Heuristic Rule-Based Approach for PWR Loading Pattern Optimization

Taeuk Moon[a], Jinhyeok Lee[b], Do-Yeon Kim[c], YuGwon Jo[c], and Ho Cheol Shin[c,*]
[a]*Department of Nuclear Engineering, Ulsan National Institute of Science and Technology,* 50 UNIST-gil, Ulsan, 44919
[b]*School of Mechanical Engineering, Pusan National University, 2, Busandaehak-ro 63beon-gil, Geumjeong-gu, Busan, 46241, Korea*
[c]*Korea Hydro & Nuclear Power Co., Ltd. Central Research Institute, 70, Yuseong-daero 1312beon-gil, Yuseong-gu, Daejeon, Korea, 34101*
[*]*Corresponding author: shin.hocheol@khnp.co.kr*

1. Introduction

In the pressurized water reactors (PWRs), the core loading pattern (LP) design is important for both the efficient utilization of fuels and the safe operation of the nuclear power plant. Due to the prohibitively large number of combinations in the LPs, the optimal LP design still relies on the “trial and error approach” of the human experts. To reduce the human expertise dependency, there have been many efforts to develop the LP optimization algorithm based on and the artificial neural network (ANN) [1,2,3] and the simulated annealing (SA) [4,5,6]. Recently, Korea Hydro & Nuclear Power Co., Ltd. Central Research Institute (KHNP CRI) also begins a project to develop the multi-cycle core design optimization technique for practical application to the PWR plants.

In this preliminary study, we have investigated the heuristic rule-based approach for both the LP optimization and big data production. The heuristic rules were extracted by investigating the LPs of the nuclear data report (NDR). Then, a script was written to generate the random LPs constrained by the heuristic rules and perform the depletion calculation with STREAM/RAST-K [7]. Besides, the depletion calculation results from the script can be incorporated into big data which will be utilized in both data mining and the ANN. For this purpose, the hierarchical data format 5 (HDF5) [8] output module for the RAST-K 2.2 [9] was developed, which is a suitable file format for big data.

2. Heuristic rule-based LP search system

2.1. Heuristic Rules in PWR Loading Pattern

The expertise considers the locations of the fresh FA as one of the most significant design parameters in the LP design. We investigated the NDRs of OPR-1000 to find out the patterns of locations of the fresh FAs. There are 12 types of patterns in the locations of fresh FAs, which are named as “root LPs”. The “branching” is defined as selecting the types of fresh FAs which determines the number of burnable absorbers of the FA. Once we select a “branch”, the locations of burned FAs are shuffled to determine one LP. Based on this approach, we narrowed down the possible LPs and provided a systematic approach to search the optimal LP. Figure 1 shows the heuristic rule-based LP search system.

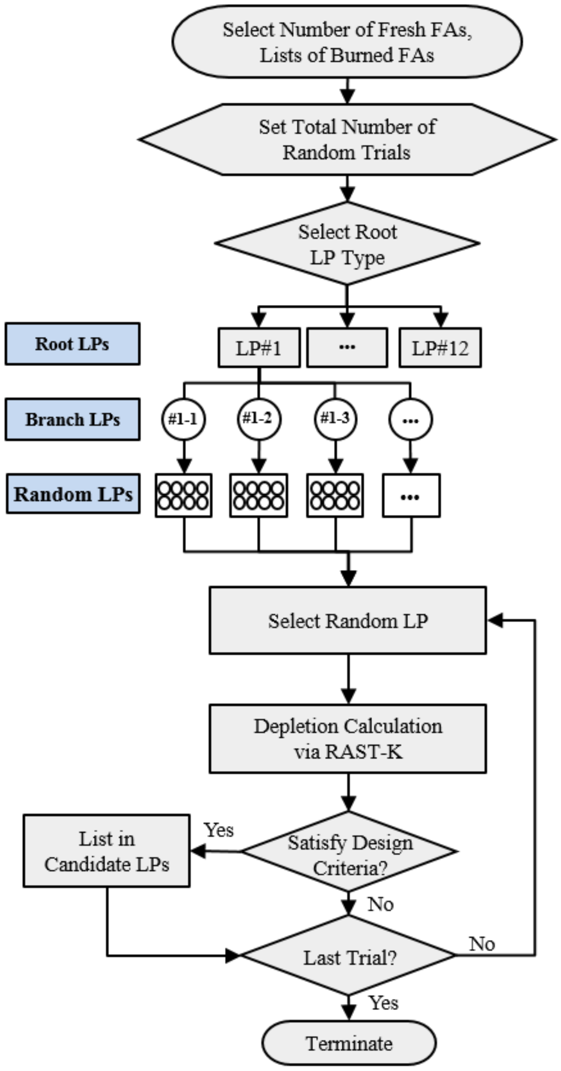

Figure 1. Heuristic rule-based LP search system

The algorithm is as follows:

1. Select the number of fresh FAs and lists of the burned FAs to be loaded based on k-infinity.
2. Set the each number of generation of branch and random LPs.
3. Select one of the root LPs.
4. Generate branch LPs (the types of fresh FAs).
5. Generate random LPs by mixing up the locations of burned FAs.
6. Select a random LP for depletion calculation.
7. Perform the depletion calculation via RAST-K.
8. If a LP satisfies the design criteria, list the LP in candidate LPs.
9. Repeat Step 6 to 8 until the last trial.

As the design criteria of the heuristic rule-based LP search system, we check both the maximum Fxy and the critical boron concentration (CBC) at the end of the cycle (EOC). The maximum Fxy is the most limiting peaking factor for the safety concern, which is defined as Eq. (1).

$$\text{maximum Fxy} = \max_{z,BU}\left(\frac{P_{XY}^{max}(z,Bu)}{P_{XY}^{avg}(z,Bu)}\right), \qquad (1)$$

where $P_{XY}^{max}(z,Bu)$ and $P_{XY}^{max}(z,Bu)$ are the maximum and the average fuel pin power densities, respectively, in the two-dimensional x-y plane at the axial location *z* and the burnup step *Bu*. The CBC at EOC is the performance index for the neutron economic concern.

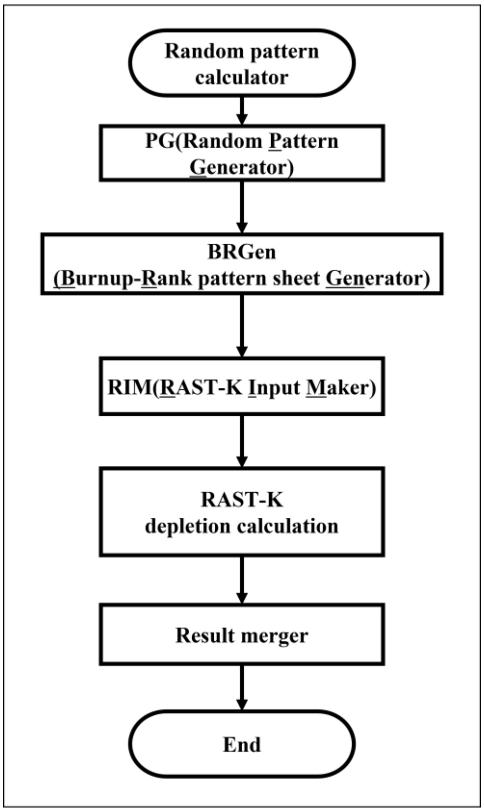

Figure 2. Flow chart of random pattern calculator

Figure 2 shows the flow chart of the random pattern calculator, which is a script to generate the random LPs according to the heuristic rules and perform numerous depletion calculations simultaneously by taking advantage of the parallel computing cluster. The procedure of the execution is as follows:

1. A bundle of text files of random patterns generated by PG(Random Pattern Generator).
2. Generated patterns gathered by BRGen(Burnup-rank pattern sheet Generator).
3. Gathered patterns will be transformed into RAST-K code input by RIM(RAST-K Input Maker).
4. Resulting RAST-K inputs are put to RAST-K depletion calculation.
5. Result merger merges the depletion calculation results.

3. Loading Pattern Big Data Based on HDF5 Format

The heuristic rules of the LP design can be incorporated into big data. Then big data will be utilized in both data mining and machine learning (or deep learning) for loading pattern optimization. As shown in Table 1, the data size of depletion calculation results for one LP is around 50 MB. When we consider 20,000 LPs [1], the size of big data ranges up to 1 TB. To efficiently handle big data, the output file of RAST-K 2.2 [9] should be a suitable format for big data.

Table 1. Data size of depletion calculation results for one loading pattern of a typical OPR-1000

Data Type	No. of Energy Groups	No. of Nuclides	No. of Burnup Steps	No. of Axial Nodes	No. of Radial Nodes (1/4 Core)	No. of Real Data (4-Byte Real Format)	Memory [MB]
$N_{nuclide}$	N/A	41	23	46	177	7,677,906	29.289
T_{fuel}		N/A	23	46	177	187,266	0.714
$T_{coolant}$			23	46	177	187,266	0.714
$\rho_{coolant}$			23	46	177	187,266	0.714
Bu			23	46	177	187,266	0.714
$P_{thermal}$			23	46	177	187,266	0.714
D	2		23	46	241	509,956	1.945
$\kappa\Sigma_f$	2		23	46	241	509,956	1.945
$\nu\Sigma_f$	2		23	46	241	509,956	1.945
Σ_a	2		23	46	241	509,956	1.945
Σ_f	2		23	46	241	509,956	1.945
Σ_r	2		23	46	241	509,956	1.945
Σ_s	2		23	46	241	509,956	1.945
Σ_{tr}	2		23	46	241	509,956	1.945
ϕ	2		23	46	241	509,956	1.945
Total						13,203,840	50.369

The hierarchical data format 5 (HDF5) [8] is an open-source file format that supports large, complex, heterogeneous data and organizes it in the "file directory" structure of UNIX. The HDF5 library supports various languages including C, C++, Java, Fortran, and Python. Using the HDF5 Fortran library, the HDF5 output module for RAST-K 2.2 was developed. Table 2 compares the output file format of RAST-K 2.2 in terms of the file size and the elapsed time for writing. If the main concern is the file size, HDF5 with 4-byte real format would be preferred. Figure 3 shows an example of the HDF5 output file using HDFView [10].

Table 2. Comparison of output file format of RAST-K 2.2 in terms of file size and elapsed time for writing

File Format	Compression	Elapsed Time [s]*	File Size [MB]
Plain Text	X	6.134	239
HDF5 (8-Byte Real Format)	X	0.249	101
	O	3.416	78
HDF5 (4-Byte Real Format)	X	0.170	51
	O	1.605	37

*Intel(R) Xeon(R) CPU E5-2687W @3.00GHz

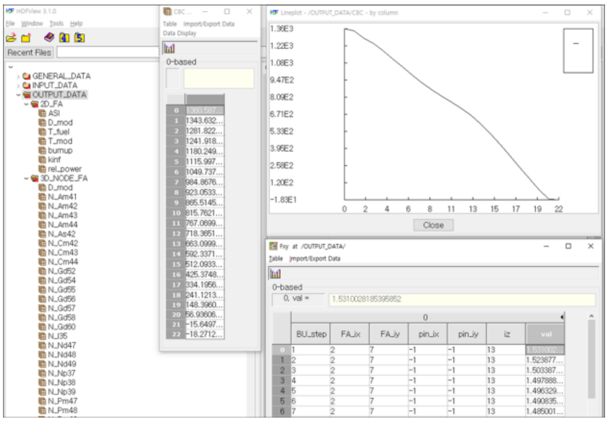

Figure 3. View of HDF5 output file using HDFView.

4. Numerical Results

To test the performance of the heuristic rule-based LP search system, we extracted 60,000 samples for the root LP type 12 of OPR-1000. The depletion calculations were performed by the reactor analysis code RAST-K 2.2 [9] on the high-performance parallel cluster of KHNP CRI, which is named as QUVICS with 214.3 TFlops.

Figure 4 shows the scattering distributions of 60,000 data points (blue dots), where the x-axis is the CBC at EOC and the y-axis is the max. Fxy. The reference (red dot) was obtained from the LP of the NDR. The black dots are the top 10 data, which are arranged in the ascending order of 60,000 data based on the maximum Fxy and represent it in Table 3. Compared to maximum Fxy of the reference, those of top 10 data show larger values, which is due to the absence of the FA rotation algorithm in this work.

5. Conclusions

We proposed the heuristic rule-based LP search system. We found the 12 patterns of the locations of the fresh FAs based on the NDRs and introduced the concept of "root LP" and "branch LP" to provide a systematic way to sample LPs. In addition, the HDF5 format output module of RAST-K 2.2 was developed to efficiently handle the depletion calculation results as big data. The numerical results show that the sampled LPs are not as good as the LP of the NDR, which can be improved by the implementing the FA rotation algorithm. In future, the LPs provided from the SA or the machine learning can be incorporated as the root LP in the proposed search system.

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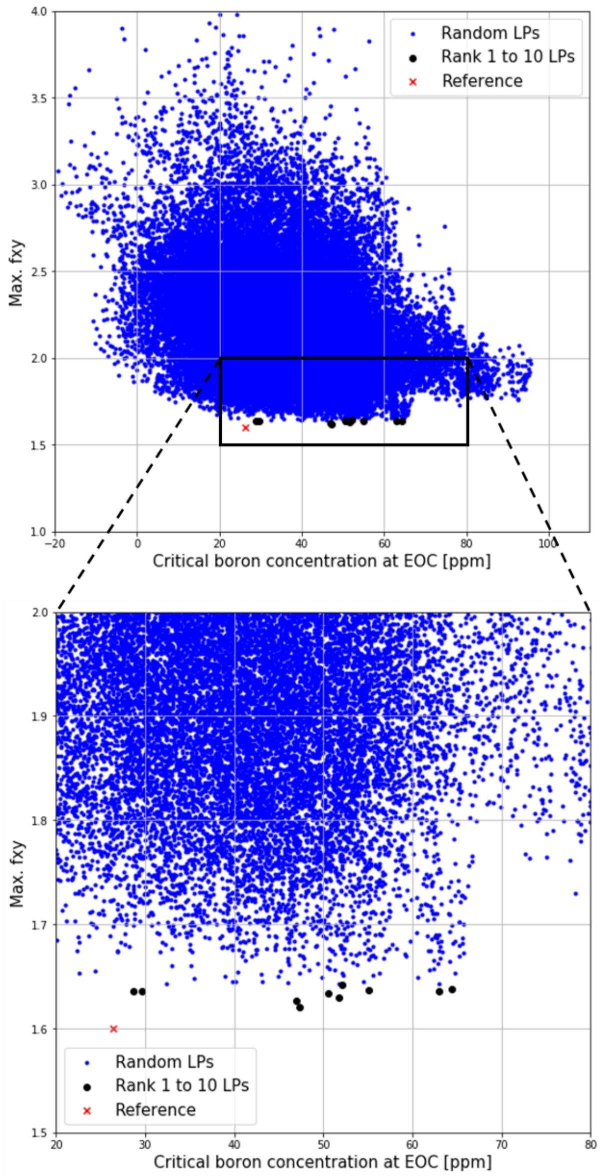

Figure 4. Scattering distributions of 60,000 data point of root LP#12

Table 3. Top 10 ranking result sorted in ascending order based on max. Fxy

Loading Patterns	CBC [ppm]	Max. Fxy
Reference	26.40	1.6000
Rank 1	47.30	1.6208
Rank 2	46.97	1.6264
Rank 3	51.71	1.6298
Rank 4	50.52	1.6338
Rank 5	28.75	1.6353
Rank 6	29.60	1.6356
Rank 7	62.96	1.6362
Rank 8	55.07	1.6367
Rank 9	64.37	1.6378
Rank 10	52.10	1.6422

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