An Optimization Study of LWR Fuel Assembly Design for TRU Burning using FCM and UO_2-ThO_2 Fuel Pins

DaeHee Hwang and Ser Gi Hong
Department of Nuclear Engineering, Kyung Hee University
1732 Deokyoungdaero, Giheung-gu, Yongin, Gyeonggi-do, 446-701
imvenatir@hanmail.net; sergihong@khu.ac.kr

1. Introduction

The objective of this work is to design optimized LWR fuel assemblies for the transmutation of TRU (transuranic) nuclides by using FCM (Fully Ceramic Micro-encapsulated)[1,2,3,4] and UO_2-ThO_2 fuel pins without degradation of safety-related parameters. In our study, the pin pitch (equivalently to P/D (Pitch-to-Diameter) ratio with a fixed fuel rod diameter) is used as a design parameter. The motivation is to make MTC (Moderator Temperature Coefficient) less negative at EOC because it was found that the small LWR core design in our previous work[5] has a very strong MTC at EOC (~-80pcm/K) which can lead to a large positive reactivity insertion under MSLB (Main Steam Line Break) accident and to a reduction of shutdown margin of the control rods. The basic idea is to increase moderator-to-fuel ratio such that the fuel assemblies have less negative MTC due to increase the moderation. The results show that a small increase of P/D ratio by 3.8% can give a considerably less negative MTC and an increase of TRU destruction rate without an increase of pin power peaking.

2. Methods and Results

All calculations were performed by using DeCART[6] (Deterministic Core Analysis based on Ray Tracing) code which were developed in KAERI (Korea Atomic Energy Research Institute). The DeCART code is a whole core neutron transport code which is capable of depletion calculation. The reference assembly is the ABB-CE 16x 16 type which has one central water hole for in-core instrumentation and four water holes for inserting control rods. Axial height was fixed 1 cm to analyze two-dimensional fuel assembly model and the boundary conditions of both axial and radial directions are reflective. The pin pitch of the reference fuel assembly is 1.2882 cm which corresponds to a P/D ratio of 1.33. The one-fourth configuration of the reference fuel assembly is shown in Fig. 1. As shown in Fig. 1, the full assembly consists of 84 FCM fuel pins whose kernel contains TRU nuclides and 152 UO_2-ThO_2 pins. The reference fuel assembly uses an enrichment zoning to reduce the pin power peaking, which places low uranium enrichment fuel pins around the water holes. Table 1 summarizes main design parameters for the reference fuel assembly.

Table I Composition of reference assembly

Type	ABB-CE 16 x 16	
UO_2-ThO_2 fuel pins		
U-235 enrichment	11%	8.5%
The number of pins in whole assembly	92	60
Wt% of ThO_2	50 wt%	
FCM fuel pin		
The number of pins in whole assembly	84	
Matrix	SiC	
Packing fraction (TRISO/BISO)	44/4.0	
Kernel diameter (TRISO/BISO)	600/500 μm	
Burnable Absober material	Gd_2O_3	

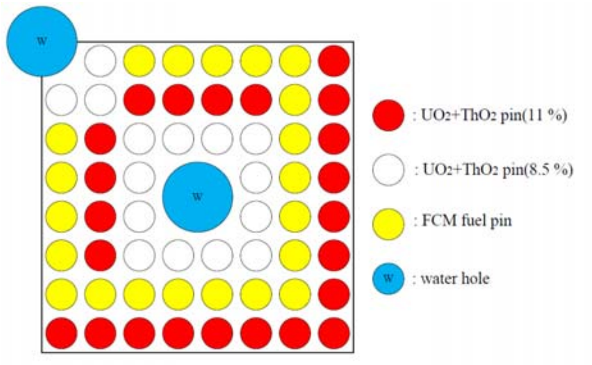

Fig.1 Configuration of fuel assembly (1/4)

The contents of ThO2 in UO2+ThO2 is 50 wt% which was determined through a parametric study on the cycle length. FCM fuel pins have two kind of particles, i.e., TRISO and BISO that are distributed in SiC matrix. The TRISO and BISO particles include TRU nuclides and burnable absorber, respectively in their kernels. In this study, we used gadolinium as burnable absorber. The packing fractions of TRISO and BISO are 44 % and 4 %, respectively. Fig. 2 compares the initial k-inf versus P/D ratio. All the DeCART depletion calculations were done for 1850 EFPDs. In our analyses, EOC means the depletion time of 1850 EFPDs. As shown in Fig. 2, the initial k-inf linearly increases as P/D ratio due to the increase of neutron moderation, which means that the fuel assembly is in under-moderated region. On the other hand, all the cases have similar values of k-infs at 1850 EFPDs.

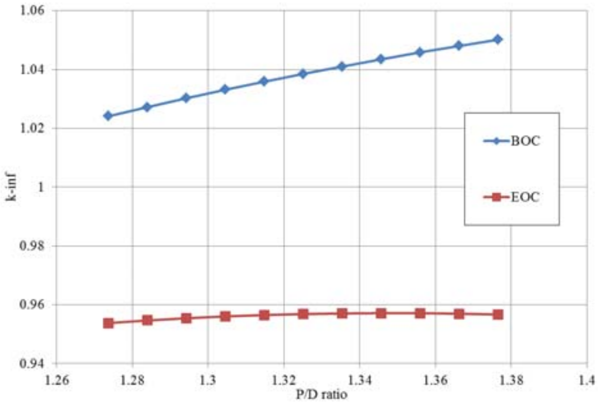

Fig. 2 Comparison of the change of k-inf versus versus P/D ratio

Fig. 3 compares evolutions of k-inf over depletion for three selected P/D ratios. Fig. 3 shows that the case having large P/D ratio has longer cycle length although all the cases have similar k-infs at 1850 EFPDs.

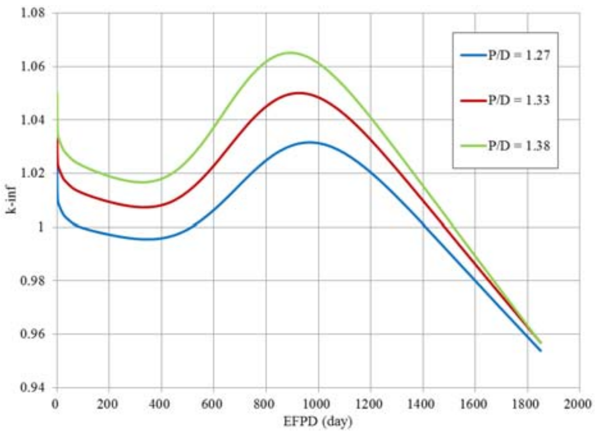

Fig. 3 Comparison of the changes of k-inf for three different P/D ratios versus depletion time

Fig. 4 compares the changes of peaking factors over depletion time for the selected three different P/D ratios (i.e., P/D=1.27, 1.33, 1.38). This figure shows that the case of P/D=1.38 has more stable and lower pin power peaking factors over 1850EFPDs than the reference case having P/D=1.33.

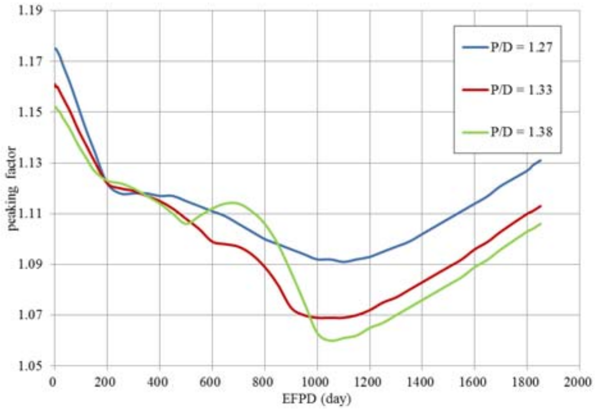

Fig. 4 Comparison of the change of peaking factor for three different P/D ratios

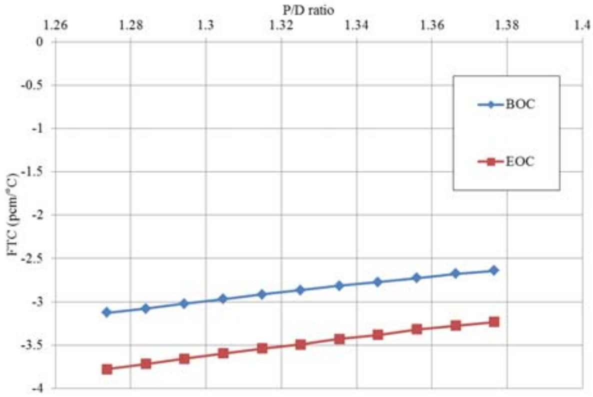

Fig. 5 FTC with increase of P/D ratio in BOC and EOC

Fig. 5 compares the changes of FTC (Fuel Temperature Coefficient) both at BOC and EOC versus P/D ratio. From this figure, it is shown that the increase of P/D ratio leads to less negative FTC due to the spectral shift toward more thermalized region which means a departure from the resonance energy region. Fig. 6 compares MTC versus P/D ratio both at BOC and EOC. This figure shows that it is possible to make MTC less negative by increasing P/D ratio. For example, the increase of P/D ratio from 1.33 (reference case) to 1.38 leads to the change of MTC from -59 pcm/°C to -49pcm/°C at EOC. In these calculations, we assumed a boron concentration of 500ppm both at BOC and EOC. Also, it is noted in Fig. 6 that the change of MTC at BOC resulted from the change of P/D ratio is smaller than the change of MTC at EOC.

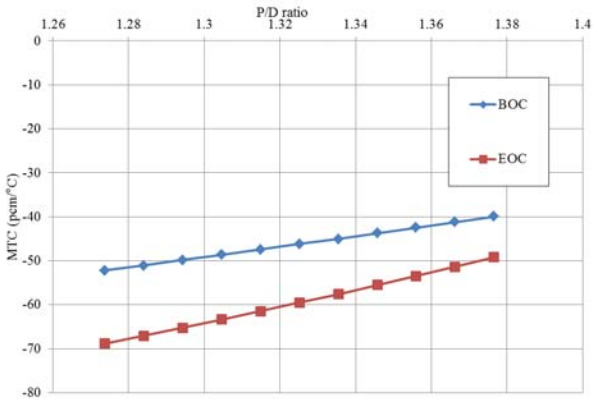

Fig. 6 MTC with increase of P/D ratio in BOC and EOC

Table II compares the TRU inventories and their changes from BOC to EOC both in FCM and UO_2-ThO_2 pins. For example, the reference case having P/D=1.33 has 40.54g TRU per 1cm axial length for the whole assembly at BOC and it decreases to 23.69g TRU at EOC while 6.14g TRU is produced through BOC to EOC. So, the destruction rate of TRU in FCM pins for the reference case from 0 to 1850EFPDs is

42% while the net destruction rate of TRU in the whole assembly is 26.4%.

Table II TRU depletion and production in both, FCM fuel pins and UO2+ThO2 pins

P/D ratio	TRU in FCM (g) BOC	TRU in FCM (g) EOC	TRU in UO2-ThO2 (g) BOC	TRU in UO2-ThO2 (g) EOC	Total TRU (g) BOC	Total TRU (g) EOC	depletion rate (%)
1.27	40.54	23.92	0.00	6.83	40.54	30.75	-24.15
1.28	40.54	23.87	0.00	6.68	40.54	30.55	-24.64
1.29	40.54	23.82	0.00	6.54	40.54	30.35	-25.12
1.30	40.54	23.77	0.00	6.40	40.54	30.18	-25.56
1.31	40.54	23.73	0.00	6.27	40.54	30.00	-26.00
1.33	40.54	23.69	0.00	6.14	40.54	29.83	-26.42
1.34	40.54	23.65	0.00	6.02	40.54	29.67	-26.80
1.35	40.54	23.61	0.00	5.91	40.54	29.51	-27.20
1.36	40.54	23.57	0.00	5.79	40.54	29.37	-27.56
1.37	40.54	23.53	0.00	5.69	40.54	29.22	-27.92
1.38	40.54	23.50	0.00	5.59	40.54	29.08	-28.26

Table II shows that an increase of P/D ratio leads to a slight increase of TRU destruction rate in FCM pins, a reduction of TRU generation in UO_2-ThO_2 pins, and an increase of net TRU destruction rate over whole assembly. For example, the increase of P/D ratio from 1.33 to 1.38 leads to the increase of net TRU destruction rate from 26.4% to 28.3%.

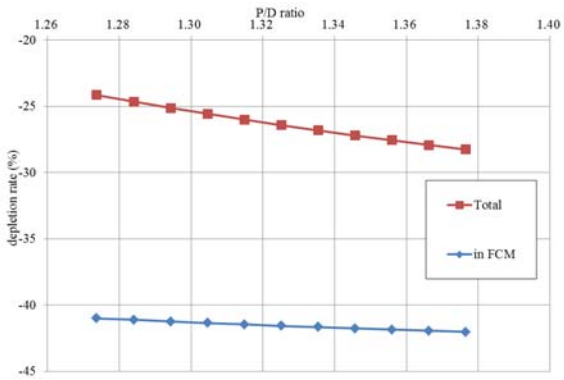

Fig. 7 Comparison of TRU destruction rate in FCM and net TRU destruction rate over whole assembly

Fig. 8 compares the changes of ^{233}U inventories over depletion time for the selected three P/D ratios and Fig. 9 shows the ^{233}U inventories at EOC versus P/D ratio. From these figures, it is shown that an increase of P/D ratio leads to a decrease of ^{233}U production at EOC.

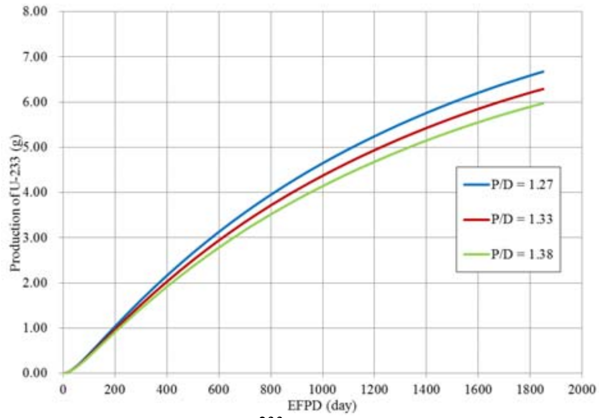

Fig. 8 Comparison of ^{233}U inventories in UO2-ThO2 pins over depletion time versus P/D ratio

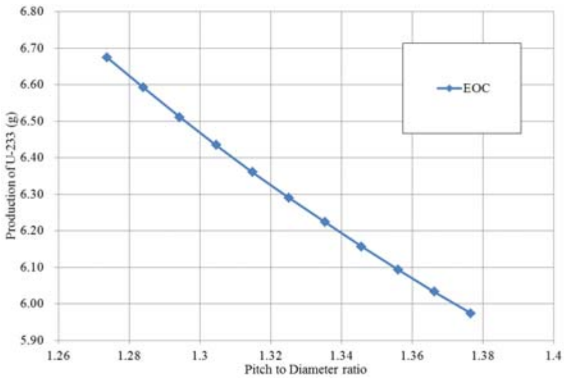

Fig. 9 Comparison of ^{233}U inventories in UO_2-ThO_2 pins at EOC versus P/D ratio

In the previous calculations, 500ppm of boron concentration was assumed but the boron concentrations at BOC are quite different from that at EOC in realistic LWR cores and also the boron concentration has a significant effect on MTC. To consider these facts, we re-performed the depletion analyses for three different boron concentrations of 10ppm, 500ppm, and 1500ppm and re-evaluated MTC both at BOC and EOC for the several selected P/D ratios. Fig. 10 and 11 show the changes of MTC versus P/D ratio at EOC and BOC, respectively. From Fig. 10, it is shown that an increase of P/D ratio leads to a less negative MTC at EOC for all the boron concentrations considered. For the 10ppm case, MTC from P/D=1.33 to P/D=1.38 at EOC is changed from -75 pcm/°C to -67 pcm/°C. Fig. 11 shows that MTC at BOC for all the boron concentrations considered are still sufficiently negative.

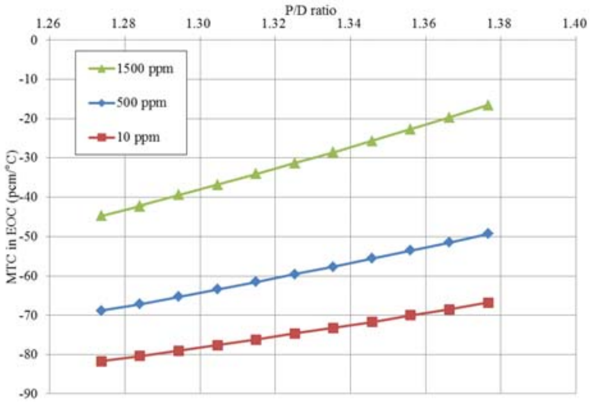

Fig. 10 MTC change following the change of P/D ratio for three cases of CBC (EOC)

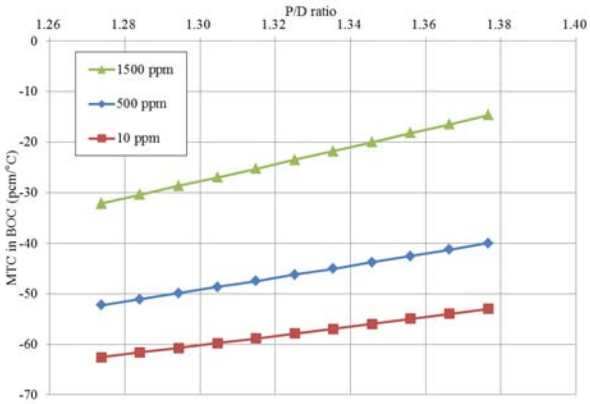

Fig. 11 MTC change following the change of P/D ratio for three cases of CBC (BOC)

2. Conclusion

In this work, we performed a detailed parametric study using P/D ratio to show its effects on the performances of the LWR fuel assemblies using UO_2-ThO_2 and TRU FCM pins for effective deep-burning of LWR spent fuel TRU. In our study, a special emphasis is given on the effects of the increased P/D ratio for MTC. From the results, it was found that an increase of P/D ratio (we considered up to P/D=1.38) leads to a less negative MTC and a less negative FTC, an increase of TRU destruction rate, and a decrease of ^{233}U production in UO_2-ThO_2 pins. In particular, a small change of P/D ratio from 1.33 to 1.38 led to a change of MTC from -75 pcm/°C to -67 pcm/°C at EOC, and a small increase of net TRU destruction rate from 26.4% to 28.3%. As conclusion, a small increase of P/D ratio is effective in obtaining the less negative MTC at EOC with a small increase of TRU destruction rate and without a significant degradation of FTC.

Acknowledgement

This work was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science, and Technology (Grant No.2013020660).

REFERENCES

[1] L. Snead and F. Venneri, "LWR Deep Burn: Near-term Route to Modified Open Cycle," Presentation Material, October (2011).
[2] F. Venneri et al., "Fully Ceramic Micro-encapsulated Fuels: A Transformational Technology for Present and Next Generation Reactors - Preliminary Analysis of FCM Fuel Reactor Operation," Transactions of the American Nuclear Society, 104, p.671 (2011)
[3] Ser Gi Hong et al., "A Neutronic Feasibility Study on the Deep-Burning of TRU in a Commercial LWR Core," Proceedings of GLOBAL 2011, No. 400856, December (2011).
[4] Ser Gi Hong et al., "Physics study of deep-burning of spent fuel transuranics using commercial LWR cores," Nuclear Engineering and Design, **259**, p.79 (2013).
[5] Gonghoon Bae, Ser Gi Hong, and Kyung Hoon Lee, "A Small LWR Core Design using ThO2-UO2 and Fully Ceramic Micro-encapsulated (FCM) Fuels for TRU Burning," Transactions of the Korean Nuclear Society Autumn Meeting, Gyeongju, Korea, October 23-25, 2013.
[6] J. Y. Cho et al., "DeCART v1.2 User's Manual", KAERI/TR-3438/2007.