Development of Control Rod Depletion Methodology for non-Boron Operation of SMR

Jinsu Park [a], Wonkyeong Kim [a], Yeongseok Kang [a], Deokjung Lee [a*]
[a]*Department of Nuclear Engineering, Ulsan National Institute of Science and Technology, 50 UNIST-gil, Ulsan, 44919*
[*]*Corresponding author: deokjung@unist.ac.kr*

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1. Introduction

Demand for small module nuclear reactors (SMRs) has increased worldwide. Additionally, soluble boron-free operation is widely considered to avoid boron dilution accidents and increase the negative moderator temperature feedback effect. New burnable absorbers such as CIMBA [1] or CSBA [2] are being developed to control reactivity during soluble boron-free operation. Since boron cannot be used to control excess reactivity, control rods are used instead. In a typical large commercial pressurized water reactor (PWR), the control rod is inserted for a short period of time, but in an SMR core, the control rod must be inserted into the core at all times. In this case, neutron spectrum hardening occurs due to control rod insertion, thereby changing nuclear fuel depletion. Additionally, the control rod worth decreases due to the depletion of the control rod material, so it is necessary to consider the effects of fuel depletion with the insertion of the control rod and the depletion of the control rod material.

Fig. 1 shows the effect of fuel assembly (FA) depletion with AIC control rod (CR) insertion. The FA depletion calculation is performed with STREAM using 2D neutron transport calculation, considering normal UO_2 FA depletion with and without CR insertion. Initially, the reactivity changes due to fuel depletion without CR insertion (All Rod Out, ARO) is approximately 61,000 pcm at 80 MWd/kg, whereas the reactivity changes due to fuel depletion with CR insertion (All Rod In, ARI) is between 31,000 and 34,000 pcm. This indicates that fuel depletion with CR insertion leads to a reactivity change difference of 27,000 to 31,000 pcm at 80 MWd/kg. The insertion of CR causes neutron spectrum hardening, altering fuel depletion behavior (e.g., initial uranium depletion and plutonium buildup).

Secondly, the control rod worth changes at 80 MWd/kg, considering CR material depletion for both ARO and ARI conditions, are approximately 2,700 to 3,000 pcm. In this FA depletion case, around 20% of the CR material is depleted at 80 MWd/kg. In other words, the difference in control rod worth between fresh and 20% depleted CR is around 3,000 pcm. Therefore, it is crucial to consider the effects of both fuel depletion due to CR insertion and CR material depletion on the cross section (XS) for nodal calculations.

The STREAM/RAST-K code system [3, 4] is a two-step code system developed in the CORE Laboratory of the Ulsan National Institute of Science and Technology. It has been verified using nuclear design information and experimental values from domestic commercial pressurized water reactors. However, its applicability should be evaluated, and additional functions should be implemented to design soluble boron-free SMRs.

This paper describes the newly developed XS treatment method to simulate control rod-inserted operation. Additionally, it presents numerical results for fuel assembly and SMR core using the new XS feedback and control rod depletion method.

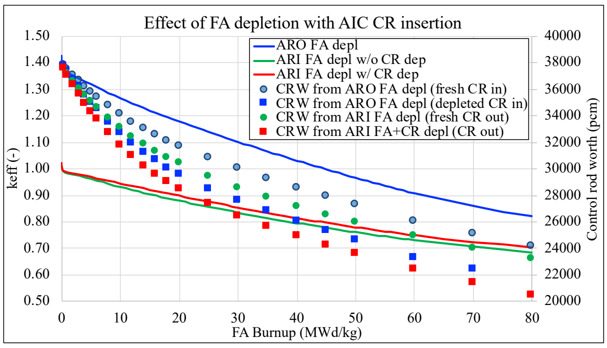


Fig. 1. Effect of FA depletion w/ and w/o AIC CR insertion.

2. XS Feedback and CR Depletion Method

This section describes the process of XS feedback for the original nodal diffusion code and the newly developed XS feedback method. Additionally, it explains the method for XS and depletion of the control rod material.

2.1 Original XS Feedback Method

In a typical two-step code system, the 2D lattice code generates group constants concerning the proper case matrix, while the nodal code performs 3D nodal calculations to demonstrate reactor behavior with fuel depletion. To create the cross section of a control rod-inserted node, the case matrix should include a branch condition for control rod insertion. However, it is challenging to create the cross section of a node where the control rod is frequently inserted and/or extracted due to two reasons: 1) The reference fuel assembly depletion calculation is conducted without control rod insertion, 2) Fresh control rod (CR) material is inserted for the branch calculation to generate the control rod-inserted node. Therefore, simulating an SMR core where the control rod is used to achieve a critical state is difficult using the original XS feedback method.

2.2 Node Indexing for Control Rod Material

Originally, the cross section of a node containing a control rod is calculated using a combination of cross sections with and without the control rod branch, in terms of residual macro cross sections. To accurately track the depletion of control rod material, the number density and micro cross section of the control rod material are extracted from the residual macro cross section. Therefore, the node-wise cross section can be calculated using the number density and micro cross section of heavy nuclides, burnable absorbers, fission products, and control rod material.

2.3 Branch of Control Rod Depleted Quantity

The quantity of depleted control rod material should be considered independently of fuel burnup. Therefore, the depleted control rod quantity ($\beta=1-N/N_0$) is introduced. When calculating the cross section of a node with a control rod, the material composition is obtained by combining the base fuel number density from the reference calculation with the fresh control rod number density. To capture the effect of control rod material depletion, several branch calculations are added to the original case matrix.

The ring-wise number density of control rod material is obtained in advance from the fuel depletion calculation with control rod insertion. The control rod material can be tabulated based on the degree of β. Then, branch calculations are added to the case matrix depending on the degree of β.

2.4 Unrodded and Rodded base XS

In the original cross section feedback method, the group constants are generated based on the unrodded (fuel depletion without control rod insertion) base depletion calculation. However, it is challenging to consider the changes in fuel depletion behavior due to spectrum hardening during control rod insertion using this method.

Therefore, two sets of group constants are generated-one with control rod insertion and one without. In the unrodded base cross section, the control rod-inserted cross section is calculated based on the degree of β. Additionally, cross sections with and without control rod insertion are calculated in the rodded base cross section.

2.5 Combination using Control Rod Insertion History

To combine the unrodded and rodded base cross sections, two sets of cross sections from unrodded and rodded base calculations are used. A control rod insertion history index is employed to blend these cross sections. The history index of a specific node is represented by the ratio of control rod-inserted volume to burnup, essentially a burnup-weighted rodded and unrodded depletion fraction. Then, the final node cross section is calculated by combining the unrodded and rodded base cross sections using the history index. Similarly, the heterogeneous form function for pin power reconstruction can be obtained through the same cross section process.

3. FA and SMR Core Results

In this section, the accuracy of the newly developed cross section model for simulating the control rod-inserted condition is evaluated for both the fuel assembly and SMR core.

3.1 FA Depletion with CR Insertion

The depletion calculation is performed for the normal 17x17 Westinghouse UO_2 fuel assembly both with and without the insertion of 24 AIC control rods. The assembly group constants are generated by the 2D lattice physics code, STREAM. Fuel assembly depletion calculations are performed using the nodal diffusion code, RAST-K, and its numerical results are compared with the reference solution generated by STREAM. Without control rod insertion, the difference in k_{eff} during fuel depletion between STREAM and RAST-K is smaller than 100 pcm. The difference in the depletion chain and the number of major nuclides for the depletion calculation causes the discrepancy in k_{eff}.

Fig. 2 shows the fuel assembly depletion calculation results with the insertion of a control rod. The reference solution is calculated by STREAM, and two RAST-K calculations are performed. The RAST-K calculation with the original cross section feedback method uses only unrodded base XS (marked with the red line). The newly developed cross section feedback method uses the combination of unrodded and rodded base XSs (marked with the blue line). By using the rodded base cross section, the k_{eff} difference is considerably decreased from 1300 to 200 pcm.

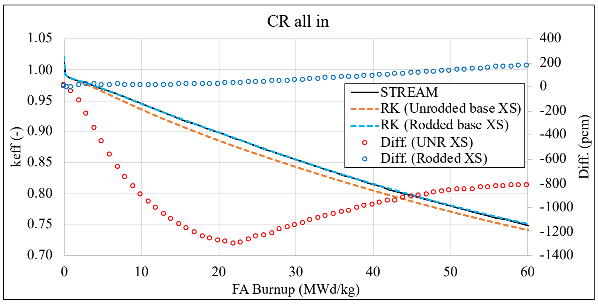
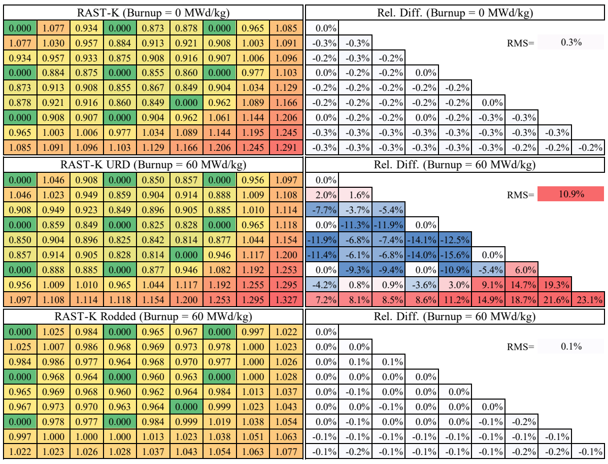


Fig. 2. Depletion calculation result for the control rod inserting fuel assembly.

Fig. 3 shows the pin power and its error compared with the STREAM solution. At 0 MWd/kg, since there is no interruption coming from control rod insertion, the root mean square (RMS) pin power error between RAST-K and STREAM is 0.3%. By using the heterogeneous form function from the rodded base calculation, the RMS pin power error decreases from 10.9% to 0.1%. It is noted that the control rod depleted quantity (β) of the AIC control rod material at 60 MWd/kg in this CR inserted FA depletion case is 15%.



RAST-K (Burnup = 0 MWd/kg)

0.000	1.077	0.934	0.000	0.873	0.878	0.000	0.965	1.085
1.077	1.030	0.957	0.884	0.913	0.921	0.908	1.003	1.091
0.934	0.957	0.933	0.875	0.908	0.916	0.907	1.006	1.096
0.000	0.884	0.875	0.000	0.855	0.860	0.000	0.977	1.103
0.873	0.913	0.908	0.855	0.867	0.849	0.904	1.034	1.129
0.878	0.921	0.916	0.860	0.849	0.000	0.962	1.089	1.166
0.000	0.908	0.907	0.000	0.904	0.962	1.061	1.144	1.206
0.965	1.003	1.006	0.977	1.034	1.089	1.144	1.195	1.245
1.085	1.091	1.096	1.103	1.129	1.166	1.206	1.245	1.291

Rel. Diff. (Burnup = 0 MWd/kg)

RMS= 0.3%

0.0%								
-0.3%	-0.3%							
-0.2%	-0.3%	-0.2%						
0.0%	-0.2%	-0.2%	0.0%					
-0.2%	-0.2%	-0.2%	-0.2%	-0.2%				
-0.2%	-0.2%	-0.2%	-0.2%	-0.2%	0.0%			
0.0%	-0.2%	-0.2%	0.0%	-0.2%	-0.3%	-0.3%		
-0.3%	-0.3%	-0.3%	-0.3%	-0.3%	-0.3%	-0.3%	-0.3%	
-0.3%	-0.3%	-0.3%	-0.3%	-0.3%	-0.3%	-0.2%	-0.2%	-0.2%

RAST-K URD (Burnup = 60 MWd/kg)

0.000	1.046	0.908	0.000	0.850	0.857	0.000	0.956	1.097
1.046	1.023	0.949	0.859	0.904	0.914	0.888	1.009	1.108
0.908	0.949	0.923	0.849	0.896	0.905	0.885	1.010	1.114
0.000	0.859	0.849	0.000	0.825	0.828	0.000	0.965	1.118
0.850	0.904	0.896	0.825	0.842	0.814	0.877	1.044	1.154
0.857	0.914	0.905	0.828	0.814	0.000	0.946	1.117	1.200
0.000	0.888	0.885	0.000	0.877	0.946	1.082	1.192	1.253
0.956	1.009	1.010	0.965	1.044	1.117	1.192	1.255	1.295
1.097	1.108	1.114	1.118	1.154	1.200	1.253	1.295	1.327

Rel. Diff. (Burnup = 60 MWd/kg)

RMS= 10.9%

0.0%								
2.0%	1.6%							
-7.7%	-3.7%	-5.4%						
0.0%	-11.3%	-11.9%	0.0%					
-11.9%	-6.8%	-7.4%	-14.1%	-12.5%				
-11.4%	-6.1%	-6.8%	-14.0%	-15.6%	0.0%			
0.0%	-9.3%	-9.4%	0.0%	-10.9%	-5.4%	6.0%		
-4.2%	0.8%	0.9%	-3.6%	3.0%	9.1%	14.7%	19.3%	
7.2%	8.1%	8.5%	8.6%	11.2%	14.9%	18.7%	21.6%	23.1%

RAST-K Rodded (Burnup = 60 MWd/kg)

0.000	1.025	0.984	0.000	0.965	0.967	0.000	0.997	1.022
1.025	1.007	0.986	0.968	0.969	0.973	0.978	1.000	1.023
0.984	0.986	0.977	0.964	0.968	0.970	0.977	1.000	1.026
0.000	0.968	0.964	0.000	0.960	0.963	0.000	1.000	1.028
0.965	0.969	0.968	0.960	0.962	0.964	0.984	1.013	1.037
0.967	0.973	0.970	0.963	0.964	0.000	0.999	1.023	1.043
0.000	0.978	0.977	0.000	0.984	0.999	1.019	1.038	1.054
0.997	1.000	1.000	1.000	1.013	1.023	1.038	1.051	1.063
1.022	1.023	1.026	1.028	1.037	1.043	1.054	1.063	1.077

Rel. Diff. (Burnup = 60 MWd/kg)

RMS= 0.1%

0.0%								
0.0%	0.0%							
0.0%	0.1%	0.1%						
0.0%	0.0%	0.0%	0.0%					
0.0%	-0.1%	0.0%	0.0%	0.0%				
0.0%	0.0%	-0.1%	0.0%	0.0%	0.0%			
0.0%	-0.1%	0.0%	0.0%	0.0%	-0.1%	-0.2%		
-0.1%	-0.1%	-0.1%	-0.1%	-0.1%	-0.1%	-0.1%	-0.1%	
-0.1%	-0.2%	-0.1%	-0.1%	-0.1%	-0.1%	-0.2%	-0.2%	-0.1%

Fig. 3. The pin power and its error at 0 and 60 MWd/kg along fuel depletion with CR insertion.

3.2 FA Depletion w/ CR Repeated Insertion/Extraction

Fig. 4 shows the depletion calculation results for the fuel assembly with repeated control rod movement. By using only unrodded base XS, the k_{eff} difference is around -100 pcm in the rod extracted condition, but it increases to around -1800 pcm under the condition of rod insertion. The k_{eff} difference decreases considerably to around -500 to -800 pcm by using the combination of unrodded and rodded base XSs.

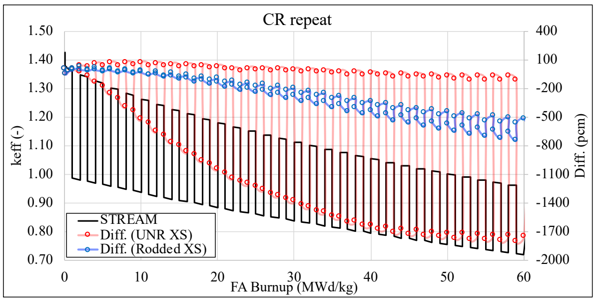
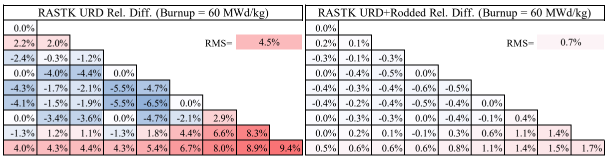


Fig. 4. Depletion calculation results for the fuel assembly with control rod repeated insertion and extraction.

Fig. 5 shows the pin power error at 60 MWd/kg after fuel assembly depletion with repeated control rod insertion and extraction. The insertion of the control rod causes a difference in pin-wise power distribution, leading to a discrepancy in the heterogeneous form function. By using the combination of unrodded and rodded base heterogeneous form function, the pin power decreases from 4.5% to 0.7%. It is noted that the beta of AIC at 60 MWd/kg in this condition is 8%.



RASTK URD Rel. Diff. (Burnup = 60 MWd/kg)

RMS= 4.5%

0.0%								
2.2%	2.0%							
-2.4%	-0.3%	-1.2%						
0.0%	-4.0%	-4.4%	0.0%					
-4.3%	-1.7%	-2.1%	-5.5%	-4.7%				
-4.1%	-1.5%	-1.9%	-5.5%	-6.5%	0.0%			
0.0%	-3.4%	-3.6%	0.0%	-4.7%	-2.1%	2.9%		
-1.3%	1.2%	1.1%	-1.3%	1.8%	4.4%	6.6%	8.3%	
4.0%	4.3%	4.4%	4.3%	5.4%	6.7%	8.0%	8.9%	9.4%

RASTK URD+Rodded Rel. Diff. (Burnup = 60 MWd/kg)

RMS= 0.7%

0.0%								
0.2%	0.1%							
-0.3%	-0.1%	-0.3%						
0.0%	-0.4%	-0.5%	0.0%					
-0.4%	-0.3%	-0.4%	-0.6%	-0.5%				
-0.4%	-0.2%	-0.4%	-0.5%	-0.4%	0.0%			
0.0%	-0.3%	-0.3%	0.0%	-0.4%	-0.1%	0.4%		
0.0%	0.2%	0.1%	-0.1%	0.3%	0.6%	1.1%	1.4%	
0.5%	0.6%	0.6%	0.6%	0.8%	1.1%	1.4%	1.5%	1.7%

Fig. 5. The pin power error at 60 MWd/kg during fuel depletion with repeated CR insertion and extraction.

3.3 KNF SMR Model

The RAST-K core calculation with the newly developed cross section feedback method is performed for the SMR core. A total of 69 fuel assemblies are loaded in the SMR core, and the active core height is 240 cm. The 17x17 Westinghouse type fuel assembly is used, with UO_2 pins enriched to 4.0% and 4.95% U-235, and Gd_2O_3 pins ranging from 0.3 to 8 w/o with natural to 70% enriched Gd-155 and Gd-157 to control excessive reactivity. The SMR core is designed for a 24-month cycle length, and equilibrium is achieved at the fifth cycle. The 28-finger control element assembly (CEA) is composed of AIC control rod material and is used to achieve a critical state with 50% overlapping movement. Fig. 6 shows the configuration of the 28-finger CEA in the fuel assembly and the position of regulating banks (R4 to R1) in the SMR core.

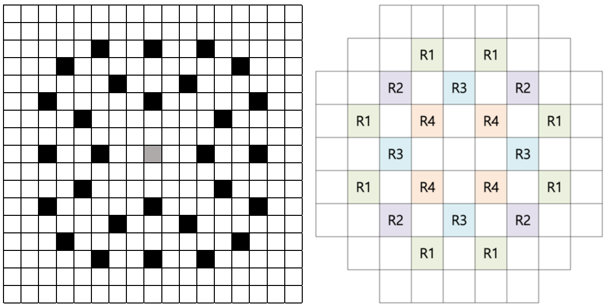


Fig. 6. Configuration 28 fingers CEA in FA and the position of regulating bank in SMR core.

3.4 SMR Core Multi-cycle Results

The depletion calculation is performed for multi-cycles of the SMR core by searching the critical control rod position. Fig. 7 shows the critical control rod position of R4 and R3 banks during the five cycles of the SMR core. The amount of control rod insertion required to achieve a critical state decrease until around 12 GWd/MT because almost all gadolinia loaded in the core is depleted. From the third cycle onward, discrepancies in the amount of control rod insertion become observable due to the depletion of control rod material. At the beginning of the equilibrium cycle, the maximum control rod depleted quantity of the R4 bank is 17%. Therefore, the maximum difference of critical control rod position of R3 bank during equilibrium cycle is around 37 cm.

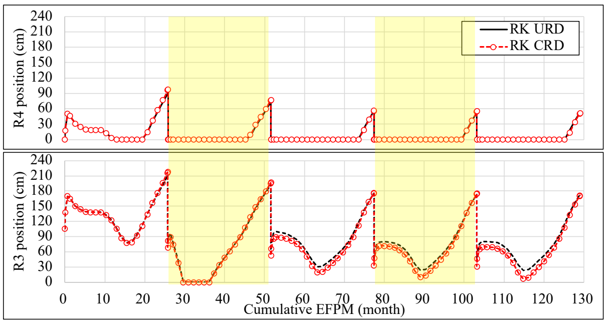


Fig. 7. Critical control rod position of R4 and R3 banks during five-cycles of SMR core.

Fig. 8 shows the pin peaking factor (Fq) during the multi-cycle calculation of the SMR. The behaviors of the pin peaking factors calculated from the original and new RAST-K methods are very similar. This similarity is because the hot pin location is irrelevant to the insertion of the control rod.

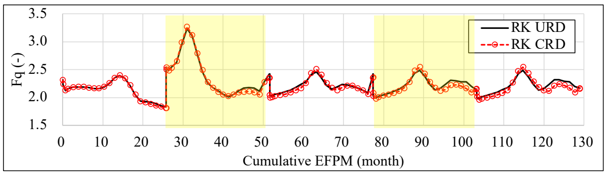


Fig. 8. Pin peaking factor during five-cycles of SMR core.

Fig. 9 shows the control rod worth of R4 bank during multi-cycle calculation of the SMR. Because the control rod material is depleted along the fuel cycle, the control rod worth decreases. By considering the depletion of control rod material, the 350 pcm of control rod worth is reduced at EOC of fifth cycle.

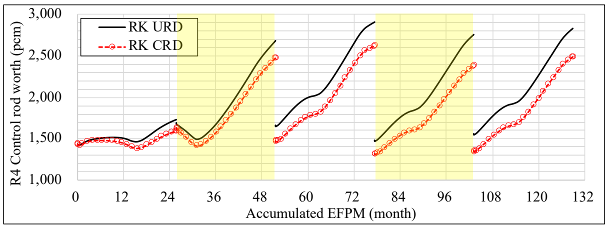
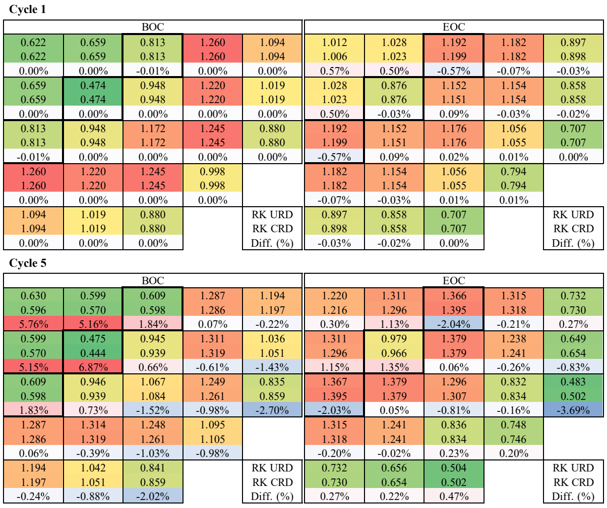


Fig. 9. R4 control rod worth during five-cycles of SMR core.

Fig. 10 shows the fuel assembly power distribution at the beginning of cycle (BOC) and end of cycle (EOC) for the initial and equilibrium cycles. At the BOC of the initial cycle, the power distribution is perfectly the same between the two methods. However, at the EOC of the initial cycle, discrepancies in the power distribution occur due to differences in the amount of control rod insertion. At EOC, more R4 and R3 rods are inserted in the case of the combination of unrodded and rodded base XSs, so the fuel assembly power at the CEA location is slightly lower than at other FA positions. At the BOC of the equilibrium cycle, the RMS difference in FA power is around 3%, decreasing to 1.3% at EOC. It is noted that the β of the R4 and R3 banks is 4% and 3%, respectively, at the EOC of the initial cycle.



Cycle 1

BOC					EOC				
0.622 0.622 0.00%	0.659 0.659 0.00%	0.813 0.813 -0.01%	1.260 1.260 0.00%	1.094 1.094 0.00%	1.012 1.006 0.57%	1.028 1.023 0.50%	1.192 1.199 -0.57%	1.182 1.182 -0.07%	0.897 0.898 -0.03%
0.659 0.659 0.00%	0.474 0.474 0.00%	0.948 0.948 0.00%	1.220 1.220 0.00%	1.019 1.019 0.00%	1.028 1.023 0.50%	0.876 0.876 -0.03%	1.152 1.151 0.09%	1.154 1.154 -0.03%	0.858 0.858 -0.02%
0.813 0.813 -0.01%	0.948 0.948 0.00%	1.172 1.172 0.00%	1.245 1.245 0.00%	0.880 0.880 0.00%	1.192 1.199 -0.57%	1.152 1.151 0.09%	1.176 1.176 0.02%	1.056 1.055 0.01%	0.707 0.707 0.00%
1.260 1.260 0.00%	1.220 1.220 0.00%	1.245 1.245 0.00%	0.998 0.998 0.00%		1.182 1.182 -0.07%	1.154 1.154 -0.03%	1.056 1.055 0.01%	0.794 0.794 0.01%	
1.094 1.094 0.00%	1.019 1.019 0.00%	0.880 0.880 0.00%		RK URD RK CRD Diff. (%)	0.897 0.898 -0.03%	0.858 0.858 -0.02%	0.707 0.707 0.00%		RK URD RK CRD Diff. (%)

Cycle 5

BOC					EOC				
0.630 0.596 5.76%	0.599 0.570 5.16%	0.609 0.598 1.84%	1.287 1.286 0.07%	1.194 1.197 -0.22%	1.220 1.216 0.30%	1.311 1.296 1.13%	1.366 1.395 -2.04%	1.315 1.318 -0.21%	0.732 0.730 0.27%
0.599 0.570 5.15%	0.475 0.444 6.87%	0.945 0.939 0.66%	1.311 1.319 -0.61%	1.036 1.051 -1.43%	1.311 1.296 1.15%	0.979 0.966 1.35%	1.379 1.379 0.06%	1.238 1.241 -0.26%	0.649 0.654 -0.83%
0.609 0.598 1.83%	0.946 0.939 0.73%	1.067 1.084 -1.52%	1.249 1.261 -0.98%	0.835 0.859 -2.70%	1.367 1.395 -2.03%	1.379 1.379 0.05%	1.296 1.307 -0.81%	0.832 0.834 -0.16%	0.483 0.502 -3.69%
1.287 1.286 0.06%	1.314 1.319 -0.39%	1.248 1.261 -1.03%	1.095 1.105 -0.98%		1.315 1.318 -0.20%	1.241 1.241 -0.02%	0.836 0.834 0.23%	0.748 0.746 0.20%	
1.194 1.197 -0.24%	1.042 1.051 -0.88%	0.841 0.859 -2.02%		RK URD RK CRD Diff. (%)	0.732 0.730 0.27%	0.656 0.654 0.22%	0.504 0.502 0.47%		RK URD RK CRD Diff. (%)

Fig. 10. Fuel assembly power distribution at BOC and EOC of initial and equilibrium cycles.

4. Conclusions

The new cross section treatment method to consider control rod depletion has been developed in the STREAM/RAST-K code system to simulate boron-free operation of SMRs. By adopting a combination of unrodded and rodded base cross sections based on the control rod insertion history index, the cross section can be calculated while considering fuel burnup and the quantity of depleted control rod material. This new cross section treatment method is utilized for the fuel assembly and SMR core multi-cycle calculation. It is observed that the consideration of rodded base cross section is particularly important when the amount of control rod insertion is considerable.

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REFERENCES

[1] Y. Jo, H. Shin, Design Optimization of Cylindrical Burnable Absorber Inserted into Annular Fuel Pellets for Soluble-Boron-Free SMR, Nuclear Engineering and Technology, Vol. 54, pp. 1464-1470, 2022.
[2] X. H. Nguyen, An Advanced Core Design for a Soluble-Boron-Free Small Modular Reactor ATOM with Centrally-Shielded Burnable Absorber, Nuclear Engineering and Technology, Vol. 51, pp. 369-376, 2019.
[3] J. Park, et al., RAST-K v2-Three-Dimensional Nodal Diffusion Code for Pressurized Water Reactor Core Analysis, Energies, Vol. 13, pp. 6324, 2020.
[4] S. Choi, D. Lee, Three-Dimensional Method of Characteristics/Diamond Difference Transport Analysis Method in STREAM for Whole-core Neutron Transport Calculation, Computer Physics Communications, Vol. 250, pp. 107332, 2020.