Accuracy Evaluation of the Resonance Treatment Method using STREAM

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

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1. Introduction

Recently, South Korea has been developing the i-SMR, which significantly enhances safety, economic efficiency, and flexibility compared to domestic and international SMRs. To meet the design requirements of a soluble boron-free core, various types of nuclear fuels, such as CIMBA, are being developed [1]. In addition, the use of enriched gadolinia or High-Assay Low-Enriched Uranium (HALEU) fuel materials is considered [2]. Since enriched gadolinia and HALEU fuel materials are not currently used in reactors operating in South Korea, sufficient research has not been conducted to verify the calculation accuracy of neutron transport analysis code. In particular, it is necessary to analyze the accuracy of the pin-based pointwise energy slowing-down method (PSM), known as the most accurate resonance treatment method in typical pressurized water reactors, in problems including fuel materials containing enriched gadolinium and HALEU [3].

This paper presents a study to verify the accuracy of neutron transport analysis codes based on different resonance treatment methods. For this study, fuel pin-cell and fuel assembly problems using enriched gadolinia or HALEU fuel materials are constructed, and the in-house developed neutron transport analysis code, STREAM, is utilized [4]. The resonance treatment methods applied in this study include the PSM, the equivalence theory with Carlvik's two-term rational approximation (Carlvik), and the Carlvik and Bondarenko iteration method (Carlvik+Bondarenko) [5]. MCS simulation results are used as a reference solution. MCS is a high-fidelity Monte Carlo code developed and maintained by the Ulsan National Institute of Science and Technology (UNIST) [6].

2. Modeling

In this section, the fuel pin-cell and fuel assembly employed in this study are described. The typical fuel pin-cell and fuel assembly designed for pressurized water reactors (PWR) are explained, and the HALEU-based fuel assembly and the enriched gadolinia-based fuel assembly are also discussed.

2.1 Typical Fuel Pin-cell and Fuel Assembly

Fig. 1 shows a typical fuel pin-cell and fuel assembly used in a PWR. Additionally, Table I presents the key information.

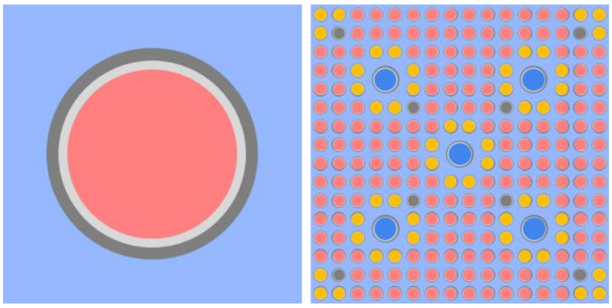


Fig. 1. Typical fuel pin-cell (left) and fuel assembly (right)

In the fuel assembly of Fig. 1, the red pin-cell, yellow pin-cell, and gray pin-cell represent normal fuel, zoned fuel, and gadolinia, respectively.

Table I: Key information on a typical fuel pin-cell and fuel assembly

Parameter	Value	Unit
Fuel enrichment	4.5	wt.%
Zoned fuel enrichment	4.0	wt.%
^{155,157}Gd enrichment	30.45	wt.%
Gadolinia content	6.0	wt.%
Number of fuel pin-cell	176	#
Number of zoned fuel pin-cell	52	#
Number of gad pin-cell	8	#

2.2 HALEU-Based Fuel Assembly

Fig. 2 shows a HALEU-based fuel assembly, and Table II presents key information on a fuel assembly using HALEU. HALEU means uranium nuclear fuel with an enrichment level of 5–20%. To study various enrichment levels, fuel enrichment ranging from 0.7 wt.% to 30.0 wt.% is used, slightly exceeding the HALEU range.

Table II: Key information on a HALEU-based fuel assembly

Parameter	Value	Unit
Fuel enrichment	0.7 ~ 30.0	wt.%
Fuel density	10.0	g/cc
Number of fuel pin-cell	236	#

2.3 Enriched Gadolinia-Based Fuel Assembly

Fig. 2 shows an enriched gadolinia-based fuel assembly, and Table III presents key information on a fuel assembly using enriched gadolinia. As shown in Table III, there are 16 gad pin-cells, and the enrichment of ^{155,157}Gd ranges from 30.45 wt.% to 70.0 wt.%. An enrichment of 30.45 wt.% corresponds to the natural state of gadolinium. The content of gadolinia ranges from 8.0 wt.% to 21.4 wt.%. As the enrichment of ^{155,157}Gd increases, the content of gadolinia also increases.

Table III: Key information on an enriched gadolinia-based fuel assembly

Parameter	Value	Unit
Fuel enrichment	4.5	wt.%
Zoned fuel enrichment	4.0	wt.%
^{155,157}Gd enrichment	30.45 ~ 70.0	wt.%
Gadolinia content	8.0 ~ 15.7	wt.%
Number of fuel pin-cell	168	#
Number of zoned fuel pin-cell	52	#
Number of gad pin-cell	16	#

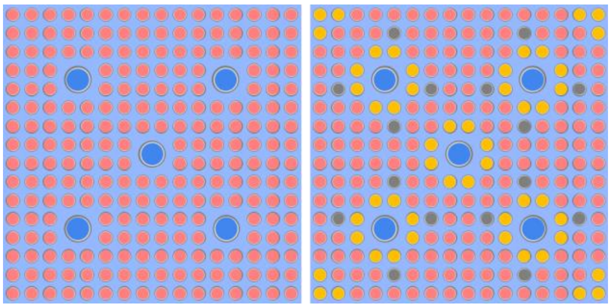


Fig. 2. HALEU-based fuel assembly (left) and enriched gadolinia based fuel assembly (right)

3. Results

In this section, a brief explanation of the resonance treatment method is provided, and STREAM calculation results applying the PSM, Carlvik, and Carlvik+ Bondarenko resonance treatment methods to each fuel pin-cell or fuel assembly are compared with MCS calculation results. The standard deviation of all MCS calculation results is approximately 30 pcm for k_{inf}. All burnup calculations are performed up to 80 MWd/kg. For STREAM calcula-tions, the same simulation conditions are used except for the resonance treatment method.

3.1 Resonance Treatment Method

PSM is a high-fidelity approach that models neutron slowing-down and resonance self-shielding using pointwise energy calculations. It provides more accurate pin-level neutron transport analysis than traditional multi-group methods. Carlvik enhances the accuracy of equivalence theory by incorporating Carlvik's two-term rational approximation. Carlvik+ Bondarenko is a method for adjusting resonance interference effects in resonance self-shielding calculations. It improves the accuracy of resonance treatment by addressing interactions between multiple resonance regions.

3.2 Typical Fuel Pin-cell and Fuel Assembly

As explained in Section 2.1, the k_{inf} for a typical fuel pin-cell and fuel assembly are calculated using STREAM with PSM, Carlvik, and Carlvik+Bondarenko resonance treatment methods and compared with MCS calculation results. Fig. 3 and Fig. 5 show the k_{inf} calculation results for a typical fuel pin-cell and fuel assembly, respectively. Fig. 4 and Fig. 6 present the differences between MCS calculation results and STREAM calculation results obtained using each resonance treatment method for a typical fuel pin-cell and fuel assembly, respectively.

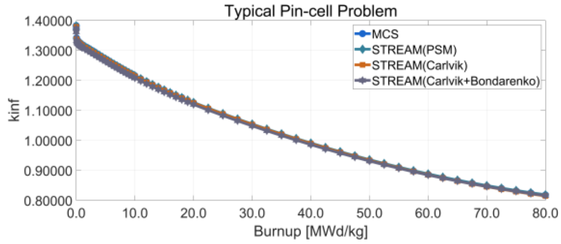


Fig. 3. k_{inf} as a function of burnup for a typical fuel pin-cell

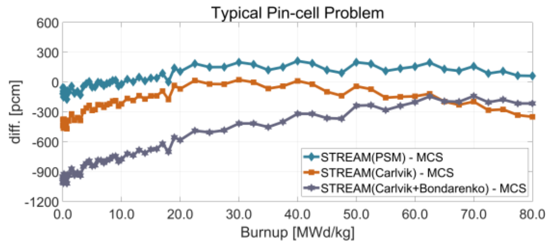


Fig. 4. Difference in the k_{inf} calculated by MCS and STREAM for a typical fuel pin-cell

As shown in Fig. 4, the difference in the k_{inf} between STREAM with PSM and MCS remains below 200 pcm at all burnup steps. However, the difference in the k_{inf} between STREAM and MCS calculated using Carlvik and Carlvik+Bondarenko exceeds 400 pcm and 1,000 pcm, respectively, at certain burnup steps.

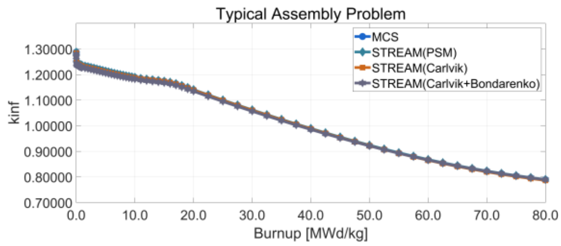


Fig. 5. k_{inf} as a function of burnup for a typical fuel assembly

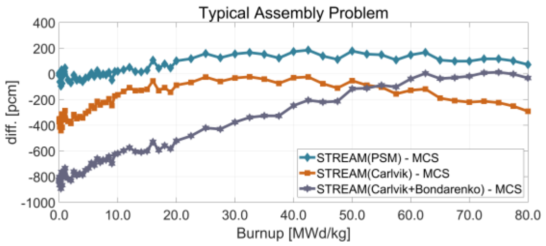


Fig. 6. Difference in the k_{inf} calculated by MCS and STREAM for a typical fuel assembly

As shown in Fig. 6, similar to the typical fuel pin-cell results, the difference in the k_{inf} between STREAM with PSM and MCS is below 200 pcm. However, the k_{inf} calculated by STREAM with Carlvik and Carlvik+ Bondarenko shows relatively larger differences compared to MCS result.

3.3 HALEU-Based Fuel Assembly

As explained in Section 2.2, the k_{inf} for a HALEU-based fuel assembly is calculated using STREAM with PSM, Carlvik, and Carlvik+Bondarenko resonance treatment methods and compared with MCS calculation results. Fig. 7 shows the k_{inf} calculation results using MCS for a HALEU-based fuel assembly with fuel enrichment ranging from 0.7 wt.% to 30.0 wt.%. Fig. 8 and Fig. 9 present the differences between MCS calculation results and STREAM calculation results obtained using each resonance treatment method.

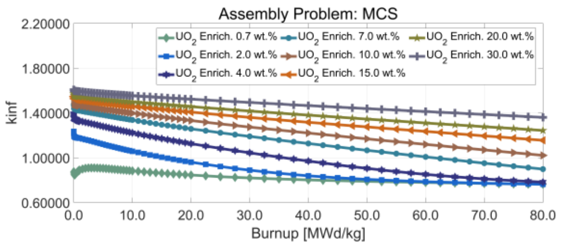
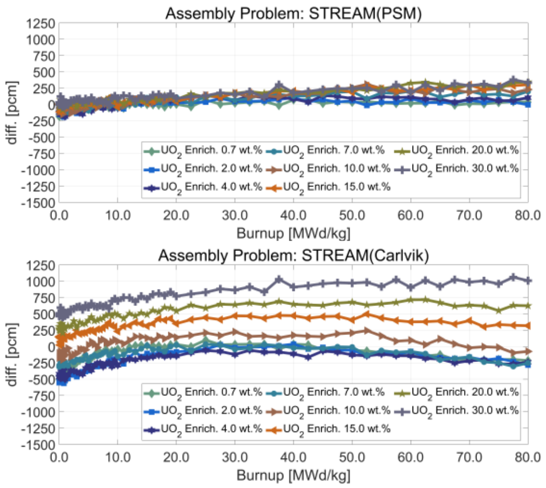


Fig. 7. k_{inf} as a function of burnup for a HALEU-based fuel assembly



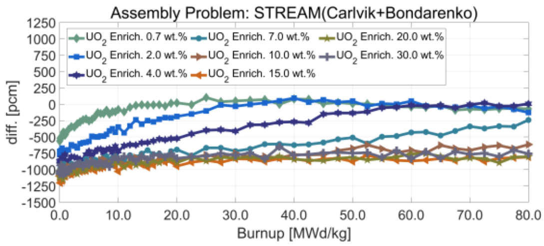


Fig. 8. Difference in the k_{inf} calculated by MCS and STREAM for a HALEU-based fuel assembly

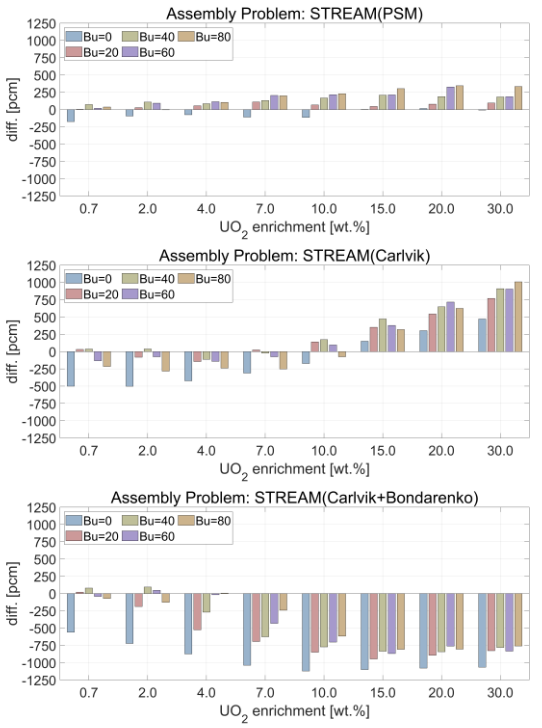


Fig. 9. Difference in the k_{inf} calculated by MCS and STREAM for a HALEU-based fuel assembly at 0, 20, 40, 60, 80 MWd/kgU

As shown in Fig. 8 and Fig. 9, the difference in the k_{inf} between STREAM with PSM and MCS remains below 350 pcm for fuel enrichment ranging from 0.7 wt.% to 30.0 wt.%. In particular, the difference in the k_{inf} between STREAM with PSM and MCS exhibits a consistent trend regardless of fuel enrichment. In contrast, the difference in the k_{inf} between STREAM with Carlvik and MCS, as well as between STREAM with Carlvik+ Bondarenko and MCS, tends to increase as fuel enrichment increases. Therefore, when designing a reactor core using HALEU, such as i-SMR, it is recommended to use a neutron transport analysis code that employs PSM resonance treatment method.

3.4 Enriched Gadolinia-Based Fuel Assembly

As explained in Section 2.3, the k_{inf} for an enriched gadolinia-based fuel assembly is calculated using STREAM with PSM, Carlvik, and Carlvik+Bondarenko resonance treatment methods and compared with MCS calculation results. Fig. 10 shows the k_{inf} calculation results using MCS for an enriched gadolinia-based fuel assembly with ^{155,157}Gd enriched enrichment ranging from 30.45 wt.% to 70.0 wt.%. Fig. 11 and Fig. 12 present the differences between MCS calculation results and STREAM calculation results obtained using each resonance treatment method. Since the burnup point at which gadolinia is depleted varies depending on the enrichment of ^{155,157}Gd, the burnup step is determined by considering the burnup point for ^{155,157}Gd enrichment.

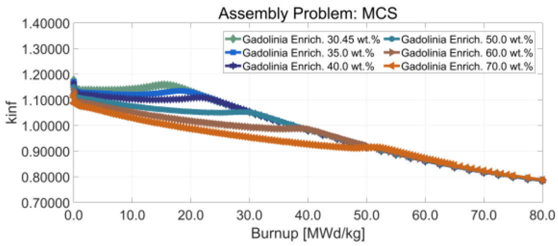


Fig. 10. k_{inf} as a function of burnup for an enriched gadolinia-based fuel assembly

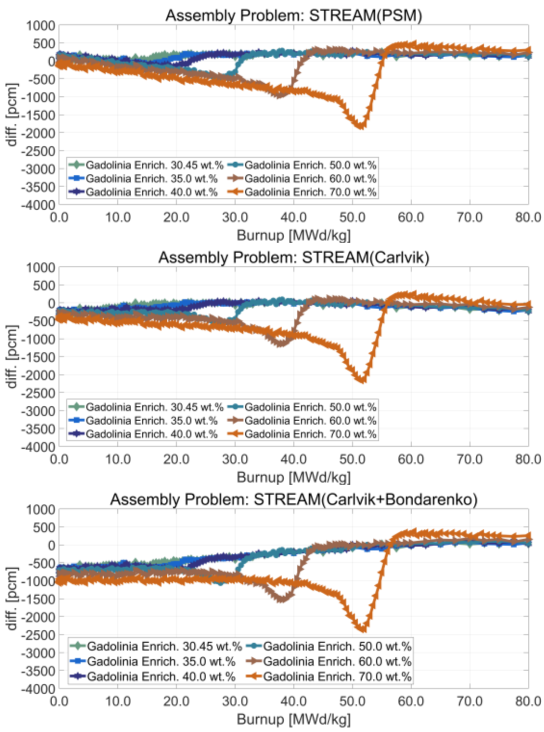
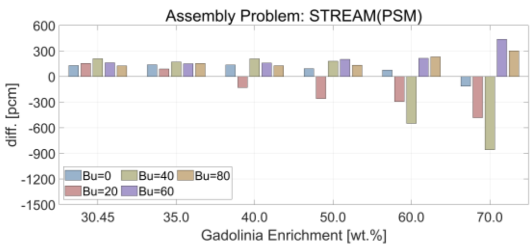


Fig. 11. Difference in the k_{inf} calculated by MCS and STREAM for an enriched gadolinia-based fuel assembly



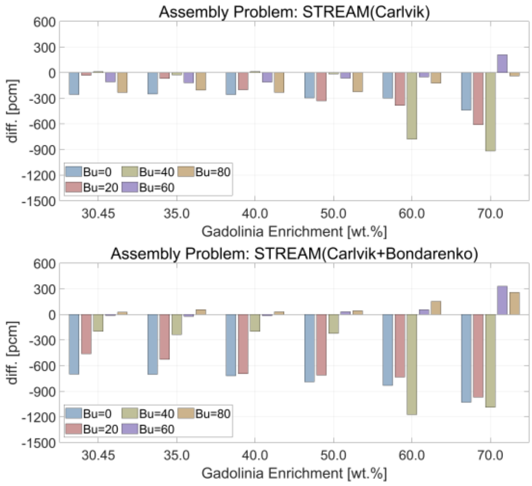


Fig. 12. Difference in the k_{inf} calculated by MCS and STREAM for an enriched gadolinia-based fuel assembly at 0, 20, 40, 60, 80 MWd/kgU

As shown in Fig. 11 and Fig. 12, the difference in the k_{inf} between STREAM with PSM and MCS remains below 300 pcm for ^{155,157}Gd enrichment ranging from 30.45 wt.% to 40.0 wt.%. However, when the enrichment of ^{155,157}Gd is above 50.0 wt.%, the difference in the k_{inf} exceeds 500 pcm, and at an enrichment of 70 wt.%, the difference in the k_{inf} reaches up to 1800 pcm. This trend is also observed in both STREAM with Carlvik versus MCS, as well as in STREAM with Carlvik+Bondarenko compared to MCS. The burnup step with the largest difference in the k_{inf} calculated by MCS and STREAM is the burnup point at which gadolinia is completely depleted.

4. Conclusions

In this study, the accuracy of resonance treatment methods is evaluated by comparing MCS calculation results with STREAM calculation results using the PSM, Carlvik, and Carlvik+Bondarenko resonance treatment methods for a typical fuel pin-cell and fuel assembly, a HALEU-based fuel assembly, and an enriched gadolinia-based fuel assembly. The k_{inf} calculated using STREAM with PSM shows the smallest difference from the k_{inf} calculated using MCS for the typical fuel pin-cell and fuel assembly. For the HALEU-based fuel assembly, the k_{inf} calculated using STREAM with PSM not only shows the smallest difference from the k_{inf} calculated using MCS but also exhibits the same trend across the fuel enrichment range of 0.7 wt.% to 30 wt.%. Additionally, even with resonance interference effects adjusted using the Bondarenko method, the accuracy does not fundamentally improve. However, all STREAM calculation results show a significant difference from MCS for the enriched gadolinia-based fuel assembly.

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