Preliminary Analysis on Accuracy of High Enriched Gadolinium Burnable Absorber Depletion

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1. Introduction

Gadolinium-155 and Gadolinium-157(^{155}Gd, ^{157}Gd) have high neutron capture cross sections in thermal neutron energy range, making them effective burnable absorbers (BAs) in commercial pressurized water reactors (PWRs). The use of gadolinia BAs is an effective method for controlling excess reactivity and power peaking by providing strong negative reactivity. The importance of gadolinia BAs has grown recently due to the increasing demand for Soluble Boron-Free (SBF) reactor operations. In SBF reactors, BAs are the primary means of controlling excess reactivity. However, the conventional gadolinia BAs typically used in commercial PWRs often fail to provide sufficient negative reactivity to effectively manage the excess reactivity in SBF reactors. ^{155}Gd and ^{157}Gd -enriched gadolinium is a promising candidate for a new BA type suitable for SBF reactors, as it can provide significant negative reactivity to compensate for the absence of soluble boron [1]. However, there have been few studies on the accuracy of enriched gadolinium depletion, despite the frequent reporting of SBF core designs using enriched gadolinium BAs.

The neutron transport code, STREAM, developed at Ulsan National Institute of Science and Technology (UNIST), solves neutron transport equation based on method of characteristics (MOC) [2]. STREAM provides explicit high-order scattering modeling and its calculation to treat with an anisotropic scattering effect. Although the explicit calculation offers precise accuracy, it requires significant computational resources. To compromise on computational resources, STREAM uses transport-corrected P0 (TCP_0) cross sections generated by the inflow transport correction method. The accuracy of the inflow transport correction method is verified with some benchmark problems [3]. However, there is no accuracy analysis of the inflow transport method for highly enriched gadolinia pin.

In this study, the accuracy of depletion calculations for two-dimensional fuel assemblies (FAs) and pins using enriched gadolinium is analyzed with both the conventional predictor-corrector (PC) method and quadratic depletion (QD) method. Additionally, the effect of inflow transport correction method and high-order scattering treating anisotropic scattering are analyzed. Reference solutions for each case are generated using the Monte Carlo method-based reactor analysis code MCS which was developed at UNIST.

2. Methods

In this study, depletion calculations with STREAM are performed with an MOC ray distance of 0.01cm, 128 azimuthal angles and 6 polar angles. Each pin is divided into 15 radial rings. For the high-order scattering, second-order Legendre polynomial is used.

The accuracy of high enriched Gd depletion is studied using a single UO_2-Gd_2O_3 gadolinia pin and a 17x17 VERA 2P FA consisting of 24 gadolinia pins, 25 guide tubes and 240 fuel fins withs 3.1 weight percent (w/o) enriched UO_2. In this study, gadolinia pin contains a mixture of 1.8% w/o enriched uranium oxide and gadolinia with various enrichment of ^{155,157}Gd, 30.2 atomic percent (a/o) which is natural gadolinium, 40 a/o, 50 a/o, 60 a/o and 70 a/o. Table I and Fig 1 show the arrangement of pins in FA and enrichment of gadolinia and fuel. Table 2 summarizes test cases for analyzing the accuracy of Gd depletion with varying depletion method, burnup step size, and enrichment of ^{155,157}Gd.

Table I: Pin arrangement of FA and its contents

Pin arrangement in FA	17 x 17
Number of UO_2 fuels	240
Enrichment of UO2 fuels [w/o]	3.1
Number of gadolinia pins	24
Enrichment of UO_2 in Gd pin [w/o]	1.8
Enrichment of $^{155+157}$Gd [a/o]	Nat, 40, 50,60,70

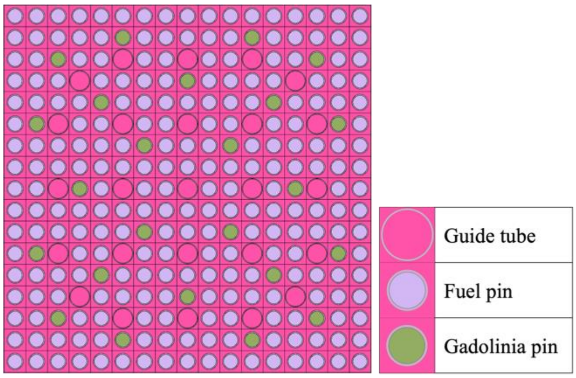

Fig. 1. Pin distribution of VERA 2P fuel assembly

Table II: Cases for analyzing Gd depletion accuracy of STREAM

CASE #	Depletion	Step size [MWd/kgU]	Treatment of Anisotropic scattering
CASE 1 (FA)	QD	0.5	Inflow transport correction
CASE 2 (FA)	QD	0.5	High-order scattering
CASE 3 (pin)	PC	0.5	Inflow transport correction
CASE 4 (pin)	PC	0.5	
CASE 5 (pin)	PC	0.5	High-order scattering

3. Gadolinium Depletion Results

3.1. 2D FA Depletion (CASE1~2)

To evaluate the impact of Gd enrichment on the accuracy of depletion calculation using STREAM (ST), depletion calculations were conducted varying ^{155}Gd and ^{157}Gd enrichment from 30 a/o (Natural Gd) to 70 a/o. QD method was applied to the Gd depletion with VERA 2P FA with a burnup step size of 0.50 MWd/kgU from 0 to 32.50 MWd/kgU, and 2.50 MWd/kgU from 32.50 to 60.00 MWd/kgU. Fig. 2 shows infinite multiplication factor along burnup steps based on MCS calculation.

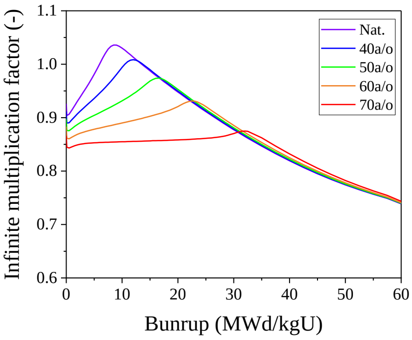

Fig. 2. Depletion results of VERA 2P FA with varying ^{155}Gd and ^{157}Gd enrichment using MCS.

The result indicates that using high-enriched gadolinium is an effective means for holding excess reactivity. The more enrichment of ^{155}Gd and ^{157}Gd used, the longer the FA can hold the excess reactivity. However, errors were observed between the depletion results obtained with ST and the reference solution. Fig. 4 and Table III shows the differences in the infinite multiplication factor, Δk_{inf} (Δ=ST-MCS), with its root mean square error (RMSE) throughout the burnup cycle.

Table III: RMSE in pcm of FA depletion results with ST

$^{155+157}$Gd Enrichment	Nat.	40a/o	50a/o	60a/o	70a/o
CASE1 QD, inflow	133	142	151	159	164
CASE2 QD, high-order	175	184	192	202	212

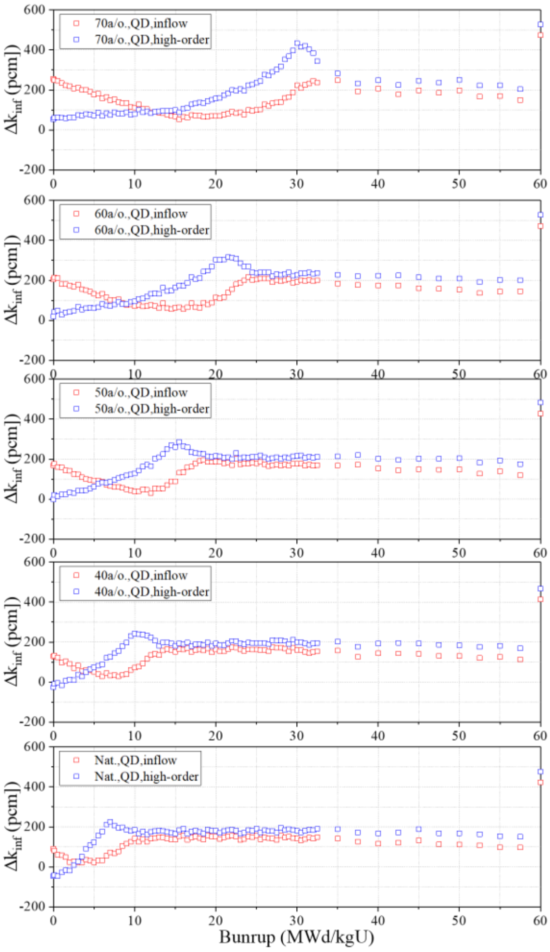

Fig. 3. Δk_{inf} of VERA 2P FA with QD method varying ^{155}Gd and ^{157}Gd enrichment.

The result shows that higher enrichment of ^{155}Gd and ^{157}Gd leads to increased RMSE and lager Δk_{inf} compared to the reference solution in both inflow case (CASE1) and high-order scattering case (CASE2). From the RMSE perspective, CASE1 appears more accurate then CASE2. However, at BOC CASE2 achieves Δk_{inf} of -46 pcm ~ 54 pcm, which is more accurate than CASE1 (91 pcm ~ 200 pcm). It means that CASE2 provides more accurate calculation at BOC, with the difference emerging during depletion due to the high-enriched gadolinium. Moreover, considering that the high-order scattering treatment is more accurate method to treat anisotropic scattering [4], CASE2 is physically more valid than CASE1. The effect of high-order scattering on the enriched gadolinium is further investigated in next section, single 2D pin depletion.

3.2. 2D Pin Depletion (CASE3~5)

Fig. 4 shows the reference case for a single gadolinia pin depletion varying the enrichment of ^{155}Gd and ^{157}Gd. As enrichment increases, k_{inf} as a function of burnup becomes flatter and the peak k_{inf} decreases due to the reduced spatial self-shielding effect with the increased enrichment, which is induced by huge capture cross section of ^{155}Gd and ^{157}Gd in thermal neutron rage.

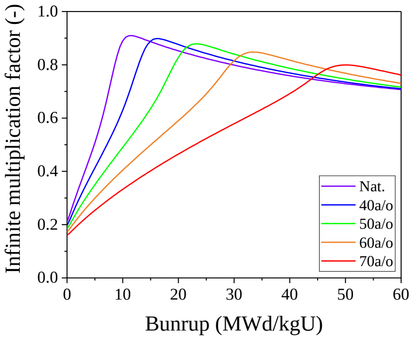

Fig. 4. Depletion results of single gadolinia pin with varying ^{155}Gd and ^{157}Gd enrichment using MCS. (step size of 0.50 MWd/ kgU)

Table IV and Fig. 5 summarize the depletion results for CASE3~5 using ST, RMSE and Δk_{inf}. CASE3 has burnup step of 0.50 MWd/kgU from 0 to 32.50 MWd/kgU and 2.50 MWd/kgU from 32.50 MWd/kgU to 60.00 MWd/kgU. In all the cases, the single pin depletion results clearly show that Δk_{inf} tends to increase with gadolinium enrichment. From comparison of CASE3 and CASE4, QD method induces more error than the PC method. As shown in Fig. 5, there is little difference between the two cases until the highest Δk_{inf} where the isotopes of Gd almost burns out. Beyond this burnup point, the QD method results in slightly larger errors in all the ^{155}Gd and ^{157}Gd enrichment cases. It means that the QD method doe not significantly improve accuracy regardless of the enrichment.

The comparison of CASE4 and CASE5 shows the effect of explicit high-order scattering treatment on accuracy of gadolinia pin depletion calculation using ST. When explicit model is applied instead of the inflow transport correction method to treat anisotropic scattering effect, the accuracy is improved, particularly in cases with high enrichment, 60 a/o and 70 a/o. In CASE4, the RMSE of the inflow method is 195 pcm and 311 pcm for 60 a/o and 70 a/o respectively. In CASE5 with the high-order scattering model, the RMSE is 170 pcm and 275 pcm for the same enrichments. In short, anisotropic scattering effect with increasing the ^{155,157}Gd enrichment is not dealt well in the inflow method.

Table IV: RMSE in pcm of single gadolinium pin depletion results with ST with burnup length of 60.00 MWd/kgU

$^{155+157}$Gd Enrichment	Nat.	40a/o	50a/o	60a/o	70a/o
CASE3 QD, inflow	139 (¶143)	164 (¶168)	198 (¶202)	267 (¶271)	209
CASE4 PC, inflow	66 (¶87)	90 (¶120)	130 (¶173)	195 (¶256)	311
CASE5 PC, high-order	72	88	117	170	275

¶: RMSE with burnup length of 32.50 MWd/kgU to compare CASE3 and CASE4

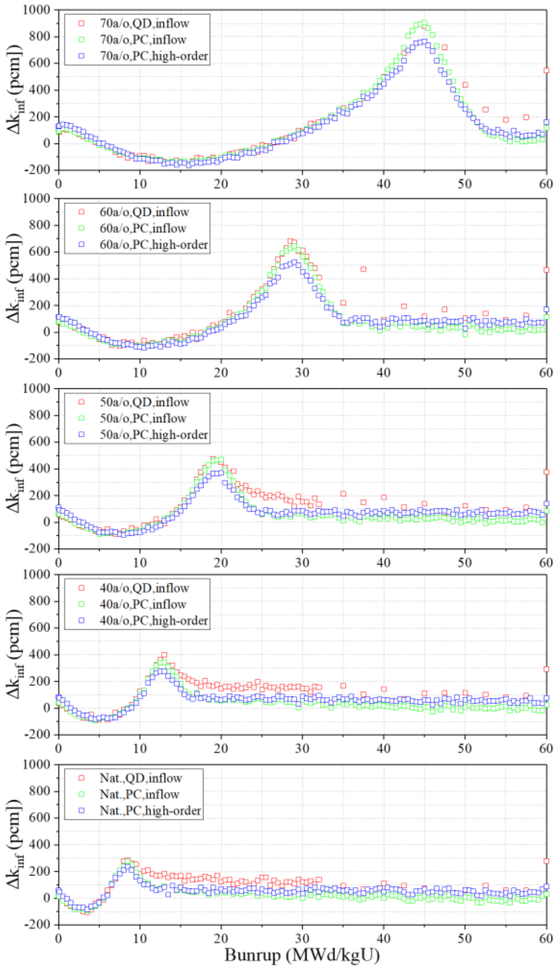

Fig. 5. Δk_{inf} of single gadolinia pin in CASE3~5.

Fig 6 and Fig. 7 are ^{155}Gd and ^{157}Gd number densities (ND) of CASE5 with natural enrichment, 50 a/o and 70 a/o and its percentage difference (ST-MCS/MCS x 100) between ST and the reference solution. ^{157}Gd depletes more faster than ^{155}Gd due to the larger capture cross section of ^{157}Gd than ^{155}Gd. Δk_{inf} of all enrichment cases increases until the number density of ^{155}Gd falls to approximately 2.0E-07 $b^{-1}\cdot cm^{-1}$, where the gadolinium isotopes almost depleted. After this point, Δk_{inf} decreases stiffly and converges to tens of pcm.

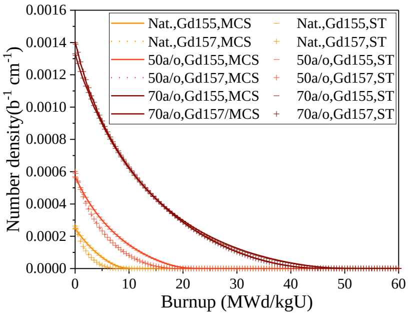

Fig. 6. ^{155}Gd and ^{157}Gd number density of CASE5

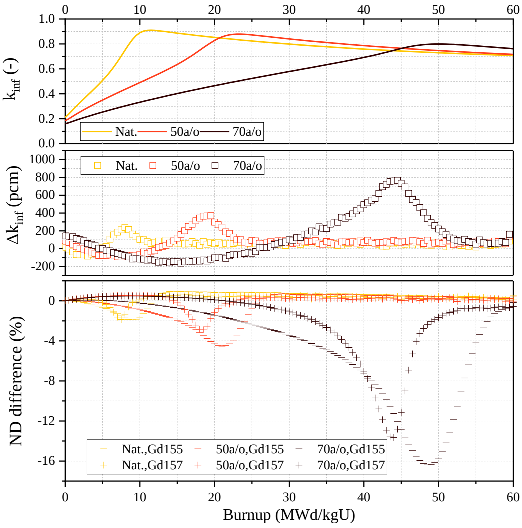

Fig. 7. ^{155}Gd and ^{157}Gd number density of CASE5

In Fig. 7, the trends of Δk$_{inf}$ follows the change of ^{155}Gd and ^{157}Gd number densities in all the cases. As depletion begins, the difference of number densities rises to +0.2 ~ +0.5% from 0.00% at BOC. In ST, gadolinium depleted and absorbed thermal neutrons more than the reference case and it induced smaller k$_{inf}$ of ST case, which means the negative Δk$_{inf}$. However, as depletion continues, the difference decreased to -16% in the highest enrichment case. This negative difference indicates that gadolinium is less depleted in ST leading to an increasing Δk$_{inf}$ up to 766 pcm in the highest case. Although the initial Δk$_{inf}$ is small with no difference in ^{155}Gd and ^{157}Gd number densities at BOC, the difference is induced as the depletion started introducing errors in k$_{inf}$ until the ^{155}Gd and ^{157}Gd almost burns out.

ST calculates multi-group cross section (MG XS) using pointwise energy slowing-down method (PSM) which calculates effective cross sections of intermediate energy range where resonances exist. In depletion problem, ST solves burnup equation based on the MG XS updating the number density of each nuclide including ^{155}Gd and ^{157}Gd. There should be some difference of the MG XSs and continuous energy group XSs (CE XS) used in MCS, the reference solution, particularly for ^{155}Gd and ^{157}Gd. These differences would cause the difference in ^{155}Gd and ^{157}Gd number density and the differences would cause Δk$_{inf}$. To enhance the accuracy of depletion problem for high-enriched gadolinia pin, generation of MG XS, particularly in resonance treatment should be improved.

4. Conclusions

The accuracy of depletion calculation of FA and pin with enriched gadolinia was analyzed. When natural gadolinia is used as a BA, RMSE of Δk$_{inf}$ of FA compared to the reference solution is around 175 pcm. However, as the enrichment of ^{155,157}Gd increases from natural enrichment to 70 a/o, the RMSE increases to 212 pcm in the FA. Although the QD method is a robust approach to gadolinium depletion, it has no effect on accuracy.

When explicit high-order scattering modeling is applied instead of the inflow transport correction to deal the anisotropic scattering effect, the error is reduced with the degree of the improvement increasing with the ^{155,157}Gd enrichment. The inflow method does not appear to treat the anisotropic scattering effects in the enriched gadolinia pin.

Δk$_{inf}$ and its increasing trend proportional to ^{155}Gd and ^{157}Gd results from the difference of MG XS calculated in ST to treat resonances based on PSM and CE XS. Solving the burnup equation with these different XSs leads to different number density of nuclides especially ^{155}Gd and ^{157}Gd and error in k$_{inf}$. To improve the depletion calculation accuracy of high-enriched gadolinia pin of ST, accuracy of PSM to calculate MG XS should be improved, at first.

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