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Preliminary Study on the Effect of Control Rod Depletion for the Operation of SMR using STREAM/RAST-K

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1. Introduction

Soluble Boron Free (SBF) operation has been widely considered for the PWR-based small modular reactor (SMR) development to avoid the boron-dilution accident and to achieve the negative enough moderator temperature coefficient (MTC). For the reactivity control without the soluble boron, several designs of burnable absorbers have been suggested, such as CIMBA [1] and CSBA [2]. Even if new burnable absorber designs are applied, control rod movement is still the major requirement to achieve the criticality.

STREAM/RAST-K two-step code system has been developed in UNIST CORE lab, and its capability to analyze PWR core has been verified and validated [3]. Since the commercial PWRs have been barely operated under rod inserted condition, the effect of the control rod depletion was not significant. So, current nodal code adopts the cross-section feedback model based on the control rod materials' cross-section by including the macroscopic cross-section in residual cross-section for the efficiency. However, it was hard to predict the effect of control rod depletion due to the lack of number density and microscopic cross-section information. At the same time, fuel depletion history under rodded condition was not considered.

In this work, control rod depletion (CRD) module was implemented in STREAM/RAST-K two-step code system. To feedback more accurate cross-section, STREAM/RAST-K treats control rod materials' isotope-wise detailed microscopic cross-section data according to the depleted quantity of control rod materials. For the specific control rod materials, which have significant resonances such as Ag-In-Cd (AIC), STREAM performed resonance treatment by pin-based point-wise energy slowing-down method (PSM) [4]. In addition, STREAM generated the cross-section under rodded condition and RAST-K performs cross-section feedback considering the rodded history.

2. Control Rod Depletion Method

Fig. 1 shows the flow of CRD module. Implemented CRD module of RAST-K divides each control rods into a few meshes by their axial position. At every burnup step, RAST-K predicts the control rod position to achieve criticality. From the control rod position, CRD module calculates the volumetric fractions of contribution between CR meshes and fuel nodes. According to the depleted quantity of major absorber materials in CR meshes, CRD module feedback the CR mesh-wise cross-section. And RAST-K updates the node-wise homogenized macroscopic cross-section by compensating the cross-section of control rods according to the contribution fraction. Finally, depletion solver updates number densities of fuel and control rod materials. These number densities can be saved and used for the multi-cycle calculation. Also, CRD module can consider the node-wise rodded history and perform the improved cross-section feedback by utilizing additional cross-section based on rodded state generated by STREAM. The additional cross-section can provide the depletion behavior due to the neutron hardening under rodded condition.

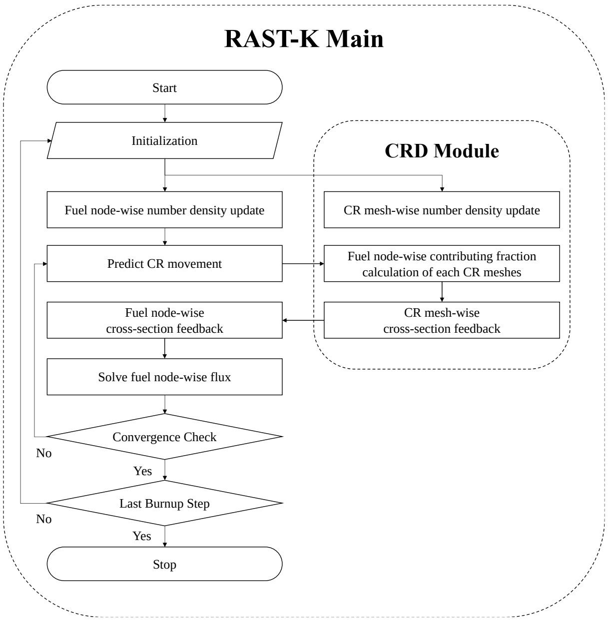

Fig. 1. Flow of RAST-K main and control rod depletion module

3. CIMBA Loaded Fuel Assembly Analysis Result

To verify the implemented CRD module, 0-D depletion analysis of CIMBA loaded fuel assembly was performed and compared with the STREAM calculation output. Fuel assembly containing 72 of CIMBA pins, 176 of UO_2 Pins and 12 gadolinia pins was used, which is a representative design of CIMBA loaded fuel assembly. A CIMBA pin contains cylindrical burnable absorber (BA) inside of an annular fuel pellet. The cylindrical shape of BA increases spatial self-shielding effect, and controls excessive reactivity for longer time compared to gadolinia pins. And AIC was selected as control rod material, which is widely used control rod material. Table 1 summarizes the model information compared CIMBA loaded fuel assembly and Fig. 2 shows the pin distribution.

Table 1. Summary of compared CIMBA loaded FA

FA geometry	17 × 17
Number of Annular UO_2 Pin	176
Number of CIMBA Pin	72
Number of Gadolinia Pin	12
Number of guide tubes	28 (+1 Inst. tube)
Control Rod Material	Ag-In-Cd (AIC)

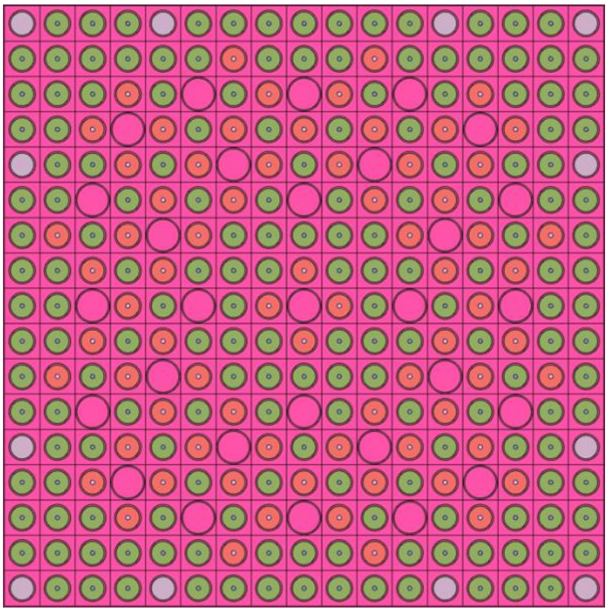

Fig. 2. Pin distribution of CIMBA loaded FA

The depletion analysis of AIC rodded CIMBA loaded fuel assembly was performed by STREAM and RAST-K. Table 2 demonstrates the calculation options for the compared cases.

Table 2. Description of calculation options

Case	**Code**	**Control Rod Depletion**	**Rodded History**
Reference	STREAM	Considered	Considered
Case 1	RAST-K	-	-
Case 2	RAST-K	Considered	-
Case 3	RAST-K	-	Considered
Case 4	RAST-K	Considered	Considered

Fig.3 shows the infinite multiplication factor of fuel assembly against the depletion time. Black solid line represents the reference case, k_∞ calculated by STREAM. The blue dotted line with squared marks represents Case 1, RAST-K output with current using options for the commercial PWR analysis. The purple dotted line with diamond marks represents Case 2, the RAST-K output considering control rod depletion but not considering rodded history. Compared to Case 1, it was observed that k_∞ was increase with the depression of the neutron absorption of control rod due to the depletion of control rod material. The green dotted line with circular marks represents Case 3, not considering control rod depletion but rodded history. Compared to Case 1, RAST-K could follow the depletion of gadolinia and fuel that predicted local maximum of k_∞ curve more accurately by considering the rodded history. The red dotted line with triangular marks represents the Case 4, considering both control rod depletion and rodded history. Compared to reference data, RAST-K predicted more accurate and less than 109 pcm of error appeared.

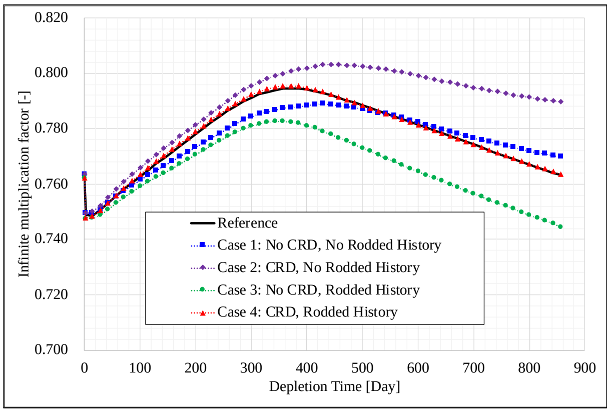

Fig. 3. Infinite multiplication factor against burnup

Fig.4 shows the decrease of total number density of major absorber materials, ^{107}Ag, ^{109}Ag, ^{110}Cd, ^{113}Cd, ^{113}In, and ^{115}In. During 850 days of depletion, around 7 % of major absorber materials were depleted. Case 2 and 4, both of RAST-K outputs considering control rod depletion predicted number density with less than 0.1 % error.

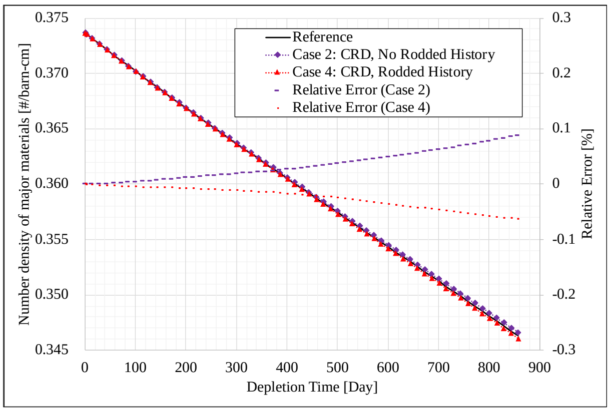

Fig. 4. Decreasing curve of total number density of major absorber materials

4. Conclusions

To analyze the soluble boron free SMR core more accurately, prediction of control rod depletion (CRD) effect was required. In this work, CRD module was implemented in STREAM/RAST-K two-step code and performed fuel assembly depletion analysis. By the implementation of CRD module, RAST-K could consider depletion of control rod and rodded history. To verify the CRD module, STREAM and RAST-K performed depletion analysis of Ag-In-Cd rodded CIMBA loaded fuel assembly. Infinite multiplication factor and number density of major absorber materials were compared under four different cases: (1) no CRD or rodded history considered; (2) CRD considered, but rodded history not considered; (3) rodded history considered, but CRD not considered; and (4) both CRD and rodded history considered. The results showed that RAST-K predicted more accurate infinite multiplication factor when both CRD and rodded history were considered. The difference was less than 109 pcm. Also, implemented CRD module predicted the total number density of major absorber materials with less than 0.1% error. The results demonstrate the capability of the STREAM/RAST-K to improve the accuracy of SMR analysis under soluble boron free operation. In this work, only fully rodded case was considered. To consider complexed rodded history accurately, history-follow cross-section feedback and rod cusping effect correction should follow.

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