Calculation of Nuclear Heating and B-10 Neutron Absorption Rate at Boron Carbide Burnable Absorber Rods in LEU+ Core

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1. Introduction

Recently, the SMR core design using low enriched uranium plus (LEU+) is being highlighted as a solution for reducing the amount of spent fuel per electricity generation [1]. To achieve higher burnup of fuel with longer cycle length, the B_4C-Al_2O_3 burnable absorber can be utilized to effectively handle the excessive reactivity throughout the cycle. However, the He gas release from the neutron absorption reaction of B-10 is a serious issue because increased rod internal pressure can finally lead to rod rupture. For this reason, in the LEU+ core applying B_4C burnable absorber rod, the amount of He gas release during operation should be evaluated using fuel simulation code. The nuclear heating and B-10 neutron absorption rate history is required as input data, which can be calculated with neutronics codes.

There are various previous studies calculating nuclear heating using Monte Carlo transport codes [2-5]. Among them, McCARD [6] has the capability to calculate neutron heating and prompt photon heating from the eigenvalue calculation, and delayed photon heating from the source mode calculation by automatically generating delayed photon source from the burnt material composition. Although it is appropriate for heating calculation, it is still burdensome to conduct whole core following calculations with McCARD considering T/H and equilibrium xenon effect, and even more time-consuming if the burnup cells are axially divided to consider dependence on axial position. Therefore, in the study, the hybrid method using DeCART2D/MASTER [7-8] whole core following calculation and McCARD 2D infinite assembly calculation is suggested. From the given LEU+ core design, the representative assembly is first selected which achieves the largest burnup throughout the operation among the whole assemblies. Then, the nuclear heating and B-10 neutron absorption rate history of the axially divided nodes of B_4C burnable absorber rods in the assembly is calculated using the suggested method.

2. Selection of Representative Assembly

Based on the preliminary LEU+ core design employing B_4C-Al_2O_3 burnable absorber, an assembly having maximum discharge burnup is selected as a limiting case which is expected to generate the largest He gas release. The full information of the LEU+ core design and operating history are omitted in this paper. Instead, the basic information for the representative assembly is given in Table I. The pin arrangement of the 'C1' type assembly is given in Fig. 1. The fuel lattices and B_4C burnable absorber lattices are composed of pellet, gap, cladding, and moderator. It can be noted from Fig2. that there are B_4C burnable absorber rods whose pellet density is different according to axial position. The length of each axial node of the rod is 10cm, by dividing axial height by 24 nodes. For the rods in this selected assembly, B-10 neutron absorption rate and nuclear heating are calculated along 1860 EFPD, which is the sum of cycle length of cycle 3 and cycle 4.

Table I: Basic Information of Representative Assembly

Parameter	Value	
Assembly type	C1	
Enrichment of fuel	8.1 [w/o]	
Weight percent of Gadolinium	8.0 [w/o]	
Operation cycles	Cyc 3	Cyc 4
Cycle length of cycles	930 [d]	930 [d]
Loading position in the core	D,3	G,7
Axial average assembly burnup	63.784 [MWd/kgU]	
Maximum assembly burnup in axial nodes	76.858 [MWd/kgU]	
Axial height	240 [cm]	

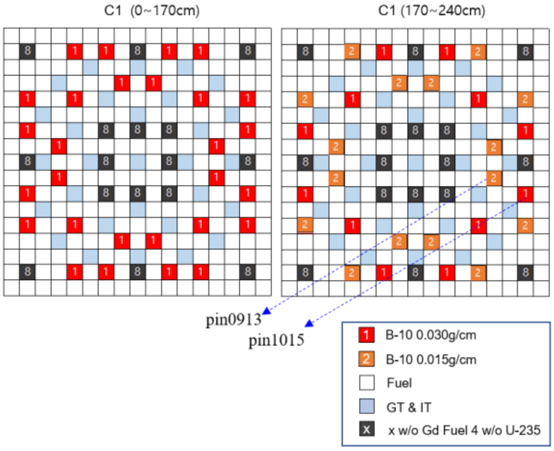

Fig. 1. Pin arrangement of C1 type assembly depending on axial position

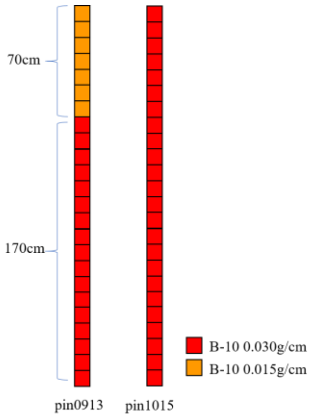

Fig. 2. Axial configuration of B_4C burnable absorber rod of C1 type assembly

3. Calculation Methods

3.1 DeCART2D/MASTER whole core following calculation

The whole core following calculation from cycle 1 to cycle 7 is conducted using DeCART2D/MASTER code system. The objective of the calculation is to generate data following the core design as it is. For each cycle, MASTER is used to perform depletion calculation with the group cross section generated from DeCART2D infinite assembly calculation, considering the change in the loading pattern of fuel assemblies. T/H and equilibrium xenon effect is considered, and depletion calculation is conducted for axially divided nodes.

3.2 McCARD 2D-infinite assembly calculation

A 2D-infinite assembly calculation for representative assembly is conducted using McCARD. The objective of McCARD calculation is to generate reference data of nuclear heating according to assembly burnup. McCARD eigenvalue burnup calculation is performed for 3000 day with the 'NP' mode option, which simulates neutron and also prompt photon. The neutron heating and prompt photon heating at all burnup steps are tallied. At each burnup step, a source mode calculation with delayed photon source is performed to calculate delayed photon heating. To consider B_4C burnable absorber rods that has axially different B-10 composition, these procedure are performed with two different pin arrangements shown in Fig. 1.

3.3 B-10 neutron absorption rate

The B-10 neutron absorption rate history of representative assembly is calculated from the output of DeCART2D/MASTER whole core following calculation results. The B-10 neutron absorption rate can be calculated as

$$R^{B-10}_{ijk,(n,abs)} = \sum_{g=1,2} \phi_{g,ijk} N^{B-10}(Bu_k)\sigma^{B-10}_{g,(n,abs)}(Bu_k)\ldots(1)$$

where i,j is row and column index of B_4C burnable absorber rods in an assembly, k is axial index in axial nodes, g is group index, R is reaction rate, ϕ is flux, N is number density, σ is microscopic cross section of reactions, Bu is assembly burnup. Here, the flux can be found in the MASTER pin-by-pin information file (MAS_PPI). The number density and microscopic cross section can be interpolated from the DeCART2D homogenized group constant (HGC) file with the burnup of corresponding axial node. The overall procedure is shown in Fig 3.

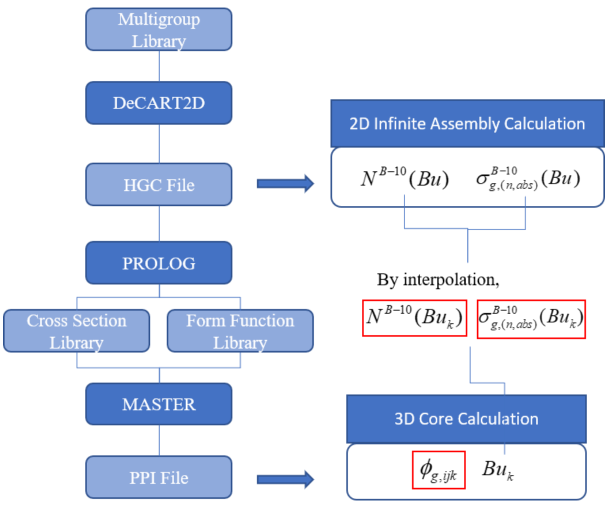

Fig. 3. Overall procedure to calculate B-10 neutron absorption rate using DeCART2D/MASTER

3.4 Nuclear heating

The nuclear heating is calculated using both whole core following calculation results and McCARD results. The nuclear heating can be calculated as

$$Q_{ijk} = \frac{Q_{np}}{R^{B-10}_{(n,abs)}}(Bu_k) R^{B-10}_{ijk,(n,abs)} + Q_{dg}(Bu_k)\ldots(2)$$

where Q_{np} is a sum of neutron and prompt photon heating, Q_{dg} is delayed gamma heating, and the other indices are same with Eq.(1). Here, the ratio of Q_{np} per B-10 neutron absorption rate according to burnup can be earned from McCARD results, and it can be interpolated with the assembly burnup of corresponding axial position. And it can be noted that sum of neutron and prompt photon heating at position *i,j,k* is calculated by multiplying B-10 neutron absorption rate at the position by the interpolated ratio. This is based on the fact that the neutron absorption reaction in B_4C burnable absorber is the dominant source of neutron and prompt photon heating. Now, the second term in Eq. (2) can be also earned from McCARD results by interpolating with the assembly burnup. The overall procedure is shown in Fig. 4.

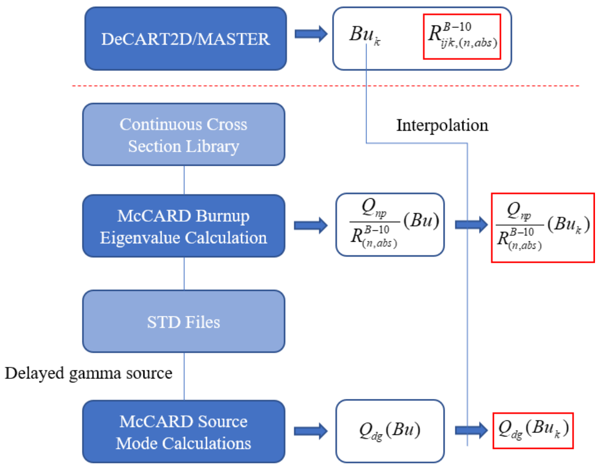

Fig. 4. Overall procedure to calculate nuclear heating using DeCART2D/MASTER and McCARD

4. Results

Two sample pins, pin0913 and pin1015 are selected in the representative assembly out of 28 pins to show the results considering symmetry. Fig. 5 and Fig. 6 show the axially averaged B-10 neutron absorption and nuclear heating history of pin0913 in representative assembly. The decrease in B-10 neutron absorption rate is mainly due to B-10 depletion, and it can be observed that nuclear heating follows the overall trend of the absorption rate. The sudden drop at day 930 can be explained by the change in assembly power due to the position change of the C1 assembly in the core from cycle 3 to cycle 4. A slight increase near day 1860 is also observed because the average neutron amplitude increases near the end of cycle (EOC).

Fig. 7 and Fig. 8 show the B-10 neutron absorption rate and nuclear heating according to axial position at 5 EFPD. Two B_4C burnable absorber pins with different radial positions are compared. As pin0913 is closer to the center of assembly than pin1015, it shows larger reaction rate due to higher flux from 0 to 170 cm. However, at the axial position from 170 cm to 240 cm, the reaction rate of pin0913 is smaller because the density of B-10 is much lower than that of pin1015.

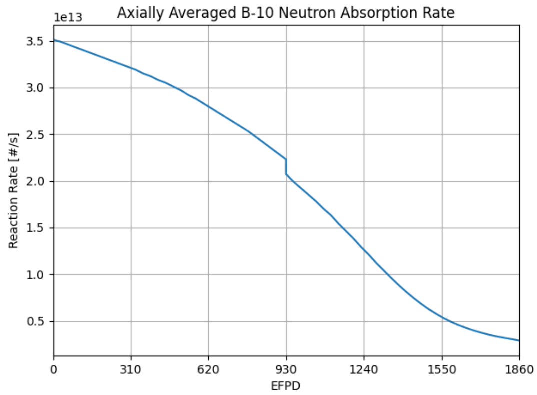

Fig. 5. Axially averaged B-10 neutron absorption rate history of B_4C burnable absorber pin0913

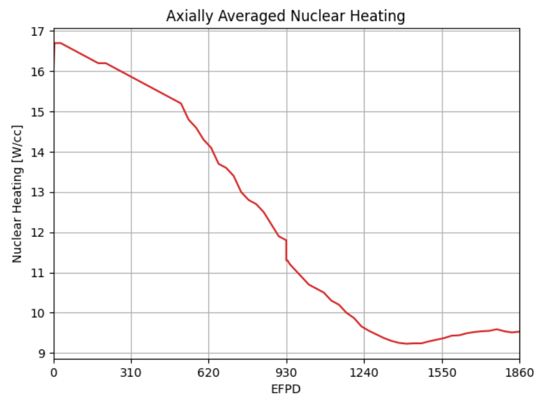

Fig. 6. Axially averaged nuclear heating history of B_4C burnable absorber pin0913

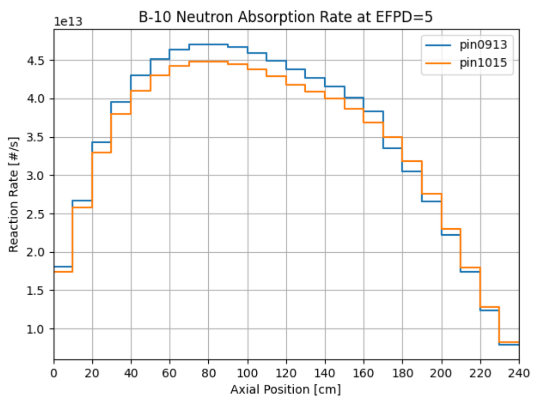

Fig. 7. B-10 neutron absorption rate according to axial position at EFPD=5[day]

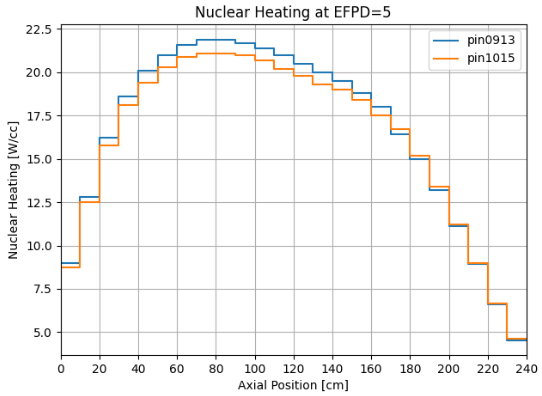

Fig. 8. Nuclear heating according to axial position at EFPD=5[day]

5. Conclusions

The B-10 neutron absorption rate and nuclear heating of B_4C burnable absorber rods in LEU+ core using them as burnable absorbers are evaluated. A representative assembly with the largest discharge assembly burnup is selected as a limiting case, which is expected to release the most He gas over the operation history. The whole core following calculation is performed with DeCART2D/MASTER code system and used to calculate the B-10 neutron absorption rate. Then, McCARD 2D-infinite assembly calculations are performed for representative assembly and nuclear heating is calculated using both the McCARD results and DeCART2D/MASTER results. While both the B-10 neutron absorption rate and nuclear heating decreased over operation history, nuclear heating showed a slight increase at EOC. Both parameters showed similar trends over time and along the axial position. The effect of axial density difference of B-10 is observed in the results.

There are two major assumption in this study. The first is that the temperature condition of assembly doesn't seriously affect the B-10 reaction rate or nuclear heating. The next point is that the parameters calculated in 2D infinite assembly according to burnup may show negligible differences compared to the actual 3D whole core following calculation. These two assumptions should be evaluated carefully for the further application of the suggested methods.

ACKNOWLEDGMENT

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REFERENCES

[1] IAEA, "Light Water Reactor Fuel Enrichment beyond the Five Per Cent Limit: Perspectives and Challenges," IAEA-TECDOC-1918, ECDOC series, 2020. ISSN 1011-4289.
[2] Chul Gyo Seo et al., "Nuclear Heating Analysis for HANARO Cold Neutron Source", Proceeding of Korean Nuclear Society Spring Meeting, 2005.
[3] SeongWoo Yang, "Quantitative Estimation of Heating by Delayed Gamma Ray for In-Reactor Testing at HANARO," in Transactions of the Korean Nuclear Society Virtual Spring Meeting, South Korea, 2021.
[4] Sung Jae Hwang, "Nuclear Heating Analysis for HANARO Cold Neutron Source by McCARD Burnup Calculations", KNS, 2021.
[5] A. Talamo et al., "Monte Carlo Calculation of the Energy Deposition in the Transformational Challenge Reactor", ANS, 2020.
[6] H. J. Shim et al., "McCARD: Monte Carlo Code for Advanced Reactor Design and Analysis," *Nucl. Eng. Technol.*, 44, pp.151-176, 2012.
[7] C. Y. Cho et al., "DeCART2D v1.1 User's Manual," Korea Atomic Energy Research Institute, KAERI/UM-40/2016.
[8] J. Y. Cho, et al., "MASTER v4.0 User's Manual," KAERI/UM-41/2016, 2016.