of CBC over time for different radial reflectors

Fig.4 and Fig. 5 compares the evolutions of the axially integrated power peaking factors (F_r) and the nuclear power peaking factors (F_q) over time, respectively. From these figures, it is noted that the beryllium reflector causes the large power peaking factors in the fuel assemblies adjacent to the reflectors due to its strong moderating ratio. On the other hand, all the cores except the core using beryllium reflector have reasonable level of the axially integrated power peaking and the nuclear power peaking factors. Also, these figures show the cores using SS303 and lead reflectors have lower values of the nuclear power peaking factors than the core using water reflector.

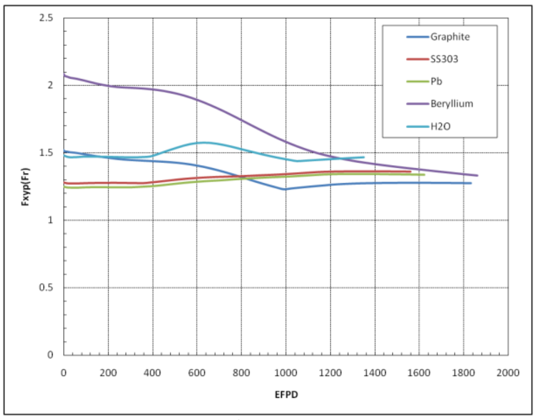

Fig. 4 Comparison of axially integrated pin power peaking factors for the new cores

Fig. 6 and Fig. 7 show the moderator temperature coefficients (MTC) in HZP and HFP for the four different reflectors. In the first half of cycle, all the cases have the small changes of MTC in compared with the typical LWR having no thorium fuels and no FCM pins (i.e., YGN unit 3 cycle 1). Also, it should be noted that MTCs of the new cores using different reflector compositions are much less negative than the core studies in our previous work. In our previous work, it was found that the core has too strong negative MTC (~80pcm/K) at EOC. When MSLB (Main Stream Line Break) accident provokes overcooling of the core, a strong negative of MTC leads to a large positive reactivity insertion and also a strong negative MTC reduces the shutdown margin. So, the effects of the strong negative MTC should be seriously considered and we are planning a work on the analysis of shutdown margin at EOC in the future.

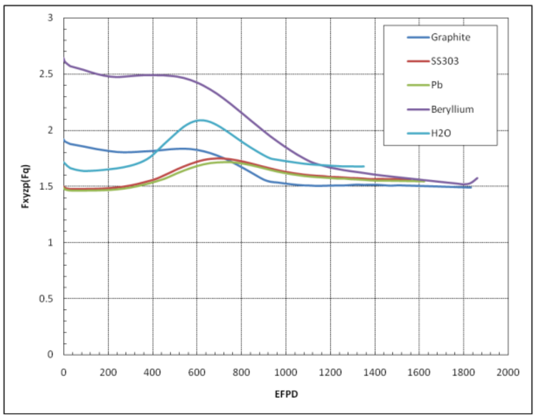

Fig. 5 Comparison of nuclear power peaking factors for the new cores

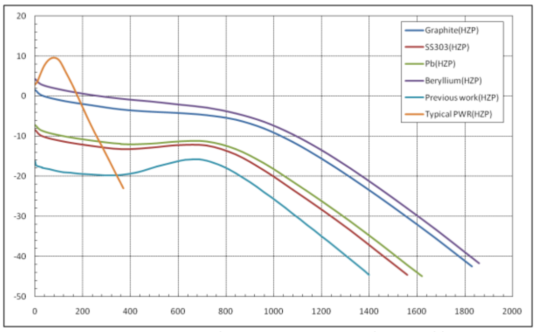

Fig. 6 Comparison of MTC (HZP) for different radial reflectors and typical LWR core

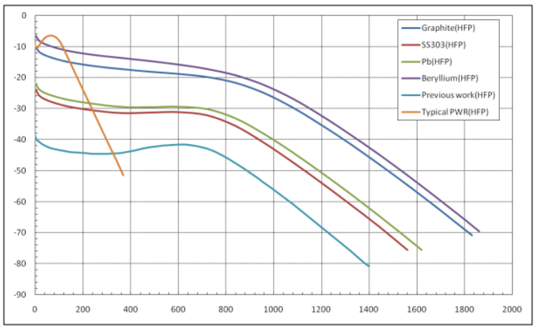

Fig. 7 Comparison of MTC (HFP) for different radial reflectors and typical LWR core

Table II shows the evolutions of TRU mass over the whole cycles for four different cases. For the core having water reflector, TRU destruction rate of the core is about 18.76% while the values of four cases in this study have higher TRU destruction rate. It is caused by high burn-up of the new cores that has extended cycle length by using different material in radial reflector. For example, the core having graphite reflector has 37.8% TRU destruction rate in FCM pins and 27.6% net TRU destruction rate over whole core.

Table II TRU mass inventories for different cases

Reflector composition	Water	Graphite	SS303	Lead	Beryllium
TRU mass (kg) in BOC	81.777				
TRU mass (kg) in EOC	66.44	59.19	63.26	64.53	58.70
TRU destruction rate in a core (%)	18.76	27.62	22.64	21.09	28.22
TRU destruction rate in FCM pins (%)	27.12	37.86	31.89	33.09	38.56

Fig. 8 shows the assembly average thermal fluxes both in the fuel and reflector assemblies. From Fig. 8 (c) and (e), it should be noted that the fuel assemblies adjacent to the reflectors have very large thermal fluxes for the cores using graphite and beryllium reflectors. In particular, the core having beryllium reflector shows the large thermal flux increases in the fuel assemblies adjacent to the reflectors, which induces the power peaking in these fuel assemblies.

			0.023	0.085	0.11	0.085	0.023			
		0.03	0.168	0.853	1.05	0.853	0.168	0.03		
	0.03	0.181	1.002	1.423	1.553	1.423	1.002	0.181	0.03	
0.023	0.168	1.002	1.493	2.318	2.4	2.318	1.493	1.002	0.168	0.023
0.085	0.853	1.423	2.318	2.413	2.433	2.413	2.318	1.423	0.853	0.085
0.11	1.05	1.553	2.4	2.433	2.363	2.433	2.4	1.553	1.05	0.11
0.085	0.853	1.423	2.318	2.413	2.433	2.413	2.318	1.423	0.853	0.085
0.023	0.168	1.002	1.493	2.318	2.4	2.318	1.493	1.002	0.168	0.023
	0.03	0.181	1.002	1.423	1.553	1.423	1.002	0.181	0.03	
		0.03	0.168	0.853	1.05	0.853	0.168	0.03		
			0.023	0.085	0.11	0.085	0.023			

(a) Core having water reflector

			2.296	3.075	3.338	3.075	2.296			
		2.894	4.521	1.478	1.488	1.478	4.522	2.894		
	2.894	4.77	1.563	1.453	1.451	1.453	1.563	4.77	2.894	
2.296	4.521	1.563	1.431	1.805	1.747	1.805	1.431	1.563	4.521	2.296
3.075	1.478	1.453	1.805	1.578	1.484	1.578	1.805	1.453	1.478	3.075
3.338	1.488	1.451	1.747	1.484	1.345	1.484	1.747	1.451	1.488	3.338
3.075	1.478	1.453	1.805	1.578	1.484	1.578	1.805	1.453	1.478	3.075
2.296	4.521	1.563	1.431	1.805	1.747	1.805	1.431	1.563	4.521	2.296
	2.894	4.77	1.563	1.453	1.451	1.453	1.563	4.77	2.894	
		2.894	4.522	1.478	1.488	1.478	4.521	2.894		
			2.296	3.075	3.338	3.075	2.296			

(b) Core having graphite reflector

			0.015	0.083	0.101	0.083	0.015			
		0.019	0.174	1.048	1.218	1.048	0.174	0.019		
	0.019	0.183	1.158	1.458	1.538	1.458	1.158	0.183	0.019	
0.015	0.174	1.158	1.486	2.131	2.153	2.131	1.486	1.158	0.174	0.015
0.083	1.048	1.458	2.131	2.081	2.048	2.081	2.131	1.458	1.048	0.083
0.101	1.218	1.538	2.153	2.048	1.942	2.048	2.153	1.538	1.218	0.101
0.083	1.048	1.458	2.131	2.081	2.048	2.081	2.131	1.458	1.048	0.083
0.015	0.174	1.158	1.486	2.131	2.153	2.131	1.486	1.158	0.174	0.015
	0.019	0.183	1.158	1.458	1.538	1.458	1.158	0.183	0.019	
		0.019	0.174	1.048	1.218	1.048	0.174	0.019		
			0.015	0.083	0.101	0.083	0.015			

(c) Core having SS303 reflector

			0.191	0.373	0.429	0.373	0.191			
		0.254	0.688	1.1	1.222	1.1	0.688	0.254		
	0.254	0.743	1.255	1.461	1.515	1.461	1.255	0.743	0.254	
0.191	0.688	1.255	1.496	2.082	2.082	2.082	1.496	1.255	0.688	0.191
0.373	1.1	1.461	2.082	1.995	1.947	1.995	2.082	1.461	1.1	0.373
0.429	1.222	1.515	2.082	1.947	1.833	1.947	2.082	1.515	1.222	0.429
0.373	1.1	1.461	2.082	1.995	1.947	1.995	2.082	1.461	1.1	0.373
0.191	0.688	1.255	1.496	2.082	2.082	2.082	1.496	1.255	0.688	0.191
	0.254	0.743	1.255	1.461	1.515	1.461	1.255	0.743	0.254	
		0.254	0.688	1.1	1.222	1.1	0.688	0.254		
			0.191	0.373	0.429	0.373	0.191			

(d) Core having lead reflector

			3.998	5.935	6.606	5.935	3.998			
		4.873	8.476	1.637	1.587	1.637	8.476	4.873		
	4.873	8.772	1.684	1.432	1.419	1.432	1.684	8.772	4.873	
3.998	8.476	1.684	1.393	1.718	1.649	1.718	1.393	1.684	8.476	3.998
5.935	1.637	1.432	1.718	1.465	1.365	1.465	1.718	1.432	1.637	5.935
6.606	1.587	1.419	1.649	1.365	1.223	1.365	1.649	1.419	1.587	6.606
5.935	1.637	1.432	1.718	1.465	1.365	1.465	1.718	1.432	1.637	5.935
3.998	8.476	1.684	1.393	1.718	1.649	1.718	1.393	1.684	8.476	3.998
	4.873	8.772	1.684	1.432	1.419	1.432	1.684	8.772	4.873	
		4.873	8.476	1.637	1.587	1.637	8.476	4.873		
			3.998	5.935	6.606	5.935	3.998			

(e) Core having beryllium reflector

Fig. 8 Comparison of thermal neutron fluxes for the cores having different reflectors (BOC)

3. Conclusions

In this work, we analyzed the effects of different reflector compositions on the neutronic performances of a small advanced LWR core having UO_2-ThO_2 pins and TRU FCM pins to effectively destroy TRU nuclides from LWR spent fuel and the results show that the reflector using SS303 or lead gives much better performance such as longer fuel cycle length, lower power peaking factors, higher TRU destruction rate and less negative MTC than the core having water reflector. Also, it was found that the cores graphite and beryllium reflectors has much longer cycle length but they shows larger thermal fluxes in the fuel assemblies adjacent to the reflectors, which leads to power rising in these fuel assemblies. And it was shown that the power peaking factors are acceptable in the core having graphite reflector. As conclusion, the advanced small LWR core having UO_2-ThO_2 pins and TRU FCM pins to effectively destroy TRU nuclides from LWR spent fuel can be designed to have better core performances using the solid reflectors such as lead and SS303.

Acknowledgement

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