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Effect of Approximations in Radial Reflector Modeling on the Neutronics of a Light-Water Small Modular Reactor

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1. Introduction

Metal reflectors, such as SS-304, are under consideration for the radial region of light-water small modular reactors (LW-SMRs) like the innovative SMR (i-SMR), replacing the conventional water reflector [1]. Metal reflectors enhance neutron economy through increased backscattering and contribute to power flattening, which can reduce power peaking factors [2, 3].

In modeling these radial reflectors, the explicit cylindrical geometry of the core periphery is often approximated using a Cartesian array of reflector assemblies to simplify the computational model. Due to their smaller core size compared to commercial PWRs, SMRs are susceptible to higher neutron leakage. The modeling of peripheral structures is therefore critical, as neutrons that leak from the core can be scattered back by these structures, subsequently impacting key neutronic parameters.

This study evaluates the neutronic impact of this geometric approximation on key core performance parameters, including the multiplication factor and power peaking factors (Fq, Fr). The analysis was performed on the soluble boron-free (SBF) LW-SMR, PRATIC benchmark core [4] using the GPU-based Monte Carlo code PRAGMA [5].

2. Methods and Problems

2.1 Code

The Korea Atomic Energy Research Institute (KAERI) is developing a Virtual SMR Platform (V-SMR) to accelerate SMR design and demonstration with rapid, high-fidelity simulations [6]. Within this platform, high-fidelity core physics is handled by PRAGMA, a GPU-accelerated Monte Carlo code developed by Seoul National University (SNU) and Korea Hydro & Nuclear Power (KHNP). Implemented in CUDA and C++, PRAGMA performs ultra-fast neutron transport simulations by leveraging NVIDIA graphics cards.

Its major capabilities include:

- Ultra-fast, continuous-energy, whole-core Monte Carlo transport simulation on GPUs.
- Utilization of mixed-precision arithmetic to maintain accuracy while achieving high performance on consumer-grade GPUs.
- Analysis of both conventional LWRs with Cartesian grids and advanced reactors with unstructured meshes.
- Specialized functions for LWRs, including criticality search with control rod movement, a built-in thermal-hydraulic (T/H) feedback module, and equilibrium xenon search.
- CMFD acceleration of the fission source distribution for inactive cycle convergence.
- Result visualization via output files in the Visualization Toolkit (VTK) [7] format.

2.2 Problems

The test calculations are performed using the PRATIC benchmark [4]. PRATIC, an acronym for "Petit REP Academique pour Tester, Innover et Concevoir" (meaning "Small Academic PWR for Testing, Innovation, and Design" in French), is a benchmark problem for a SBF LW-SMR developed by the French Alternative Energies and Atomic Energy Commission (CEA). It provides core specifications for both start-up and equilibrium cycles.

The core utilizes a 17×17 UO_2 fuel assembly design with a maximum U-235 enrichment of 5.0 wt%. The axial and radial reflectors are modeled as homogenized mixtures of water and SS-304. The key design parameters are summarized in Table I. Figures 1 and 2 show the core loading pattern and a 2D cross-sectional view of the fuel assembly, respectively.

Table I: Problem Description

Data	Value
Nominal Power	350 MW_{th}
Type of fuel assemblies	17×17 UO_2
Number of fuel assemblies	57
Enrichment of U-235	1.6~5.0 wt.%
Fuel assembly pitch at 300℃	21.5313 cm
Active core height at 300℃	200.5613 cm
Axial reflectors thickness	20.0 cm

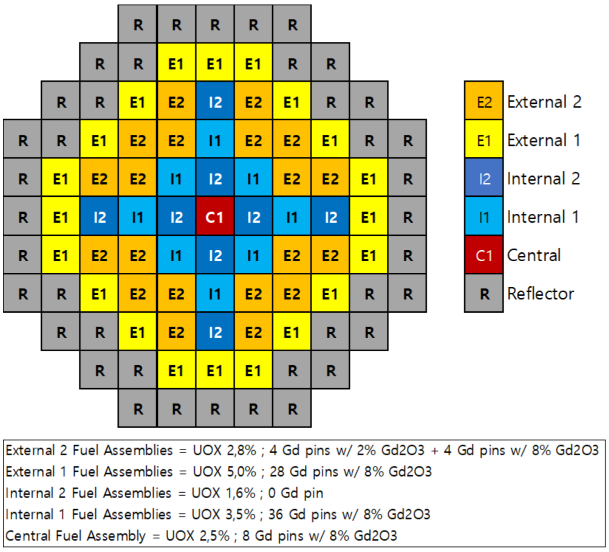

Fig. 1. Loading pattern at first cycle (PRATIC start-up core)

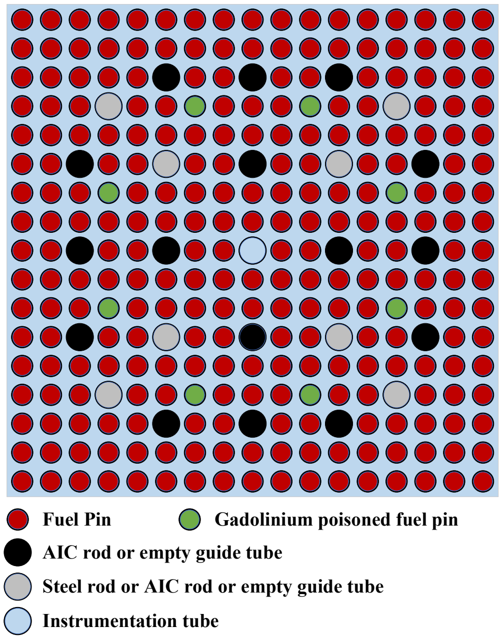

Fig. 2. 2D cross-sectional view of the C1 fuel assembly

The analysis is conducted for a total of six cases, as described in Table II. Case 0 represents the reference PRATIC benchmark with its rectangular block-type radial reflector. In Case 1, a cylindrical radial reflector with the same volume as that in Case 0 is modeled, as depicted in Fig. 3. A comparison between Case 0 and Case 1 allows for the evaluation of the effect of the geometric modeling approximation. Cases 2 through 5 are variations of Case 1, where the radial reflector thickness is increased by 1, 5, 10, and 20 cm, respectively. These cases are designed to assess the sufficiency of the reflector thickness. To isolate the effect of the radial reflector modeling, other ex-core structures, such as the reactor pressure vessel (RPV), are not included in the models for this study.

Table II: Description of the Test Cases for Analysis

Case No.	Description
0	(Reference) rectangular block-type radial reflector
1	cylindrical radial reflector with the same volume as Case 0. r_{refl} = 119.6413cm
2	radial reflector thickness: Case 1 +1cm r_{refl} = 120.6413cm
3	radial reflector thickness: Case 1 +5cm r_{refl} = 124.6413cm
4	radial reflector thickness: Case 1 +10cm r_{refl} = 129.6413cm
5	radial reflector thickness: Case 1 +20cm r_{refl} = 139.6413cm

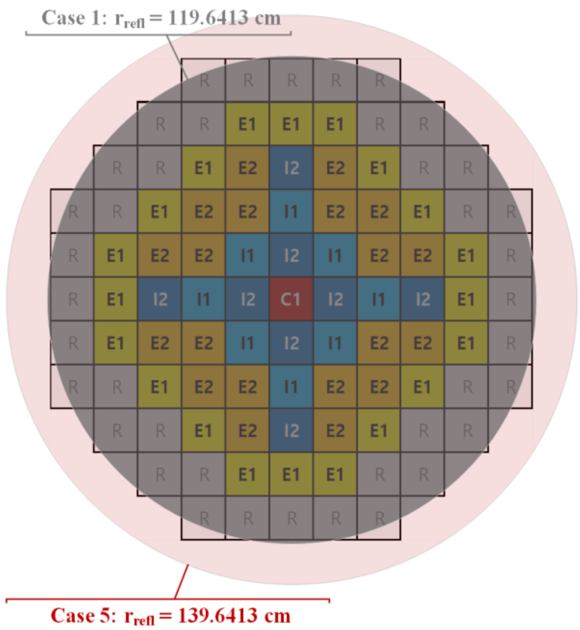

Fig. 3. Configuration of the rectangular radial reflector (marked ‘R’ for Case 0) and the cylindrical radial reflectors (Case 1 in gray; Case 5 in red)

A uniform core temperature of 300 °C was assumed for all simulations.

3. Numerical Results

The PRAGMA calculations are performed with 200 inactive and 200 active cycles, using 10,000,000 neutron histories per cycle. The ENDF/B-VIII.0 [8] continuous-energy nuclear data library is used for all simulations.

Tables III, VI, and V present the calculated results for the effective multiplication factor k_{eff}, Fq, and Fr, respectively. The results show that all cases are statistically identical within two standard deviations (2σ). This indicates that the modeling approach for the radial reflector has a negligible effect on the core performance parameters. In particular, it demonstrates that the thickness of the reference radial reflector is sufficient.

Table III: Comparisons of Calculated k_{eff} and their Differences

Case No.	**k_{eff} (SD [pcm])**	**Diff. [pcm]**
0	1.07904 (3)	-
1	1.07904 (3)	0
2	1.07911 (2)	7
3	1.07903 (2)	-1
4	1.07908 (2)	4
5	1.07902 (3)	-2

Table IV: Comparisons of Calculated Fq and their Differences

Case No.	Fq (RSD [%])	Diff. [%]
0	2.801 (1.53)	-
1	2.830 (1.45)	1.03
2	2.812 (1.50)	0.41
3	2.803 (1.39)	0.09
4	2.824 (1.53)	0.82
5	2.801 (1.46)	-0.02

Table V: Comparisons of Calculated Fr and their Differences

Case No.	Fr (RSD [%])	Diff. [%]
0	1.965 (0.29)	
1	1.971 (0.26)	0.28
2	1.961 (0.28)	-0.21
3	1.969 (0.27)	0.22
4	1.971 (0.27)	0.28
5	1.963 (0.27)	-0.13

4. Conclusions

The analysis of the PRATIC SBF LW-SMR benchmark demonstrates that the thickness of a single SS-304 metal reflector assembly block is sufficient to provide an effective reflective boundary. Consequently, the neutron leakage is minimal and has a negligible impact on the overall core performance. As a result, it was confirmed that for the neutronic analysis of this SBF LW-SMR, there is no significant difference between modeling the ex-core reflector region with an explicit cylindrical geometry and approximating it with rectangular blocks.

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