A study on the change of Optimal Loading Pattern according to the Power Level in SMR

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1. Introduction

The core design of the existing power plant consists of the nuclear fuel assembly design, the group constant production for each fuel assembly and the core loading pattern design [1]. When designing the core loading pattern, various fuel assemblies are arbitrarily arranged and changes of core characteristic factors for each burnup calculation are evaluated. The optimal core loading pattern is found by comparing and evaluating the differences between each core characteristic factors. Previous researches [2,3] have successfully demonstrated that the simulated annealing (SA) method and multi-objective function are very effective to find optimal loading pattern.

A conventional loading pattern design was made through a huge amount of burnup calculations. The core burnup calculation was performed at full power because the nuclear power plant like APR1400 or OPR1000 was in charge of the base loads and maintains full power at all times during operation. In case of small modular reactor (SMR), however, it should be able to show that it can operate not only as a base load but also at various power levels. With the recent growth of renewable energy and the diversification of energy grids, nuclear power plants also need to be evaluated for the various power levels.

In this paper, core loading patterns that can be found in various power levels were presented and each comparison data were also presented. The data used for the evaluation of the loading model used the library of the SMR core. The evaluation of each arbitrary loading pattern is performed using the SA method and multi objective function.

2. Methodology

2.1 Simulated Annealing Algorithm

When applying SA to the optimum loading pattern (LP) search for a core, the first step is to define an objective function that is appropriate for the core design requirements. Eq. (1) below shows a multi-objective function, J(X), appropriate for design requirements of the small modular reactor core.

$$J(X) = w_L J_L(X) + w_R J_R(X) + w_Q J_Q(X) + w_B J_B(X) + w_Z J_Z(X) + w_F J_F(X) \tag{1}$$

where w denotes weight for each parameter. J denotes normalized function. The subscript means cycle length (L), 2D pin power peaking factor (R), and 3D pin power peaking factor (Q), discharge burnup (B), HZP MTC (Z) and HFP MTC (F). The multi-objective function, J(X), in Eq. (1) is defined as a linear combination of six objective functions and the definitions of each term are described.

The SA algorithm proceeds with comparing objective function value of the current LP X_{cur} with that of a new LP X_{new}. X_{new} is always accepted if $J(X_{new}) < J(X_{old})$. Otherwise, it is accepted only with the probability of $\exp(-\triangle J/C)$ in which $\triangle J=J(X_{new})-J(X_{old})$ and C is a temperature parameter. In practice, X_{new} in this case is accepted if;

$$\xi < \exp(-\triangle J/C), \tag{2}$$

where ξ is a random number. If X_{new} is accepted, X_{cur} is replaced with X_{new}. Another new LP is generated and tested in the same way. This is repeated until a near-optimal LP is found. The SA algorithm is depicted in Fig. 1.

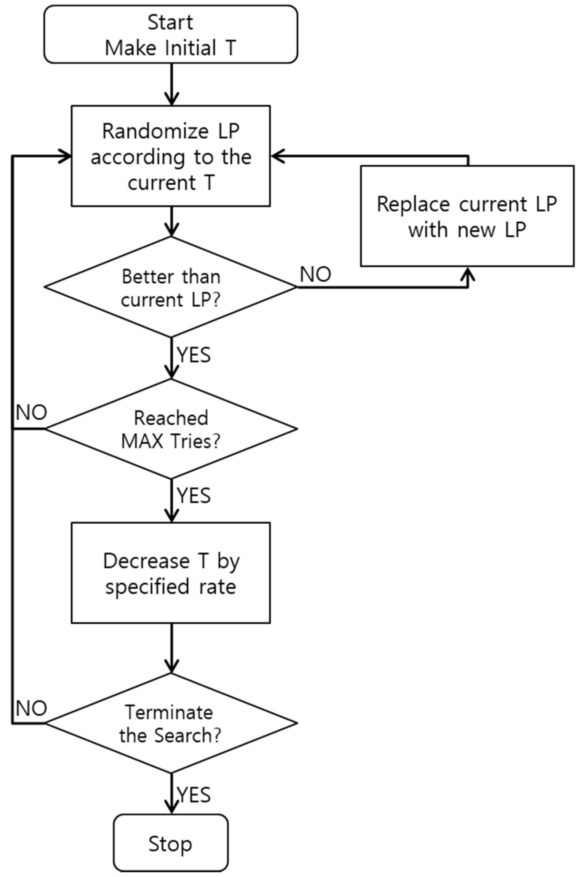


Fig. 1. SA algorithm.

About the flow chart in Fig. 1, the T means temperature which is applied in Eq. (2) temperature parameter.

2.2 SMR Core Model

The target core is rectangular in shape. It has three different fuel assembly enrichment types. Low enriched fuels and mid enriched fuels are at the core center positions with checker board pattern, while high enriched fuels are at the peripheral positions of the core. Three fuel assembly types have burnable absorbers (BAs) for reactivity balance and peaking control. Fig. 2 shows a quarter core geometry, which reflects the color-coded fuel assembly enrichment and the reflector. The white color means low enriched fuel, yellow color means mid enriched fuel, green color means high enriched fuel and blue color means reflector.

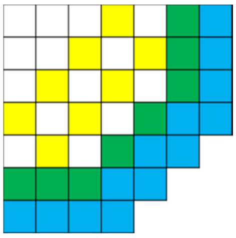


Fig. 2. Schematic core geometry of SMR.

3. Calculation Results and Assessments

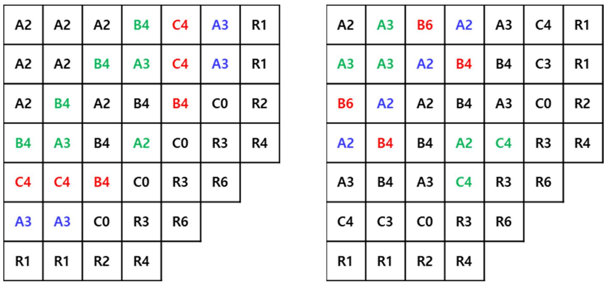
To find the optimal LP, the SA method was used under the following conditions. Initially, there were two objective functions; cycle length and discharge burnup. And the center assembly was fixed with a single type of assembly. Except the center assembly, other fuel assemblies were modified with enrichment and number of burnable poisons (BPs). For calculation conditions, the maximum number of LPs to find optimal LP was 10,000. The MPI parallel computing sped up all simulation calculations. The MASTER code [4] carried out the burnup calculations.

For each simulation, the power level between 50% and 90% was applied. Trends in cycle length, discharge burnup, and LP shape are shown for the simulation results.

First, the results of the 50% power burnup simulation were displayed in Fig. 3 and Table I. The three colors used in Fig. 3 to depict the LP results in three colors. Red denotes that it is converted to a high enriched fuel, blue to a low enriched fuel, and green to a different BP number. There were two separate LP types, each with a distinct tendency.

The first LP has high enriched zone on the periphery, while the second LP takes on a different checker board pattern in the core center region.

Table I displays evaluated values for each LP along with reference values at the bottom of the table. The table explains why multiple LPs are generated as a result of simulation. Because two objective functions are used, several LPs are proposed when determining comparative advantage among LPs is difficult. From Table I to V, the asterisk at the tables describes the calculation results of the given LPs in Fig. 2.



A2	A2	A2	B4	C4	A3	R1
A2	A2	B4	A3	C4	A3	R1
A2	B4	A2	B4	B4	C0	R2
B4	A3	B4	A2	C0	R3	R4
C4	C4	B4	C0	R3	R6	
A3	A3	C0	R3	R6		
R1	R1	R2	R4			

LP#1

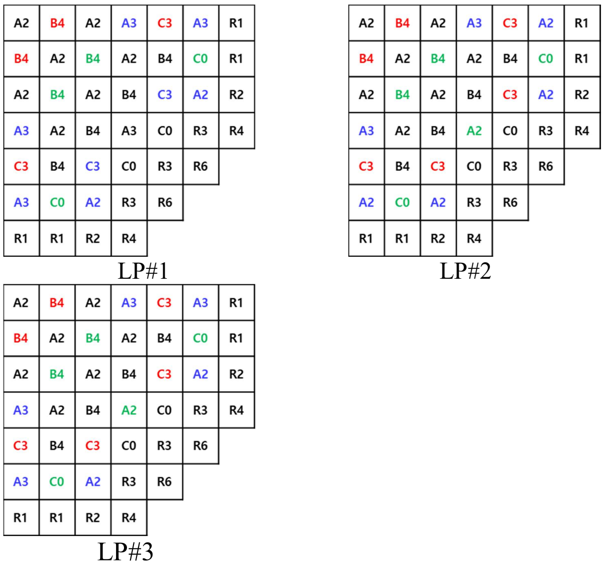
A2	A3	B6	A2	A3	C4	R1
A3	A3	A2	B4	B4	C3	R1
B6	A2	A2	B4	A3	C0	R2
A2	B4	B4	A2	C4	R3	R4
A3	B4	A3	C4	R3	R6	
C4	C3	C0	R3	R6		
R1	R1	R2	R4			

LP#2

Fig. 3. Optimized LPs for 50% power level.

Table I : Objective functions for 50% power level simulation

Objective Function	Ref. LP	LP #1	LP#2
Cycle Length (Days)	927.3	947.2	947.8
Fr / Fq	1.487 / 1.862	1.484 / 1.849	1.487 / 1.854
Discharge Burnup (GWD/MTU)	25.57	25.97	25.94



A2	B4	A2	A3	C3	A3	R1
B4	A2	B4	A2	B4	C0	R1
A2	B4	A2	B4	C3	A2	R2
A3	A2	B4	A3	C0	R3	R4
C3	B4	C3	C0	R3	R6	
A3	C0	A2	R3	R6		
R1	R1	R2	R4			

LP#1

A2	B4	A2	A3	C3	A2	R1
B4	A2	B4	A2	B4	C0	R1
A2	B4	A2	B4	C3	A2	R2
A3	A2	B4	A2	C0	R3	R4
C3	B4	C3	C0	R3	R6	
A2	C0	A2	R3	R6		
R1	R1	R2	R4			

LP#2

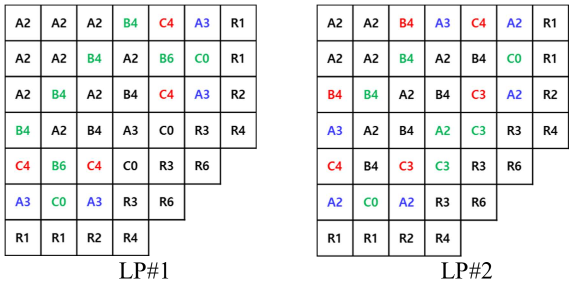
A2	B4	A2	A3	C3	A3	R1
B4	A2	B4	A2	B4	C0	R1
A2	B4	A2	B4	C3	A2	R2
A3	A2	B4	A2	C0	R3	R4
C3	B4	C3	C0	R3	R6	
A3	C0	A2	R3	R6		
R1	R1	R2	R4			

LP#3

Fig. 4. Optimized LPs for 60% power level.

Table II : Objective functions for 60% power level simulation

Objective Function	Ref. LP	LP #1	LP#2	LP#3
Cycle Length (Days)	930.3	949.0	950.3	949.7
Fr / Fq	1.499 / 1.887	1.495 / 1.886	1.499 / 1.872	1.472 / 1.874
Discharge Burnup (GWD/MTU)	25.61	26.03	25.94	26.02



A2	A2	A2	B4	C4	A3	R1
A2	A2	B4	A2	B6	C0	R1
A2	B4	A2	B4	C4	A3	R2
B4	A2	B4	A3	C0	R3	R4
C4	B6	C4	C0	R3	R6	
A3	C0	A3	R3	R6		
R1	R1	R2	R4			

LP#1

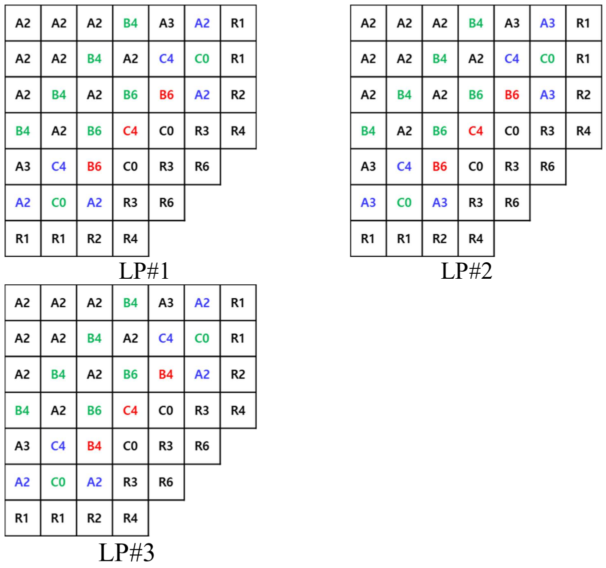
A2	A2	B4	A3	C4	A2	R1
A2	A2	B4	A2	B4	C0	R1
B4	B4	A2	B4	C3	A2	R2
A3	A2	B4	A2	C3	R3	R4
C4	B4	C3	C3	R3	R6	
A2	C0	A2	R3	R6		
R1	R1	R2	R4			

LP#2

Fig. 5. Optimized LPs for 70% power level.

Table III : Objective functions for 70% power level simulation

Objective Function	Ref. LP	LP #1	LP#2
Cycle Length (Days)	911.1	931.7	932.2
Fr / Fq	1.479 / 1.845	1.469 / 1.835	1.476 / 1.834
Discharge Burnup (GWD/MTU)	25.13	25.64	25.43



A2	A2	A2	B4	A3	A2	R1
A2	A2	B4	A2	C4	C0	R1
A2	B4	A2	B6	B6	A2	R2
B4	A2	B6	C4	C0	R3	R4
A3	C4	B6	C0	R3	R6	
A2	C0	A2	R3	R6		
R1	R1	R2	R4			

LP#1

A2	A2	A2	B4	A3	A3	R1
A2	A2	B4	A2	C4	C0	R1
A2	B4	A2	B6	B6	A3	R2
B4	A2	B6	C4	C0	R3	R4
A3	C4	B6	C0	R3	R6	
A3	C0	A3	R3	R6		
R1	R1	R2	R4			

LP#2

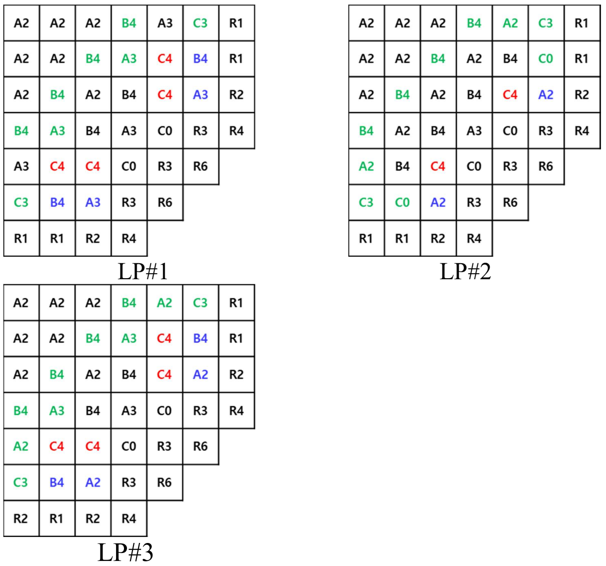
A2	A2	A2	B4	A3	A2	R1
A2	A2	B4	A2	C4	C0	R1
A2	B4	A2	B6	B4	A2	R2
B4	A2	B6	C4	C0	R3	R4
A3	C4	B4	C0	R3	R6	
A2	C0	A2	R3	R6		
R1	R1	R2	R4			

LP#3

Fig. 6. Optimized LPs for 80% power level.

Table IV : Objective functions for 80% power level simulation

Objective Function	Ref. LP	LP #1	LP#2	LP#3
Cycle Length (Days)	901.8	920.1	921.8	924.3
Fr / Fq	1.483 / 1.813	1.484 / 1.828	1.469 / 1.801	1.465 / 1.789
Discharge Burnup (GWD/MTU)	25.13	25.37	25.32	25.27



A2	A2	A2	B4	A3	C3	R1
A2	A2	B4	A3	C4	B4	R1
A2	B4	A2	B4	C4	A3	R2
B4	A3	B4	A3	C0	R3	R4
A3	C4	C4	C0	R3	R6	
C3	B4	A3	R3	R6		
R1	R1	R2	R4			

LP#1

A2	A2	A2	B4	A2	C3	R1
A2	A2	B4	A2	B4	C0	R1
A2	B4	A2	B4	C4	A2	R2
B4	A2	B4	A3	C0	R3	R4
A2	B4	C4	C0	R3	R6	
C3	C0	A2	R3	R6		
R1	R1	R2	R4			

LP#2

A2	A2	A2	B4	A2	C3	R1
A2	A2	B4	A3	C4	B4	R1
A2	B4	A2	B4	C4	A2	R2
B4	A3	B4	A3	C0	R3	R4
A2	C4	C4	C0	R3	R6	
C3	B4	A2	R3	R6		
R2	R1	R2	R4			

LP#3

Fig. 7. Optimized LPs for 90% power level.

Table V : Objective functions for 90% power level simulation

Objective Function	Ref. LP	LP #1	LP#2	LP#3
Cycle Length (Days)	897.1	923.2	929.5	924.9
Fr / Fq	1.500 / 1.885	1.477 / 1.855	1.500 / 1.884	1.486 / 1.830
Discharge Burnup (GWD/MTU)	25.01	25.56	25.34	25.53

Changes in enrichment and the number of BPs occurred in any part of the core regions between 60% and 70% of power level. The change in enrichment occurred only at the peripheral fuel assemblies when the power level was 80-90%. And the LP tendency becomes similar with a small change in BPs.

The enrichment at the inner core region was increased at low power level to allow for more efficient core burnup. At relatively high power levels, on the other hand, there was a tendency to move low enriched fuel to the periphery to reduce neutron leakage.

4. Conclusion

The optimal loading patterns at part power state (50%-90%) were obtained and shown. The optimal loading pattern for each power level tended to increase core efficiency while decreasing neutron leakage, when compared with the LP optimized at HFP-ARO condition. These findings suggest that the loading pattern should be determined considering the relevant power state if the core is expecting extended load following operations.

As a future work, core safety parameters need to be estimated to determine whether the core is safe to operate.

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REFERENCES

[1] H. C. Lee, C. H. Kim, H. J. Shim, Parallel Computing Adaptive Simulated Annealing Scheme for Fuel Assembly Loading Pattern Optimization in PWR, Nuclear Technology, 135, 29, 2001

[2] T. K. Park, H. C. Lee, H. K. Joo, C. H. Kim, Screening Technique for Loading Pattern Optimization by Simulated Annealing, Proceedings of the Korean Nuclear Society Conference, May 26, 2005.

[3] T. K. Park, H. C. Lee, H. K. Joo, C. H. Kim, Loading Pattern Optimization by Multi-Objective Simulated Annealing with Screening Technique, PHYSOR-2006, Vancouver, BC, Canada, September 10-14, CD-ROM, 2006

[4] H. J. Jeong, J. Y. Cho et al., Verification and Validation of MASTER Code for Steady-State and Transient Benchmark Core Calculations, Transactions of the KNS Spring Meeting, May 17-18, 2018, Jeju, R.O.Korea.