Loading Pattern Optimization by Multi-objective Simulated Annealing with Screening Technique

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Abstract

This paper presents a new multi-objective function which is made up of the main objective term as well as penalty terms related to the constraints. All the terms are represented in the same functional form and the coefficient of each term is normalized so that each term has equal weighting in the subsequent simulated annealing optimization calculations. The screening technique introduced in the previous work is also adopted in order to save computer time in 3-D neutronics evaluation of trial loading patterns. For numerical test of the new multi-objective function in the loading pattern optimization, the optimum loading patterns for the initial and the cycle 7 reload PWR core of Yonggwang Unit 4 are calculated by the simulated annealing algorithm with screening technique. A total of 10 optimum loading patterns are obtained for the initial core through 10 independent simulated annealing optimization runs. For the cycle 7 reload core one optimum loading pattern has been obtained from a single simulated annealing optimization run. More SA optimization runs will be conducted to optimum loading patterns for the cycle 7 reload core and results will be presented in the further work.

KEYWORDS: Loading Pattern Optimization, Simulated Annealing, Multi-objective Function, Screening Technique

1. Introduction

The simulated annealing (SA) algorithm [1,2] has been popularly adopted for the optimum fuel assembly (FA) loading pattern (LP) search calculations in initial/reload core design of light water reactors. However, it has a major drawback of long computing time because it requires neutronics evaluation of tens of thousands of trial LPs in the course of the optimization. In our previous work, we introduced a screening technique (ST) aimed at reducing computing time for SA LP optimization with 3-dimensional (3D) neutronics evaluation model [3]. We demonstrated the effectiveness of the ST using the conventional single objective SA LP optimization algorithm for Yonggwang Unit 4 (YGN4) cycle 7 LP optimization problem. The optimum LP in the single-objective LP optimization problem was defined as the one that minimizes the end-of-cycle (EOC) soluble boron concentration at a given cycle burnup within design constraints imposed on pin power peaking factor, the critical soluble boron at the beginning-of- cycle (BOC), maximum fuel assembly discharge burnup, etc. In this paper, we introduce a new multi-objective function which treats the main objective term and the penalty terms related to the constraints with equal importance in the SA optimization calculations. Thus the new multi-objective function is represented by a sum of the main objective term and the penalty terms. All the terms are expressed in the same functional form. Each term is normalized so that each term has similar importance. Then the SA LP optimization algorithm with incorporation of ST is applied to find the optimum LP for the initial and cycle 7 reload core of YGN4. The applicability and effectiveness of the multi-objective SA algorithm are discussed.

2. LP Optimization by Multi-objective SA

2.1 Multi-Objective Function

In applying SA algorithm to the optimum LP search for an initial or reload core, one characterizes first an objective function fit for the core design requirements. Equation (1) below shows a multi-objective function, $J(X)$, appropriate for design requirements of a pressurized water reactor(PWR) core. The cycle length, the pin power peaking factor (PPPF), the maximum pin discharge burnup, and the moderator temperature coefficient (MTC) at BOC hot zero power (HZP) state and BOC hot full power (HFP) state are generally considered as the main design constraints.

$$J(X) = w_L J_L(X) + w_P J_P(X) + w_B J_B(X) + w_Z J_Z(X) + w_F J_F(X)\,, \tag{1}$$

where

w_L : user defined weight for the cycle length term,

w_P : user defined weight for the pin power peaking constraint term,

w_B : user defined weight for the pin discharge burnup constraint term,

w_Z : user defined weight for the HZP MTC constraint term,

w_F : user defined weight for the HFP MTC constraint term,

$J_L(X)$: normalized cycle length objective function term,

$J_P(X)$: normalized pin power peaking objective function term,

$J_B(X)$: normalized pin discharge burnup objective function term,

$J_Z(X)$: normalized HZP MTC objective function term.

$J_F(X)$: normalized HFP MTC objective function term.

The multi-objective function, $J(X)$, in Eq. (1) is defined as a sum of four objective functions. Each objective function is defined as follows:

$$J_L(X) = \begin{cases} 1 + \frac{1}{\overline{L}}\left(L(X) - L_{\lim}\right)^2 & \left(L(X) < L_{\lim}\right) \\ 0 & otherwise \end{cases}, \tag{2a}$$

$$J_P(X) = \begin{cases} 1 + \frac{1}{\overline{P}}\left(P(X) - P_{\lim}\right)^2 & \left(P(X) > P_{\lim}\right) \\ 0 & otherwise \end{cases}, \tag{2b}$$

$$J_B(X) = \begin{cases} 1 + \frac{1}{\overline{B}}\left(B(X) - B_{\lim}\right)^2 & \left(B(X) > B_{\lim}\right) \\ 0 & otherwise \end{cases}, \tag{2c}$$

$$J_Z(X) = \begin{cases} 1 + \frac{1}{\overline{Z}}\left(Z(X) - Z_{\lim}\right)^2 & \left(Z(X) > Z_{\lim}\right) \\ 0 & otherwise \end{cases}, \qquad (2d)$$

$$J_F(X) = \begin{cases} 1 + \frac{1}{\overline{F}}\left(F(X) - F_{\lim}\right)^2 & \left(F(X) > F_{\lim}\right) \\ 0 & otherwise \end{cases}, \qquad (2e)$$

where

$L(X)$ = the cycle length of LP X ,
$P(X)$ = the maximum pin power of LP X during the cycle,
$B(X)$ =the maximum pin discharge burnup of LP X ,
$Z(X)$ = MTC of LP X at BOC HZP,
$F(X)$ = MTC of LP X at BOC HFP,
$L_{\lim}$ = the minimum target cycle length,
$P_{\lim}$ = the pin power peaking limit,
$B_{\lim}$ = the pin discharge burnup limit,
$Z_{\lim}$ = the HZP MTC limit,
$F_{\lim}$ = the HFP MTC limit,
$\overline{L}$ = the normalization factor of the cycle length objective function,
$\overline{P}$ = the normalization factor of the pin peaking objective function,
$\overline{B}$ =the normalization factor of the pin discharge burnup objective function,
$\overline{Z}$ = normalization factor of the HZP MTC objective function,
$\overline{F}$ = normalization factor of the HFP MTC objective function.

Each objective function has a jump at the limiting value of the related design parameter and it has a quadratic form beyond the limit. The jump at the limiting value plays a role similar to that of large penalties beyond the limiting values in a single-objective function. The average values of the quadratic terms beyond the limiting values evaluated from about 100 LPs generated randomly are used as the normalization factors in Eq. (3) in order to make the expected values of the quadratic terms become some number around 1.

3. Results and Discussions

3.1 LP Optimization for Initial Core of YGN4

The multi-objective function is incorporated into the SA LP optimization routine of UNCARDS(Unified Nodal Code for Advanced Reactor Design and Simulation). To examine its validity, LP optimization calculation is performed for the initial core of YGN4, which contains a total of 177 FA's. Table 1 shows the specifications of the fuel assemblies used in the real loading pattern for the initial core of YGN4.

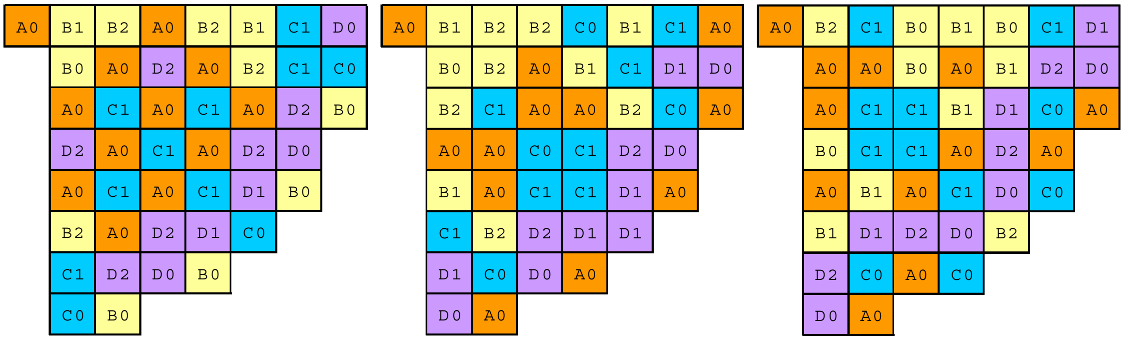
During the LP optimization by SA, a new LP is generated from the current LP in two ways. One is to exchange randomly chosen two FA's and the other is to change the number of BP rods in a randomly chosen FA. Whenever a new LP is generated, one of the two methods is chosen randomly with the same probability. Octant symmetry of the LP and the total number of FA's in a FA group are preserved during the optimization process. For example, the total number of FA's of type B0, B1, and B2 is kept at 44 during the process. As for the design constraints, the PPPF limit of 1.500 is imposed for all the FA's. The upper limits of BOC MTC are set at 5.0 pcm/□ and 0.0 pcm/□ for HZP and HFP, respectively. Slightly longer cycle length(=13.8MWD/kg) than that of real LP(=13.5MWD/kg) is set as the minimum target cycle length. Table 2 summarizes the design parameters of the real LP for initial core of YGN4 and the LP's obtained from 10 independent SA optimization runs. All the LP's satisfy all the design constraints as imposed. The LP's obtained from SA optimization calculation have longer cycle lengths within the design limits for PPPF, HZP MTC, and HFP MTC. In this conjunction, it is interesting to note that all the optimum LPs found from the multi-objective SA optimization calculations satisfy all the design constraints but with little margin. Figure 1 shows the real LP and the LPs obtained from SA optimization calculations. Table 3 shows the statistics of the 10 independent SA optimization runs. The efficiency of the ST is 18.5% on the average, which is quite lower than that demonstrated in our previous work [3]. The cause of the low efficiency of the ST is not identified yet but it will be addressed in the further work.

Table 1. Specifications of the fuel assemblies for the initial core of YGN4

FA Group	FA Type	Enrichment (wt%)	No. of Fuel Rods per FA	No. of Gd BP Rods per FA	Gd_2O_3 wt% in Nat'l UO_2	No. of FA's used in the Real LP	
A	A0	1.30	236	0	-	45	45
B	B0	2.36	236	0	-	20	44
	B1	2.36 / 1.30	176 / 52	8	4.0	8	
	B2	2.36	232	4	4.0	16	
C	C0	2.86 / 2.36	184 / 52	0	-	12	44
	C1	2.85 / 2.36	176 / 52	8	4.0	32	
D	D0	3.35 / 2.85	184 / 52	0	-	12	44
	D1	3.36 / 2.85	176 / 52	8	4.0	8	
	D2	3.36 / 2.85	128 / 100	8	4.0	24	

Table 2 Design parameters of the real LP and the optimum LP's for the initial core of YGN4

	PPPF (<1.500)	HZP MTC (<5.0pcm/□)	HFP MTC (<0.0pcm/□)	Cycle Length (>13.8MWD/kg)
Real LP	1.487	2.592	-6.138	13.5
LP1	1.498	4.710	-4.883	14.2
LP2	1.498	4.269	-5.390	13.9
LP3	1.494	4.304	-4.599	14.2
LP4	1.496	4.208	-3.904	14.2
LP5	1.486	4.625	-3.653	14.0
LP6	1.490	4.785	-4.406	14.0
LP7	1.497	4.623	-4.369	13.8
LP8	1.492	4.156	-4.775	14.0
LP9	1.493	4.612	-4.889	14.1
LP10	1.491	4.380	-4.184	13.9



Real LP

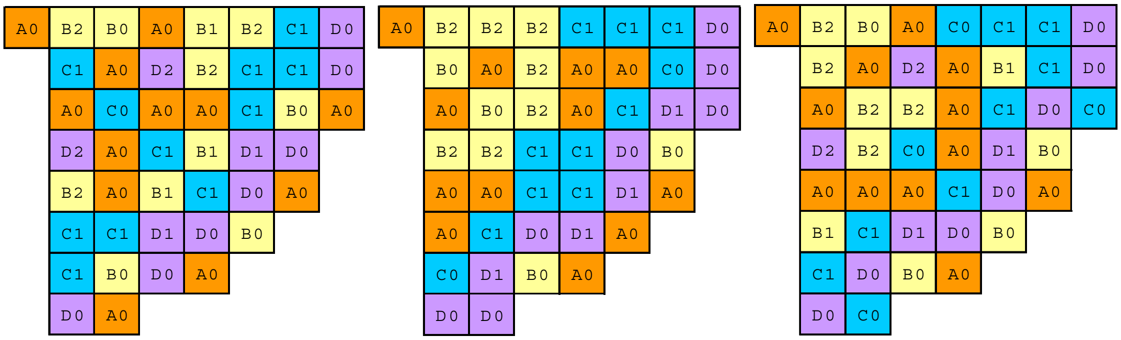
A0	B1	B2	A0	B2	B1	C1	D0
	B0	A0	D2	A0	B2	C1	C0
	A0	C1	A0	C1	A0	D2	B0
	D2	A0	C1	A0	D2	D0	
	A0	C1	A0	C1	D1	B0	
	B2	A0	D2	D1	C0		
	C1	D2	D0	B0			
	C0	B0					

LP1

A0	B1	B2	B2	C0	B1	C1	A0
	B0	B2	A0	B1	C1	D1	D0
	B2	C1	A0	A0	B2	C0	A0
	A0	A0	C0	C1	D2	D0	
	B1	A0	C1	C1	D1	A0	
	C1	B2	D2	D1	D1		
	D1	C0	D0	A0			
	D0	A0					

LP2

A0	B2	C1	B0	B1	B0	C1	D1
	A0	A0	B0	A0	B1	D2	D0
	A0	C1	C1	B1	D1	C0	A0
	B0	C1	C1	A0	D2	A0	
	A0	B1	A0	C1	D0	C0	
	B1	D1	D2	D0	B2		
	D2	C0	A0	C0			
	D0	A0					



LP3

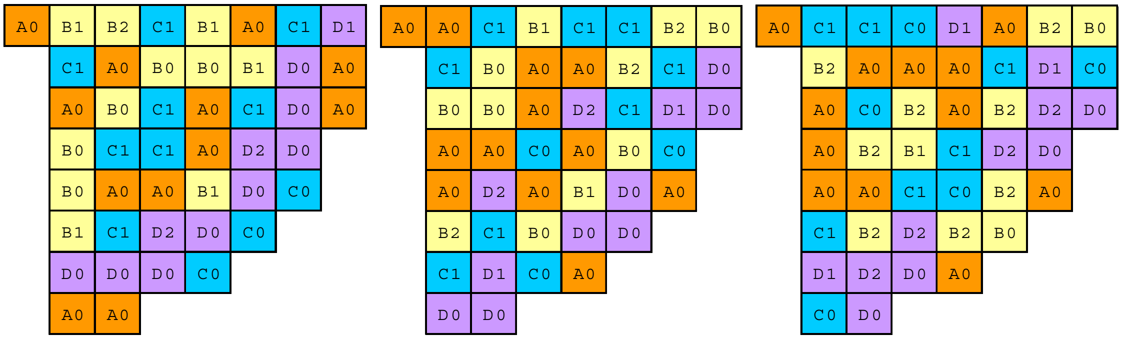
A0	B2	B0	A0	B1	B2	C1	D0
	C1	A0	D2	B2	C1	C1	D0
	A0	C0	A0	A0	C1	B0	A0
	D2	A0	C1	B1	D1	D0	
	B2	A0	B1	C1	D0	A0	
	C1	C1	D1	D0	B0		
	C1	B0	D0	A0			
	D0	A0					

LP4

A0	B2	B2	B2	C1	C1	C1	D0
	B0	A0	B2	A0	A0	C0	D0
	A0	B0	B2	A0	C1	D1	D0
	B2	B2	C1	C1	D0	B0	
	A0	A0	C1	C1	D1	A0	
	A0	C1	D0	D1	A0		
	C0	D1	B0	A0			
	D0	D0					

LP5

A0	B2	B0	A0	C0	C1	C1	D0
	B2	A0	D2	A0	B1	C1	D0
	A0	B2	B2	A0	C1	D0	C0
	D2	B2	C0	A0	D1	B0	
	A0	A0	A0	C1	D0	A0	
	B1	C1	D1	D0	B0		
	C1	D0	B0	A0			
	D0	C0					



LP6

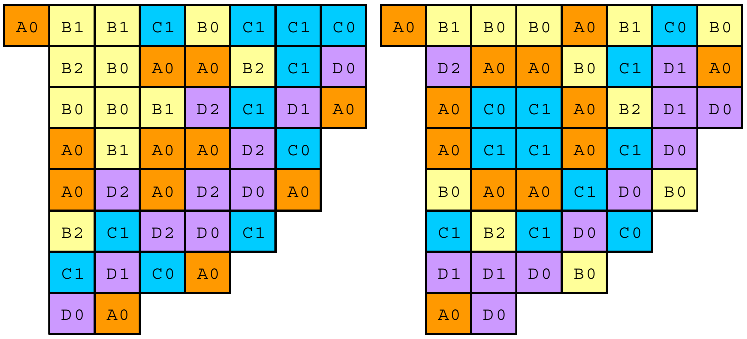
A0	B1	B2	C1	B1	A0	C1	D1
	C1	A0	B0	B0	B1	D0	A0
	A0	B0	C1	A0	C1	D0	A0
	B0	C1	C1	A0	D2	D0	
	B0	A0	A0	B1	D0	C0	
	B1	C1	D2	D0	C0		
	D0	D0	D0	C0			
	A0	A0					

LP7

A0	A0	C1	B1	C1	C1	B2	B0
	C1	B0	A0	A0	B2	C1	D0
	B0	B0	A0	D2	C1	D1	D0
	A0	A0	C0	A0	B0	C0	
	A0	D2	A0	B1	D0	A0	
	B2	C1	B0	D0	D0		
	C1	D1	C0	A0			
	D0	D0					

LP8

A0	C1	C1	C0	D1	A0	B2	B0
	B2	A0	A0	A0	C1	D1	C0
	A0	C0	B2	A0	B2	D2	D0
	A0	B2	B1	C1	D2	D0	
	A0	A0	C1	C0	B2	A0	
	C1	B2	D2	B2	B0		
	D1	D2	D0	A0			
	C0	D0					



LP9

A0	B1	B1	C1	B0	C1	C1	C0
	B2	B0	A0	A0	B2	C1	D0
	B0	B0	B1	D2	C1	D1	A0
	A0	B1	A0	A0	D2	C0	
	A0	D2	A0	D2	D0	A0	
	B2	C1	D2	D0	C1		
	C1	D1	C0	A0			
	D0	A0					

LP10

A0	B1	B0	B0	A0	B1	C0	B0
	D2	A0	A0	B0	C1	D1	A0
	A0	C0	C1	A0	B2	D1	D0
	A0	C1	C1	A0	C1	D0	
	B0	A0	A0	C1	D0	B0	
	C1	B2	C1	D0	C0		
	D1	D1	D0	B0			
	A0	D0					

Figure1. Real LP and the optimum LP’s for the initial core of YGN4

Table 3 Statistics of the 10 independent SA optimization runs for the initial core of YGN4

Run	No. of Stages	No. of LP's Sampled	No. of 3D evaluations	No. of LP's Screened out	No. of LP's Accepted	Screening Eff. (%)
1	63	13353	9634	3719	3847	27.9
2	82	18401	15258	3143	4975	17.1
3	76	16787	14809	1978	4574	11.8
4	56	10311	9030	1281	3551	12.4
5	52	8623	7525	1098	2982	12.7
6	57	10672	7450	3222	3457	30.2
7	66	13822	11580	2242	3912	16.2
8	75	16564	13643	2921	4485	17.6
9	66	13862	11509	2353	4087	17.0
10	60	12560	9798	2762	3722	22.0
Average	65	13496	11024	2472	3959	18.5
Std. Dev.	9.7	3115	2830	848	591	6.3

3.2 LP Optimization for Cycle 7 Reload Core of YGN4

LP optimization calculation is also performed for the cycle 7 reload core of YGN4. Table 4 shows specifications of the feed assemblies for the cycle 7 reload core. The information about the burned fuels is obtained by core follow calculation from cycle 1 to cycle 6.

Table 4. Specifications of the fuel assemblies for cycle 7 reload core of YGN4

FA Group	FA Type	Enrichment (wt%)	No. of Fuel Rods per FA	No. of Gd BP Rods per FA	Gd_2O_3 wt% in Nat'l UO_2	No. of FA's used in the Real LP	
KA	KA	4.5 / 4.0	172 / 52	8	8.0	45	4
K	K0	4.5 /4.0	184 / 52	0	-	20	60
	K1	4.5 /4.0	176 / 52	8	6.0	8	
	K5	4.5 /4.0	176 / 52	8	8.0	16	
	K6	4.5 /4.0	172 / 52	12	8.0	12	
	K7	4.5 /4.0	168 / 52	16	6.0	32	

A new LP is generated from the current LP in two ways as described in the previous section. One of the two methods was randomly chosen with a probability of 0.7 for the first method and 0.3 for the second method, respectively. Like the initial core, octant symmetry of the core is assumed. The total number of fresh FA's in a fresh FA group is preserved during the optimization process. So, the total number of FA's of type K0, K1, K5, K6, and K7 is kept as 60 during the process. For design constraints, the PPPF limit of 1.425 is imposed for 4 advanced FA's (KA) loaded for their performance test while that of 1.500 is imposed for the rest of FA's. The minimum target cycle length is set at 16.0 MWD/kgU. The upper limit of BOC MTC is set at 5.0 pcm/□ and 0.0 pcm/□ for HZP and HFP, respectively. The pin discharge burnup limit is set at 58.0MWD/kg. For performance test, the advanced FA's designated as KA are not allowed at the periphery of the core.

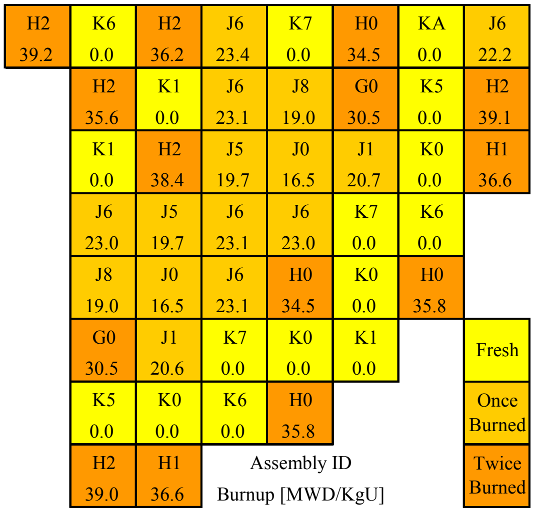
We obtained an optimum LP from a single SA optimization run. Table 5 shows the design parameters of the optimum LP of the run. The optimum LP is shown in Figure 1. All the design requirements are met by the optimum LP. Table 6 shows the result of a single LP optimization calculation run. About 15000 LPs out of about 49000 LPs are found to be screened out by the ST and the screening efficiency is noted to be 31% for this optimization run.

Table 5. Design parameters of the optimum LP for the cycle 7 reload core of YGN4

	Design Limit	Optimum LP
Cycle Length	> 16.00	16.03
Pin peaking	< 1.500	1.500
Pin peaking for FA type KA	< 1.425	1.413
Pin discharge bunnup [MWD/kgU]	< 58.00	55.3
MTC at BOC HZP [pcm/□]	< 5.000	4.39
MTC at BOC HFP [pcm/□]	< 0.000	-22.1

Table 6. Results of a LP optimization calculation run for the cycle 7 reload core of YGN4

Number of stages	94
Number of LP's sampled	49212
Number of 3D evaluation	34045
Number of LP's screened out	15167
Number of LP's accepted	10567
Screening Efficiency (%)	30.8



H2 39.2	K6 0.0	H2 36.2	J6 23.4	K7 0.0	H0 34.5	KA 0.0	J6 22.2
	H2 35.6	K1 0.0	J6 23.1	J8 19.0	G0 30.5	K5 0.0	H2 39.1
	K1 0.0	H2 38.4	J5 19.7	J0 16.5	J1 20.7	K0 0.0	H1 36.6
	J6 23.0	J5 19.7	J6 23.1	J6 23.0	K7 0.0	K6 0.0	
	J8 19.0	J0 16.5	J6 23.1	H0 34.5	K0 0.0	H0 35.8	
	G0 30.5	J1 20.6	K7 0.0	K0 0.0	K1 0.0		Fresh
	K5 0.0	K0 0.0	K6 0.0	H0 35.8			Once Burned
	H2 39.0	H1 36.6	Assembly ID Burnup [MWD/KgU]				Twice Burned

Figure 2. Optimum LP for the cycle 7 reload core of YGN4

4. Concluding remarks

In this paper, we presented a new multi-objective function for LP optimization by SA. We showed applicability and the effectiveness of the SA LP optimization calculation with the new multi-objective function for the initial core and the cycle 7 reload core of YGN4. Specifically, we obtained 10 optimum LPs for the initial core of YGN4 from 10 independent SA optimization runs. All of them satisfied all the design constraints for the initial core of YGN4. We observed that the ST efficiency is lower in the SA optimization calculation for the initial core of YGN4 than that shown in our previous work. The cause of the low efficiency of ST is not clear yet and it should be addressed in the further work. We presented only one optimum LP for the cycle 7 reload core of YGN4 from a single SA optimization run. As in the case of initial core problem, the LP obtained from the SA optimization calculation is also found to satisfy all the constraints for the cycle 7 reload core design. More optimum LP's for the reload core from more SA optimization runs will be presented in the further work.

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