

New Design of the Mobile Nuclear Fuel Assembly System for the Reactivity Control Purpose

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1. Introduction

With the growing demand for carbon neutrality and the expansion of distributed power generation, interest in next-generation nuclear reactors has increased, leading to active research on core design concepts that can simultaneously enhance safety and operational flexibility. In reactor cores, reactivity is generally controlled by mechanisms such as control rods, burnable absorbers, and adjustments of soluble boron concentration in the coolant. Although these conventional control systems have demonstrated sufficient reliability, the introduction of additional reactivity control measures from the perspective of redundancy and diversity can be an important consideration in safety design. Accordingly, this study proposes an additional concept for criticality control. This concept is not limited to specific accident conditions, but rather represents a generally applicable passive mitigation system to suppress the increase in core reactivity.

To evaluate the feasibility of the proposed concept, an *i*-SMR core design was adopted. By employing a relatively compact core configuration, the neutronic effects of variations in fuel assembly spacing can be more clearly evaluated. The reactor was used as a reference model for analyzing core reactivity behavior.

2. Core Design Methodology

Figure 1 presents the core loading pattern adopted in this study. The detailed geometry and configuration of each fuel assembly type (A01-A05) are shown in Figure 2, where the internal structure and design features of the assemblies are described. The core is designed to operate 540MWth with a 24-month-refueling cycle. UO₂ is used as the fuel material, and the core lattice follows a 17×17 square pitch configuration. [2]

The neutronic analysis in this study was performed using the *k*-eigenvalue mode of MCNP. A total of 10,000 neutron histories per cycle were tracked, and among 130 total cycles, 30 were set as inactive cycles for convergence, followed by 100 active cycles to estimate the effective multiplication factor. The initial *k*-eff was set to 1.0. The fuel and moderator temperatures were set to 900K and 600K, respectively, to simulate hot full power operating conditions. Considering the statistical characteristics of the Monte Carlo method, the calculation parameters were selected

to achieve sufficiently low statistical uncertainty in *k*-eff, thereby ensuring the convergence and reliability of the results.

A03	A05	A05	A05	A02
A05	A04	A03	A02	A01
A05	A03	A04	A03	A02
A05	A02	A03	A01	
A02	A01	A02		

Fig1. Loading pattern of the *i*-SMR core

SIZE (cm)	A1	A2	A3	A4	A5
10	C/B	C/B	C/B	C/B	C/B
10					
220	A1	A2	A3	A4	A5

Fig 2. Axial configurations of the FAs.

Under the aforementioned simulation conditions, the preliminary results obtained are as follows. Figure 3 shows the radial power distribution at the beginning of cycle (BOC). The BOC condition corresponds to the initial state without fission products, represents the most conservative condition with the highest *k*-eff. The numerical values indicated at each assembly location represent the normalized assembly power factors. At the BOC, the maximum radial power factor is 1.18 in the central region of the core, while the minimum value of 0.81 is observed in the lower interior region. Figure 4 illustrates the axial power distribution at the BOC. A top-skewed power profile is observed, which is attributed to the axial configuration of the burnable

absorber rods. In the present design, gadolinium is not included in the upper cutback region of the burnable absorber rods but is applied only in the lower region.

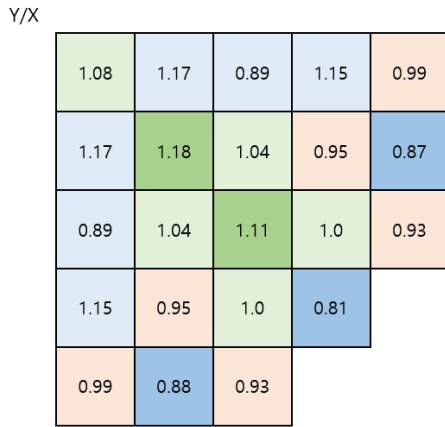


Fig 3. Radial power distribution

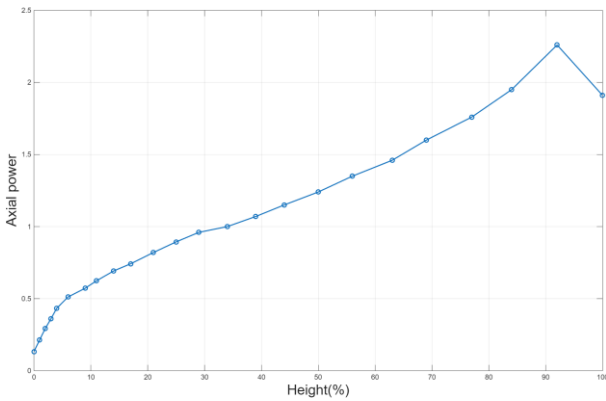


Fig 4. Axial power distribution

3. Assembly Spacing-based Reactivity Reduction Concept

In this study, the Monte Carlo neutron transport code MCNP was employed for the neutronic analysis. MCNP is a well-established and extensively validated high-fidelity code that has been widely used in various reactor physics applications. ENDF/B-based neutron cross-section libraries were used in this study. Furthermore, MCNP provides versatile tally capabilities, enabling precise evaluation of key physical parameters such as reactivity, neutron flux distribution, and power distribution, which are essential for assessing the effectiveness of the proposed assembly spacing-based reactivity reduction concept.[3]

Figure 5 illustrates the core configuration simulating the concept of inducing negative reactivity through the separation and the relocation of fuel assemblies under accident conditions. The spatial rearrangement of the fuel assemblies creates additional moderator regions, resulting in a reduction of the effective multiplication factor. This analysis was conducted to evaluate the feasibility of introducing negative reactivity to reduce the effective multiplication factor(k-eff). The simulation was performed at the beginning of cycle (BOC), where

the core consists of fresh fuel without fission products, resulting in the greatest k_{eff}. This condition is considered the most conservative for assessing reactivity behavior under accident conditions.



Fig 5. Loading pattern implementing the assembly spacing-based reactivity reduction concept

4. Results

The simulation results show that the effective multiplication factor of the reference core decreased from 1.042563 ± 0.00084 to 0.948160 ± 0.00071 after introducing the moderator regions. Correspondingly, the reactivity decreased significantly from 4082pcm(6.28\$) to -5468pcm(-8.41\$). The obtained negative reactivity(-5468pcm, -8.41\$) is of the same order of magnitude as typical shutdown margin requirements, which are generally on the order of several thousand pcm.[4]. It also corresponds to a substantial fraction of the soluble-boron reactivity control capability in large PWR cores, where the differential boron worth is typically on the order of 7 pcm/ppm and the critical boron concentration at hot power generally ranges from 1400 to 1500 ppm.[5]

These results suggest that increasing the spacing between fuel assemblies and introducing additional moderator regions may contribute to the suppression of excess reactivity. Furthermore, based on the preliminary simulation results, the proposed concept appears to have potential applicability in terms of reactivity reduction.

5. Conclusions

In this study, a concept of increasing the spacing between fuel assemblies under accident conditions was proposed for an i-SMR core, and its effects were investigated through neutron transport simulations. The results indicate that increasing the assembly spacing and introducing additional moderator regions in the central area tend to reduce the effective multiplication factor and reactivity.

This finding suggests that the proposed concept can serve as an additional control system idea to suppress the increase in core k-eff. Furthermore, this concept is not limited to specific conditions but is proposed as a generally applicable passive mitigation system, and this study represents a preliminary investigation to assess its feasibility.

However, for practical implementation, further improvements are required in both mechanical design and reactor physics aspects. Future work will focus on evaluating the feasibility of the concept for real applications, along with additional design refinements and analyses.

6. Acknowledgements

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