Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 20-21, 2022

Fuel Loading Pattern Optimization of a Load-Follow Operating SMR using A-Genre_LP

Kibeom Park*, Byeong-hyeok Ha, Byeongmun Ahn, Tongkyu Park, Sung-Kyun Zee, Soo-Youl Oh
FNC Tech., 46 Tapsil-ro, Giheung-gu, Yongin-si, Gyeonggi-do, 17084, Republic of Korea
**Corresponding author: kpark1026@fnctech.com*

1. Introduction

Load following operation of a nuclear power plant has not been strongly requested in Korea and nuclear power plants have served as the base load plants of the electricity grid. However, a diversification of the power systems with, for instance, renewable energy needs a load following operation of nuclear power plants. Furthermore, such a need in an SMR is higher than that in a large NPP when SMRs are deployed in an isolated, small grid which is more sensitive to fluctuations in power demand. These reasons necessitate a design that makes an SMR be capable of routine power maneuvering.

Nuclear fuel loading pattern (LP) of a PWR is searched for an optimal distribution of fuel assemblies using a conventional two step method [1]. The LP is determined upon fuel economics and safety parameters. For base-loader NPPs, the LP optimization is done assuming continuous full power operation throughout the cycle. However, in case that a routine, maybe every day, load following operation is supposed, the optimal loading pattern must be determined taking into account power maneuvering scenarios based on control rod movements rather than full power operation.

In this paper, we present results of LP optimization of an SMR being load following operated employing Advanced Genre_LP (A-Genre_LP) computer code. The candidate loading pattern is found using the Simulated Annealing (SA) [2] algorithm. A load following (LF) algorithm [3] is also introduced to simulate load following operations.

2. Methodology

2.1 Simulated Annealing Algorithm

When applying SA to the optimum LP search, 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 a small modular reactor core.

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

where X is an LP, w weight factor for each parameter, and J a normalized function of X. The subscripts mean: cycle length (L), 2D pin power peaking factor (R), 3D pin power peaking factor (Q), discharge burnup (B), HZP MTC (Z), HFP MTC (F), and control rod moving steps (CR). The multi-objective function, J(X), in Eq. (1) is defined as a linear combination of seven objective functions.

To reflect the load following operation, the term of control rod moving steps was introduced. The reason for adding this term is that the number of control rod moving steps is considered as one of the important factors in judging whether the load following operation is practical. Note that the number of moving steps has a great influence on the maintenance of the control rod drive mechanism. The EUR documents [4] require limiting the number of movements of the control rod.

The SA algorithm [1] with load following is depicted in Fig. 1.

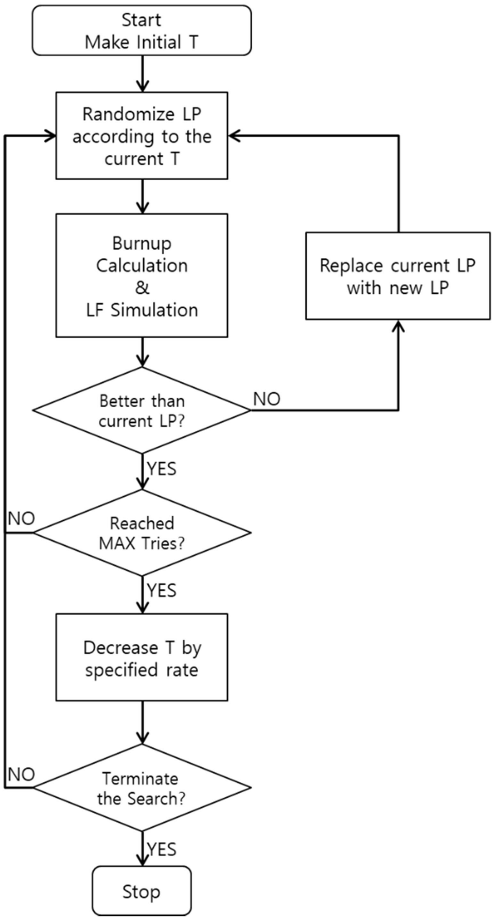


Fig. 1. SA algorithm with load following simulation.

In the flow chart, T means temperature which is needed for temperature dependent parameters in Eq (1). Burnup calculation and LF simulation are performed separately to obtain objective function parameter.

2.2 Load Following Algorithm

Considered load following operations are extended daily load following for consecutive days and quick return-to-full power during the daily load following operation. The load following algorithm uses the core outlet temperature and axial offset (AO) as the control parameters to minimize the variations in outlet temperature and AO caused by control rod movements and xenon oscillation. The boron concentration is also adjusted in the algorithm to meet specific safety requirements and operation limits. Fig.2 shows the flow of LF operation simulation.

In order to verify this algorithm, we simulated a long-term daily LF operation over 7 days following the EUR and EPRI requirements [4, 5]. Fig. 3 shows the results. As shown, the temperature and AO were well controlled within the allowed band, respectively.

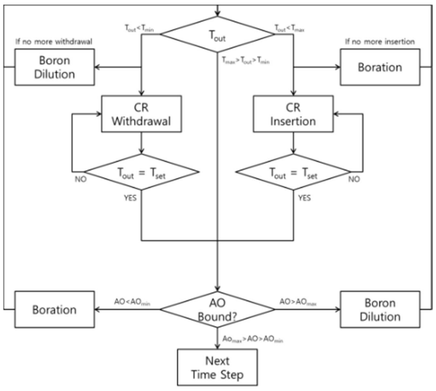


Fig. 2. Load following algorithm.

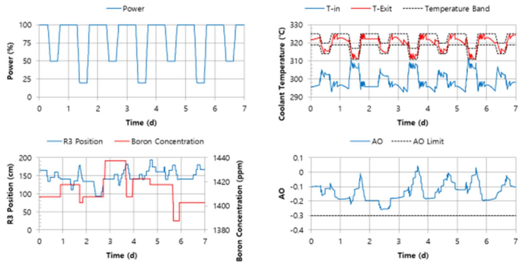


Fig. 3. Validation results of load following algorithm.

2.3 SMR Core Model

The schematic geometry of target core problem is shown in Fig. 4. It has three kinds of fuel assemblies with different enrichments. 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. All the assemblies have burnable absorbers (BAs) for reactivity balance and peaking control. Fig. 4 shows the quarter core geometry of the reference LP, identifying the fuel enrichment with color low enriched fuels in white, mid in yellow, high in green, and reflector in blue.

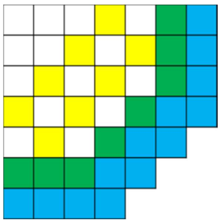


Fig. 4. Schematic core geometry of SMR.

3. Calculation Results and Assessments

To find out an optimal LP, the SA method was used under following conditions. At first, adopted are four sub-objective functions; cycle length, power peaking factor, discharge burnup, CR moving steps. The center assembly was fixed with a predetermined type of assembly. Except the center position, the fuel assemblies with different enrichments and with different number of burnable poisons (BPs) were shuffled. The maximum number of trial LPs to find out the optimal LP was set to 10,000. MPI parallel computing was used to make simulation faster. Burnup calculation was performed by MASTER code [6].

Simulated load following operations are shown in Fig. 5 (a) 100-50% operation and (b) 100-50-100% operation, respectively. Then, searched LPs are shown in Figs. 6 and 7, and the results such as cycle length and discharge burnup are given in following Tables.

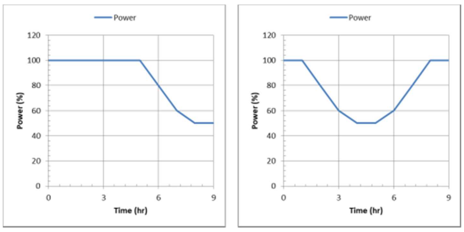
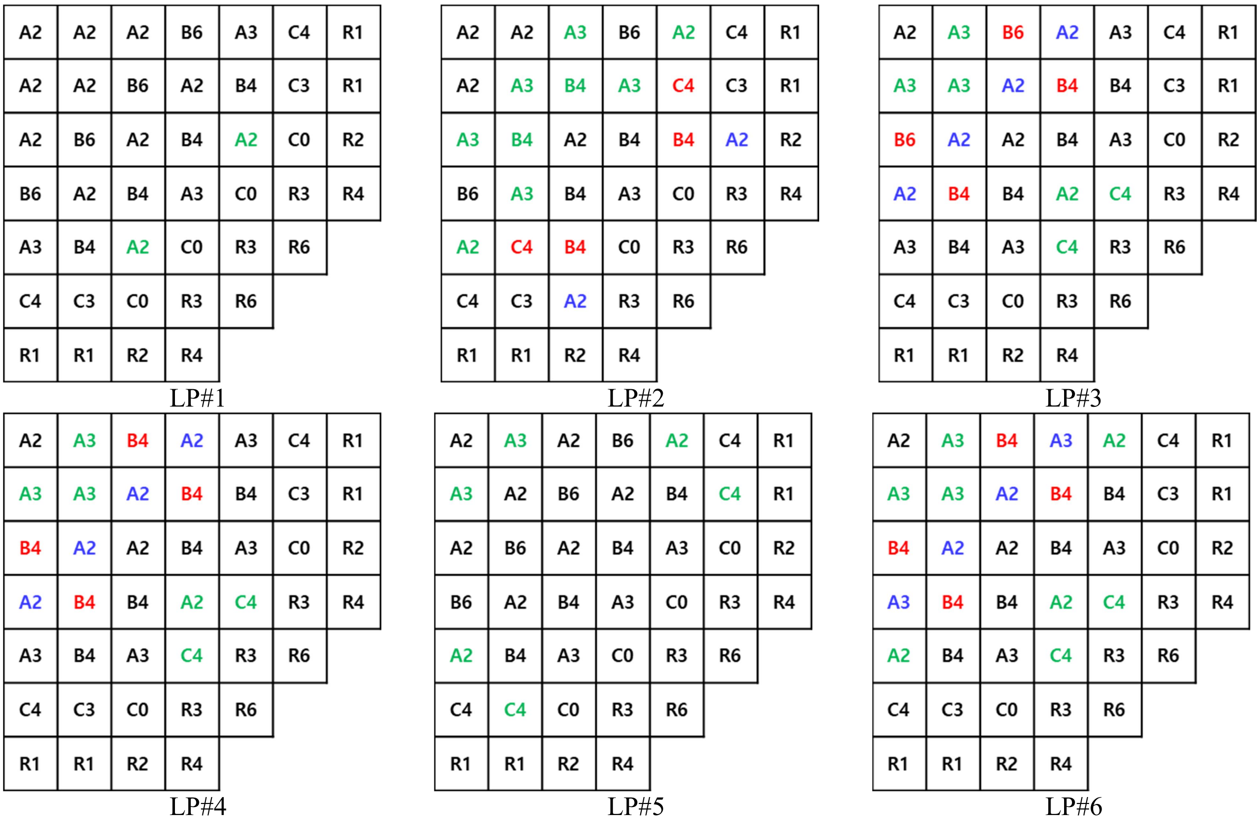


Fig. 5. Power change for load following simulation.

In Figs. 6 and 7, six searched LPs for each LF operation were shown in 3 colors. Alphabet in fuel ID represents the enrichment and the number in ID is the number of burnable poison. Fuel ID in red indicates the position where higher enrichment assembly is loaded instead of the assembly in the reference pattern. Positions in blue are occupied by assemblies with lower enrichment than that in the reference pattern, and green one is changed with different number of BPs.

Two LF cases show different tendency in loading patterns. For the first LF operation, the inner parts of core were shuffled, while the outer parts of core were shuffled for the second type of operation. The number of BPs increased at positions where the control rods are inserted in order to reduce the peaking factors.

As shown in Tables I and II, the number of CR moving steps became 10% reduced for both simulations. Through these results, it was verified that the SA algorithm for finding out the optimal LPs considering load following is well implemented.



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

LP#1

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

LP#2

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#3

A2	A3	B4	A2	A3	C4	R1
A3	A3	A2	B4	B4	C3	R1
B4	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#4

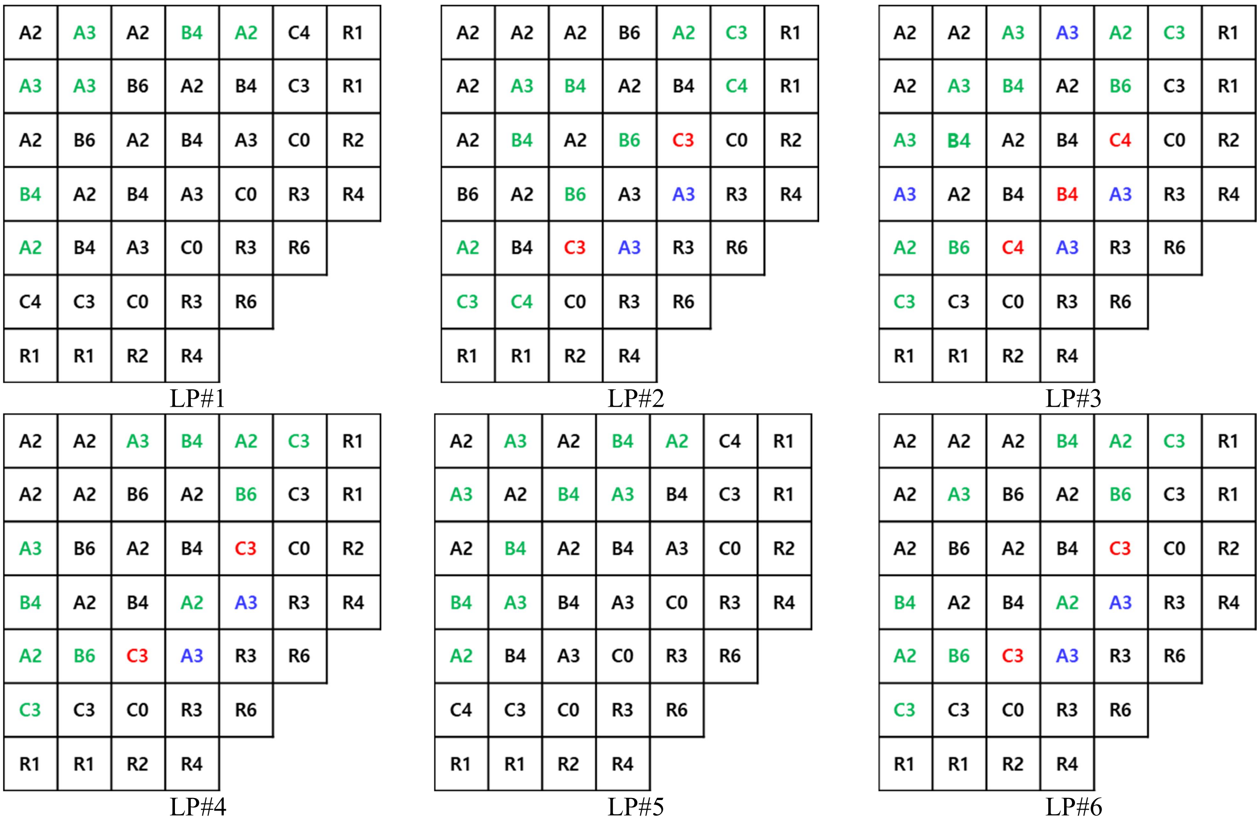
A2	A3	A2	B6	A2	C4	R1
A3	A2	B6	A2	B4	C4	R1
A2	B6	A2	B4	A3	C0	R2
B6	A2	B4	A3	C0	R3	R4
A2	B4	A3	C0	R3	R6	
C4	C4	C0	R3	R6		
R1	R1	R2	R4			

LP#5

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

LP#6

Fig. 6. Optimized LPs for 100%-50% simulation.



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

LP#1

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

LP#2

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

LP#3

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

LP#4

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

LP#5

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

LP#6

Fig. 7. Optimized LPs for 100%-50%-100% simulation.

Table I : Objective Functions for 100%-50% Load Following Simulation

Objective Function	Reference LP	LP#1	LP#2	LP#3	LP#4	LP#5	LP#6
Cycle Length (days)	868.1	872.0	871.6	863.1	864.4	867.8	864.6
Fr / Fq	1.463 / 1.876	1.405 / 1.848	1.497 / 1.877	1.454 / 1.880	1.485 / 1.894	1.413 / 1.900	1.439 / 1.896
CR Moving steps	105	97	97	98	96	90	94
Discharge Burnup (GWD/MTU)	24.12	24.10	24.36	24.12	24.21	24.16	24.20

Table II : Objective Functions for 100%-50%-100% Load Following Simulation

Objective Function	Reference LP	LP#1	LP#2	LP#3	LP#4	LP#5	LP#6
Cycle Length (days)	868.1	871.8	884.3	883.0	885.8	874.0	885.8
Fr / Fq	1.463 / 1.876	1.446 / 1.863	1.491 / 1.888	1.455 / 1.891	1.470 / 1.861	1.426 / 1.874	1.473 / 1.862
CR Moving steps	251	229	238	231	239	237	239
Discharge Burnup (GWD/MTU)	24.12	24.19	24.66	24.25	24.49	24.30	24.56

4. Conclusion

The optimal loading pattern for an SMR which is supposed to perform load following operation routinely was obtained by A-Genre_LP code. Through the SA algorithm considering LF, the result of 10% improvement in the CR moving steps was confirmed. Additionally, cycle length and discharge burnup become different with changed LP. It shows that the effect from load following operation need to be considered to make a reactor more efficient in power maneuvering operation.

As a future work, it is needed to perform a sensitivity study with further various load following scenarios in order to obtain the optimal loading pattern representing the load following in overall.

Acknowledgement

This work was supported by the National Research Foundation of Korea funded by the Ministry of Science and ICT of Korea. (NRF-2020M2D 7A1079181).

REFERENCES

[1] J. H. Jung, Y. S. Ban, H. G. Joo, Establishment and Preliminary Verification of the nTRACER-RENUS Core Analysis System, Transactions of the Korean Nuclear Society Spring Meeting, Jeju, May 18-19, 2017.

[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] K. Park, T. K. Park, S. Zee, B. S. Koo, Evaluation of Automatic Control System for Long Term Load Following Operation using Control Rod for a SMR, Transactions of the Korean Nuclear Society Spring Meeting Online, May 13-14, 2021.

[4] EUR, 2001. The European Utility Requirement (EUR) document, Volume 2 revision C, April 2001.

[5] A. Sowder, S. Bernhoft, and D. Moneghan, Expanding the Concept of Nuclear Flexibility for the Current Fleet and the Next Generation of Advanced Reactors, NREL Technical Report Template.

[6] 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.