Axial Distribution of Gd-155 and Gd-157 in an i-SMR Core Considering Coolant Temperature Gradients

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1. Introduction

The Innovative Small Modular Reactor (i-SMR) employs a compact core design with relatively high gadolinium loading to manage excess reactivity without soluble boron [1]. In such systems, the axial coolant temperature gradient induces significant variations in neutron moderation and spectrum characteristics along the core height [2]. Since the absorption cross-sections of Gd-155 and Gd-157 are highly sensitive to the neutron spectrum, the temperature-driven density changes can lead to non-uniform depletion rates of these isotopes. This study focuses on investigating the axial depletion behavior of Gd-155 and Gd-157 under a coolant temperature gradient in an i-SMR core. By analyzing the segment-wise burnout of gadolinium isotopes, this research clarifies how the axial moderation profile alters the local depletion characteristics of burnable absorbers.

2. Methods and Results

In this section, the modeling framework used to investigate axial gadolinium depletion behavior is described. The framework incorporates an energy-balance-based axial coolant temperature distribution with a 35K linear gradient, equal-height axial segmentation of the fuel rod (10 cm per segment), and segment-wise depletion calculations using Serpent 2 to isolate the effect of local thermal–hydraulic conditions on gadolinium depletion.

2.1. Serpent 2

In this study, Serpent 2 was employed to perform coupled neutronic and depletion calculations for the i-SMR. The use of Serpent 2 allows direct implementation of axially segmented fuel and coolant regions with region-wise material properties, which is essential for capturing axial variations in moderation conditions and gadolinium depletion behavior [3].

For i-SMR applications, Serpent 2 provides distinct advantages due to its flexibility in geometry definition, accurate treatment of strong absorbers such as Gd-155 and Gd-157, and capability to resolve localized spectral effects arising from axial thermal–hydraulic gradients. These features enable a physically consistent evaluation of gadolinium consumption under non-uniform coolant temperature and density conditions, which are characteristic of compact and strongly coupled i-SMR cores.

2.2. i-SMR

i-SMR is an advanced nuclear reactor concept in which the core, steam generator, pressurizer, and primary coolant system are integrated into a single pressure vessel. This configuration significantly simplifies system design and reduces the potential for large-break loss-of-coolant accidents.

The compact core geometry and strong thermal–hydraulic coupling in i-SMR results in axial and radial variations in neutron moderation and spectrum. Compared to large pressurized water reactors, i-SMR typically operates with shorter fuel assemblies and lower coolant flow rates, leading to relatively steep axial coolant temperature gradients. These characteristics amplify the impact of local thermal–hydraulic conditions on neutronic behavior, making axial effects particularly important in i-SMR core analysis.

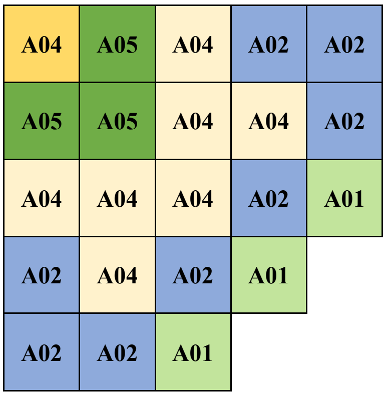
Gadolinium-bearing fuels are commonly employed in i-SMR as burnable absorbers to suppress excess reactivity during the early stages of the fuel cycle and to improve power distribution. However, the strong neutron absorption cross sections of Gd-155 and Gd-157 make their depletion behavior highly sensitive to local neutron spectrum and moderation conditions.

Therefore, in this study, the axial coolant temperature distribution is modeled and the fuel is segmented into equal-height regions to examine how axial thermal–hydraulic variations influence gadolinium depletion. By evaluating gadolinium depletion under identical axial fuel inventories, this work aims to clarify the role of spectral effects driven by varied coolant temperature on burnable absorber behavior in an i-SMR core.

2.3. Modeling

The core consists of 69 fuel assemblies categorized into four distinct types (A01, A02, A04, and A05), which are strategically arranged to flatten the radial power distribution through varying gadolinium loading. All simulations were performed under a non-control rod condition. This deliberate exclusion of control rods reduces external perturbations, allowing for a pure observation of how the coolant temperature gradient inherently drives the axial offset of gadolinium depletion.

Fig. 1. presents the quarter-core loading pattern of the modeled i-SMR.



A04	**A05**	**A04**	**A02**	**A02**
A05	**A05**	**A04**	**A04**	**A02**
A04	**A04**	**A04**	**A02**	**A01**
A02	**A04**	**A02**	**A01**	
A02	**A02**	**A01**		

Fig. 1. i-SMR radial quarter-core loading pattern

The active core height of 240 cm was discretized into 24 axial nodes at 10 cm intervals. The lower 210 cm consists of Gd_2O_3–UO_2 fuel, while the upper 30 cm consists of lower-enriched UO_2 fuel. Each of the 24 axial nodes was treated as an independent depletion zone, enabling a granular trace of the depletion rates for the major gadolinium isotopes (Gd-155, Gd-157) as a function of core depletion. Fig. 2. represents the radial view and axial side view of the modeled i-SMR.

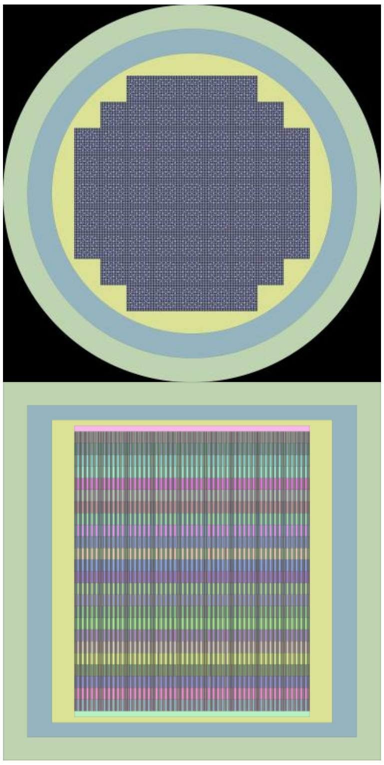


Fig. 2. i-SMR radial and axial view

To reflect the thermal-hydraulic characteristics of the coolant during operation, a linear axial temperature gradient was applied across these nodes. Specifically, a temperature rise (ΔT) of 35K was applied between the core inlet (lower core) and outlet (upper core), with the temperature of each segment determined through linear interpolation. This 35K linear induces a continuous decrease in coolant density toward the upper regions of the core. Table I provides the assigned coolant temperature for each of the 24 segments, whereas the density of the coolant varies from 0.675g/cm^3 to 0.753g/cm^3.

Table I. Assigned coolant temperature for each segment

Core Height (cm)	Coolant Temperature (K)
0-10 (1st floor)	559.88
10-20 (2nd floor)	561.34
20-30 (3rd floor)	562.80
30-40 (4th floor)	564.25
40-50 (5th floor)	565.71
50-60 (6th floor)	567.17
60-70 (7th floor)	568.63
70-80 (8th floor)	570.09
80-90 (9th floor)	571.55
90-100 (10th floor)	573.00
100-110 (11th floor)	574.46
110-120 (12th floor)	575.92
120-130 (13th floor)	577.38
130-140 (14th floor)	578.84
140-150 (15th floor)	580.30
150-160 (16th floor)	581.75
160-170 (17th floor)	583.21
170-180 (18th floor)	584.67
180-190 (19th floor)	586.13
190-200 (20th floor)	587.59
200-210 (21st floor)	589.05
210-220 (22nd floor)	590.50
220-230 (23rd floor)	591.96
230-240 (24th floor)	593.42

3. Results

3.1. k_{eff}

All neutronic and depletion calculations were conducted utilizing the continuous-energy ENDF/B-VII.1 cross-section library over a simulated 2-year operating cycle, corresponding to a cumulative core burnup of 20 MWD/kgU. To achieve high statistical confidence in the Monte Carlo calculations, the neutron population was set to 5,000,000 histories per cycle, executing 100 active cycles and 40 inactive cycles. This rigorous computational configuration ensured that the statistical uncertainty of the k_{eff} was maintained below 10 pcm across all depletion steps, thereby guaranteeing highly converged spatial power distributions for the accurate evaluation of the axial gadolinium depletion behavior. Fig. 3. represents the change in k_{eff} throughout the depletion cycle for cases with coolant at the same temperature and at different temperatures.

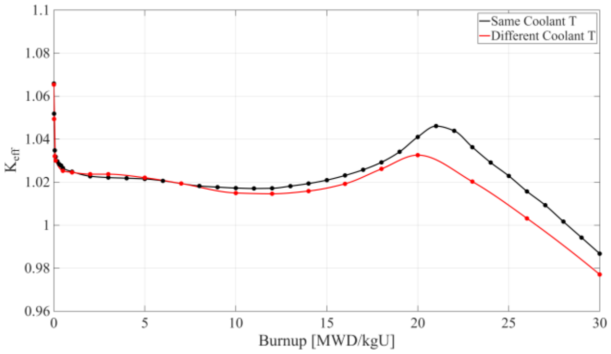


Fig. 3. k_{eff} change through depletion cycle

3.2. Gadolinium Depletion

The analysis was performed at the 1st, 5th, 9th, 13th, 17th, and 21st axial nodes corresponding to the Gd-containing fuel layers. Fig. 4. shows the change in Gd-155 atomic density as a function of depletion, while Fig. 5. presents the corresponding variation for Gd-157.

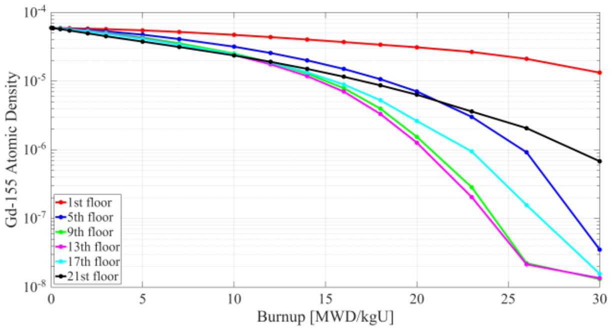


Fig. 4. Gd-155 atomic density changes through depletion cycle

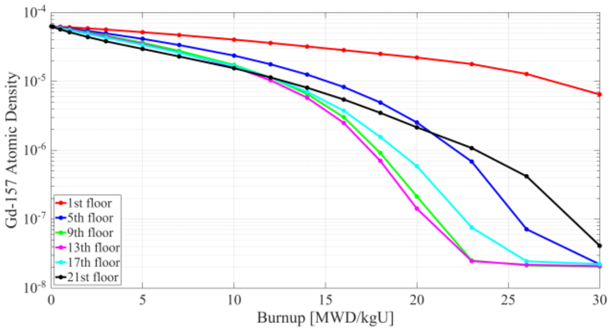


Fig. 5. Gd-157 atomic density changes through depletion cycle

Analysis of the axial depletion behavior indicates that the depletion rates of Gd-155 and Gd-157 are higher in the upper regions of the core. This trend is attributed to the combined effects of axial flux distribution and coolant temperature distribution. As the coolant temperature increases toward the top of the core, the reduction in moderator density decreases moderation efficiency, resulting in a harder neutron spectrum and altered reaction rates for gadolinium isotopes.

To further examine this behavior, the changes in the overall gadolinium atomic density, represented by Gd-155 and Gd-157, were also analyzed in Fig. 6. and Fig. 7.

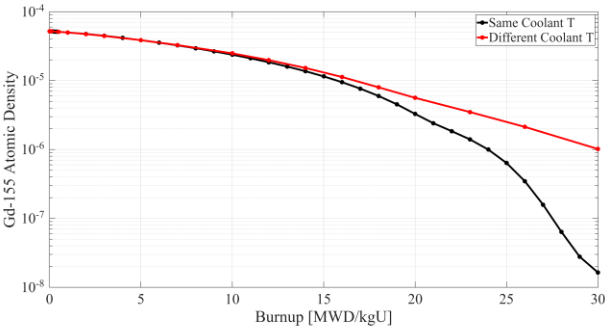


Fig. 6. Gd-155 atomic density changes by same and different coolant temperature cases

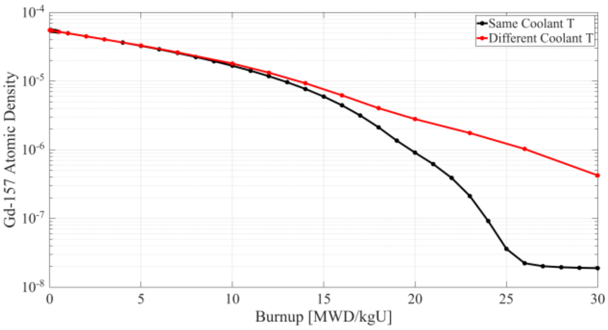


Fig. 7. Gd-157 atomic density changes by same and different coolant temperature cases

The case with different coolant temperatures shows less Gadolinium depletion than the case with the same coolant temperature, as evidenced by the higher Gadolinium atomic density. As shown in Fig. 4. and Fig. 5., this behavior is mainly attributed to the reduced depletion of Gadolinium in the floors located in the lower region of the core.

3.3. Axial Power Distribution

The non-uniform depletion of gadolinium isotopes directly influences the axial power distribution of the core over the operational cycle. Fig. 8. represents the axial power distribution obtained at BOC (0 MWD/kgU), MOC (10 MWD/kgU), EOC (20 MWD/kgU).

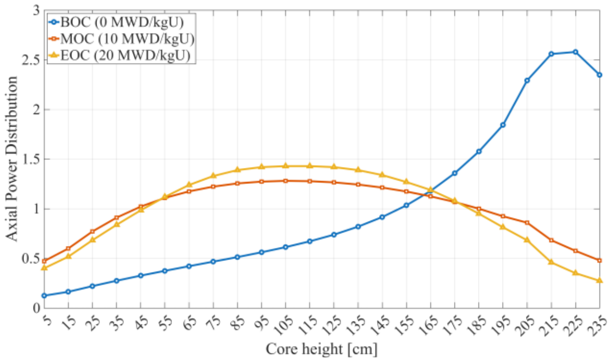


Fig. 8. BOC, MOC, EOC axial power distribution

At BOC, the power profile is highly tilted toward the upper core. This is primarily due to the axial fuel zoning, where the upper 30 cm lacks gadolinium absorbers, combined with the initial coolant density gradient. As depletion progresses to MOC, the depletion of gadolinium in the lower 210 cm restores the local reactivity, causing the power distribution to shift downward and naturally converge to a cosine shape. At EOC, this trend becomes even more pronounced, and the power profile exhibits an even clearer cosine shape.

4. Discussions and Conclusion

The present study confirmed that the axial coolant temperature gradient significantly influences the depletion behavior of Gd-155 and Gd-157 in the i-SMR core. Compared with the uniform coolant temperature case, the different coolant temperature case showed less overall gadolinium depletion, mainly because gadolinium in the lower axial region was burned less.

This non-uniform depletion behavior affects reactivity recovery and the evolution of axial power distribution during the fuel cycle. These results indicate that axial thermal-hydraulic conditions should be explicitly considered in the design of gadolinium-bearing fuel in soluble-boron-free i-SMRs.

As a future work, the authors plan to further evaluate the height-wise gadolinium depletion behavior and investigate whether reversing the axial orientation of the fuel rod or modifying the axial gadolinium loading pattern can improve the depletion balance between the lower and upper core regions.

5. Acknowledgement

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