Characteristic Analysis and Generation of New Neighbor Solutions for Fuel Assembly Optimization

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1. Introduction

Reactor core design technologies are being developed to provide innovative small modular reactors (iSMR) with the highest level of safety and economic efficiency. One of these core design innovations focuses on the optimization of fuel assemblies. The optimal design of fuel assemblies requires confirming core characteristics, such as how long it can be used and how stably it reacts, depending on the arrangement and type of fuel pins in the fuel assembly. This study examines the core characteristics of candidate fuel assembly configurations and evaluates which configuration excels in safety and economic efficiency when compared to other assemblies.

2. Methods

2.1 Generation of New Fuel Assembly Configurations

New configurations were generated to compare with previous fuel assembly design. In order to develop neighborhood solutions that are more suited for comparisons, an approach that involves only minor modifications was used rather of generating configurations at random. Pin configurations in fuel assemblies can be changed in two main ways: (1) changing the type of pin at a specific location, and (2) switching the locations of two pins of different types. Pins are classed as fuel rods, burnable absorber rods, and guide tubes. Since the positions of guide tubes or instrument tubes are fixed and cannot be altered, only the positions and types of fuel rods and burnable absorber rods are changed. when the type of pin is altered, the quantity of each type varies; however, swapping the positions maintains the quantities constant. Pin configurations typically use symmetries such as 1/2, 1/4, or 1/8. When swapping pins located at symmetry boundaries, the total number must be considered. Pins at boundaries should be exchanged either with other boundary pins or internally to maintain overall symmetry.

2.2 Selection of Core Characteristics

The core characteristics to be evaluated were selected to identify configurations that offer higher safety and economic efficiency. Optimal fuel assembly design ensures safe and cost-effective operation of a core. Safety is improved when the variation in multiplication factor due to burnup is limited, and the peaking factor is low. Economic efficiency improves when the multiplication factor is higher when the core reaches equilibrium. The selected core characteristics were as follows:

- KINF_EQ: The infinite multiplication factor (KINF) value at its peak during the burnup cycle, where higher values indicate better economic efficiency.
- GRAD_SUM: The average difference in KINF from the beginning of the cycle to the inflection point, with smaller values indicating better safety.
- GRAD_MAX: The maximum absolute slope of KINF within specific intervals, where smaller values indicate better safety.
- FXY: The maximum planar pin peaking factor during the burnup cycle, where smaller values indicate better safety.

2.3 Generation of Candidates

It is challenging to definitively compare configurations among multiple attributes, especially as economic efficiency and safety often contrast. The Pareto front[1] was used to generate candidates, which are a set of solutions that are not dominated by others and are widely used for multi-objective optimization. Representative values were derived by standardizing the characteristics (mean = 0, standard deviation = 1) and adding them together in order to rank these candidates. Prior to calculation, the maximum values were converted to minimizing values by multiplying them by -1. Additionally, weights were assigned to the characteristics during the representative value calculation.

3. Analyses & Results

Figure 1 shows the pin configuration of the reference fuel assembly. The assembly is 17×17 and has 1/8 symmetry. Pins are divided into five types: fuel rods, guide tubes, instrumentation tube, low burnable absorber rods, and high burnable absorber rods. Neighboring solutions were generated by swapping the positions of pins without altering their types, as changing the types would affect the number of burnable absorber rods. This approach generated a total of 194 neighboring solutions.

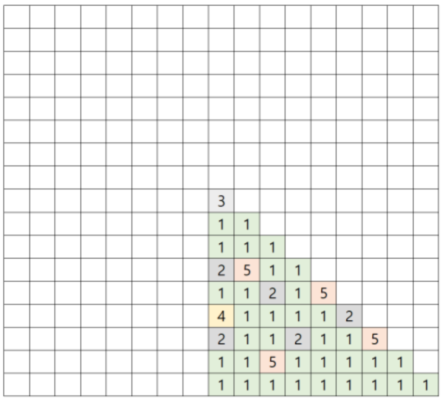

Fig. 1. The reference fuel assembly configuration

Core characteristics were calculated using the KARMA[2] code. Results for the reference configuration indicated that:

- The extreme point occurred at 28 MWD/kgU (red mark),
- The inflection point appeared at 33 MWD/kgU (green mark), and
- The maximum FXY was 1.155.
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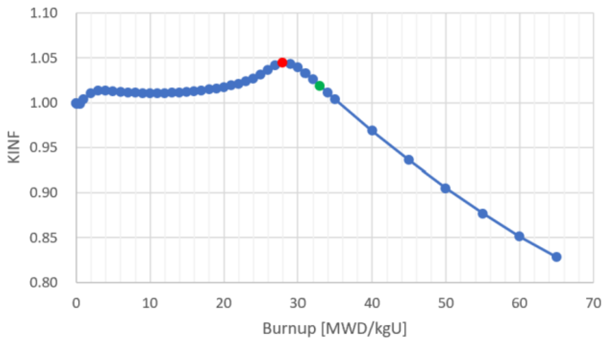

Fig. 2. KINF graph of the reference fuel assembly

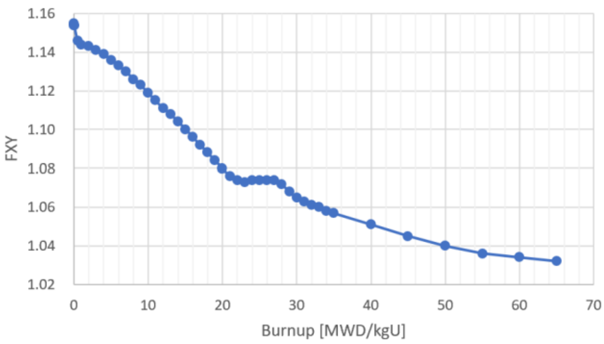

Fig. 3. FXY graph of the reference fuel assembly

For each neighboring solution, KINF and FXY values were extracted, and KINF characteristics (KINF_EQ, GRAD_SUM, GRAD_MAX) were computed. The Pareto front and representative values were calculated to compare the solutions. Weights of 1, 0.5, 0.5, and 1 were assigned to KINF_EQ, GRAD_SUM, GRAD_MAX, and FXY, respectively. Among the reference and 194 neighboring solutions, 69 solutions formed the Pareto front. On the Pareto front, 12 solutions, including the reference, were selected as candidates based on the lowest representative values. Solutions such as Swap 84, Swap 92, Swap 109, and Swap 102 showed better safety, whereas Swap 32 and Swap 31 exhibited better economic efficiency. Solutions like Swap 63, Swap 61, and Swap 60 had comparable results as the reference configuration.

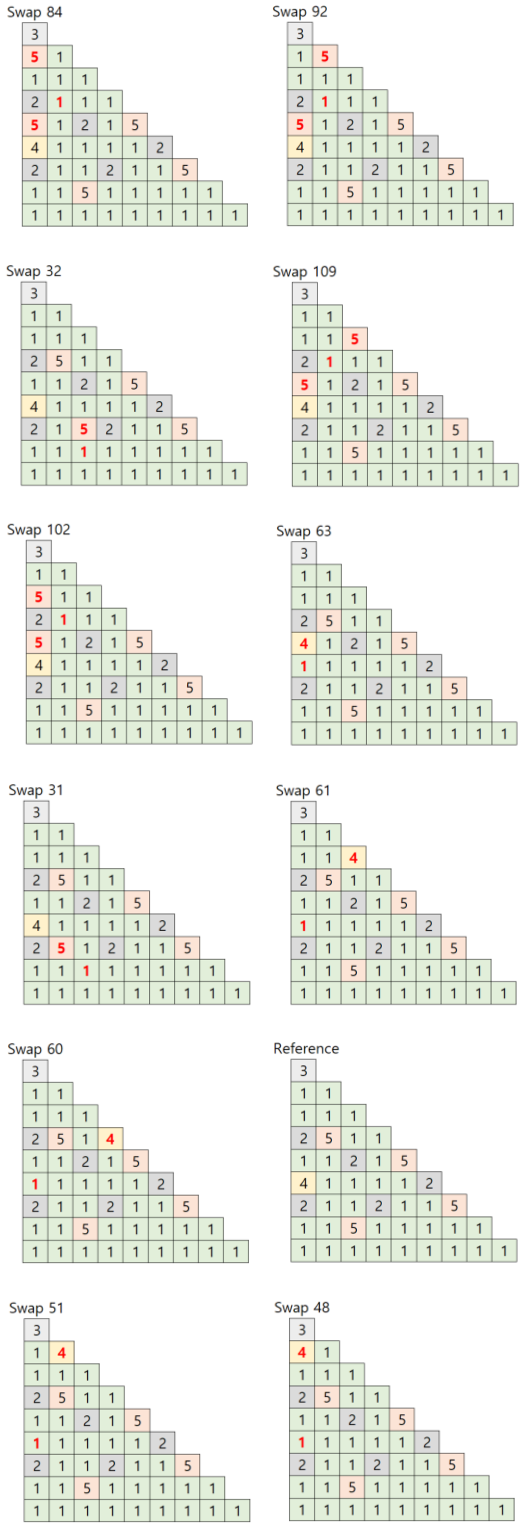

Fig. 4. Candidates of fuel assembly configurations

Table I: Mean and standard deviation of core characteristics

	Mean	standard deviation
KINF_EQ	1.0324	0.0081
GRAD_SUM	0.0022	0.0002
GRAD_MAX	0.0070	0.0005
FXY	1.2134	0.0426

Table II: Candidates of fuel assembly

	Representative	KINF_EQ	GRAD_SUM	GRAD_MAX	FXY
Swap 84	-2.771	1.0387	0.0020	0.0071	1.147
Swap 92	-2.588	1.0404	0.0021	0.0073	1.149
Swap 32	-2.520	1.0468	0.0024	0.0073	1.158
Swap 109	-2.508	1.0425	0.0022	0.0073	1.149
Swap 102	-2.454	1.0431	0.0022	0.0074	1.150
Swap 63	-2.402	1.0438	0.0023	0.0074	1.151
Swap 31	-2.363	1.0454	0.0022	0.0073	1.170
Swap 61	-2.289	1.0438	0.0023	0.0074	1.158
Swap 60	-2.252	1.0438	0.0023	0.0074	1.158
Reference	-2.242	1.0438	0.0023	0.0074	1.155
Swap 51	-2.207	1.0439	0.0023	0.0074	1.161
Swap 48	-2.156	1.0439	0.0023	0.0074	1.161

4. Conclusions

The reference configuration is a good solution included on the Pareto front; however, alternative solutions with better economic efficiency or safety also exist. If economic efficiency is prioritized, Swap 32 is a suitable alternative, while Swap 84 is a viable option for enhanced safety. Additional criteria can be considered to choose between these configurations, including those with comparable performance to the reference. Although this study focused on neighboring solutions obtained by a single swap, additional iterations of this process could yield even better optimal configurations.

Acknowledgements

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