EFFECT OF CORE CALCULATION ACCURACY ON FUEL CYCLE COST

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ABSTRACT

In this paper, the impact of prediction accuracy of core characteristics on the fuel cycle cost was examined. The prediction accuracy is limited to due to uncertainties from nuclear data and approximations adopted in calculation methods. These prediction uncertainties require design margins that place restrictions on feasible loading patterns and decrease core performance and economic efficiency. Since the radial peaking factor is one of the most restrictive safety parameters, the impact of radial peaking factor accuracy on fuel cycle costs was investigated in 2-loop and 3-loop WH type PWRs using several cycle lengths and fuel types. Equilibrium cores were generated assuming various radial peaking factor limitations that correspond to different design margins. From the calculation results, the gain in discharge burnup, which can be considered an index of improvement in fuel cycle costs, was evaluated for each case. In order to make accurate comparisons, the generated equilibrium cores were optimized using the OPAL code by the simulated annealing method. From the calculation results, the effect of prediction accuracy of the radial peaking factor on fuel cycle cost was quantitatively estimated. Because a considerable impact on fuel cycle cost was found, the above results can provide a strong motivation to improve in-core fuel management methods.

1. INTRODUCTION

Accuracy of a core calculation code is influenced not only by its calculation methods, but also by nuclear data, a lattice calculation, an assembly calculation and a cross section table. Since modeling capability of neutronics calculation codes is limited due to available computation resources, accuracy of core calculation codes is inevitably limited; it is compromised by the calculation time. Consequently, the limited accuracy requires some design margins on safety parameters as uncertainty factors. Since the design margin restrict feasible candidates of loading patterns, it inevitably decreases core performance and economic efficiency.

Prediction accuracy of several parameters (e.g. radial peaking factor, moderator temperature coefficient, maximum burnup, core reactivity) could restrict feasible loading patterns. The author will focus on the radial peaking factor to evaluate the effects of prediction accuracy on fuel cycle cost, since it is a most critical safety parameter for the loading pattern design.

Figure 1 and Fig. 2 show distributions of the radial peaking factor and the moderator temperature coefficient, for randomly generated 350,000 loading patterns, respectively[(1)]. The target reactor type is a Westinghouse type 870MWe PWR and feed enrichment is fixed to 4.1wt%. The number of feed assembly is fixed to 60. Since a design target of the radial peaking factor is generally 1.435 in Japanese PWRs, fraction of feasible loading patterns is less than 0.04% in this case. On the other hand, about half of loading patterns are feasible in the viewpoint of moderator temperature coefficient. Therefore, limitation of the radial peaking factor is much more serious than that of the moderator temperature coefficient.

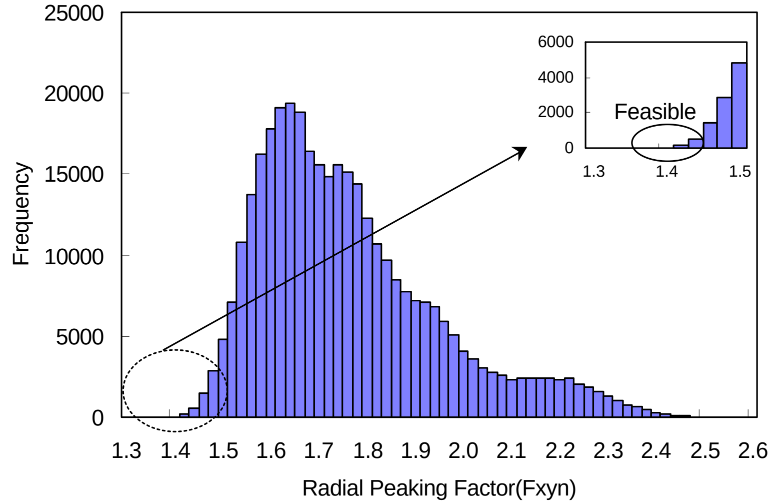


Figure 1. Distribution of radial peaking factor for randomly generated 35 thousands loading patterns in a typical PWR core

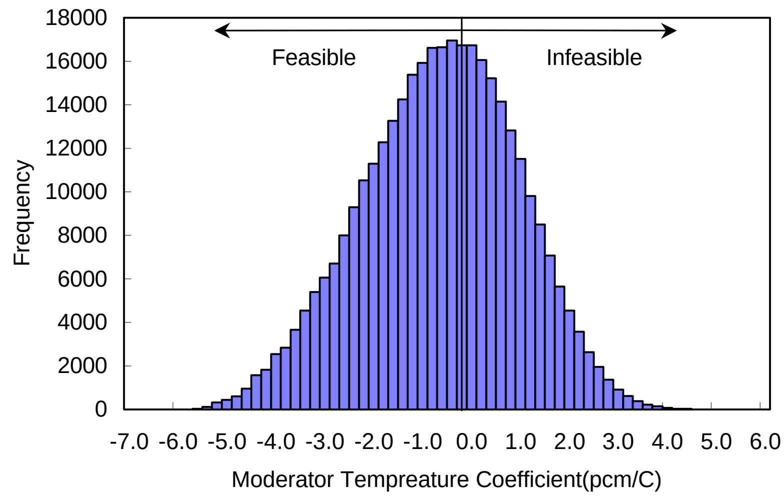


Figure 2. Distribution of moderator temperature coefficient for randomly generated 35 thousands loading patterns in a typical PWR core

In this study, impact of prediction accuracy of the radial peaking factor on fuel cycle cost was evaluated for typical Japanese PWR cores. In the concrete, average discharge burnup of fuel assembly was calculated for different limit values of the radial peaking factor, which are considered as different design margins. Since the fuel cycle cost is directly associated with the average discharge burnup under fixed feed enrichment, effects of the design margin on fuel cycle costs can be quantitatively evaluated from these results.

The above results can be also used to evaluate a gain from relaxation of radial peaking factor limitation, which can achieve by improvements of a DNB evaluation method or mechanical modifications of fuel assembly and so on.

Some investigations have already been performed concerning the relaxation of peaking factor limitation(2) and they provided interesting results. However, they were restricted in single cycle calculations. To perform accurate comparison of fuel cycle cost for different radial peaking factor limitations, multi-cycle analyses should be carried out to consider a reactivity carry-over effect between successive cycles. Therefore, equilibrium cores were used in this study since they can be considered as one of typical situations of successive multiple cycles.

In Chap.2, an equilibrium core optimization method will be described. All loading patterns in this study were generated through the optimization method to make accurate comparison among loading patterns. In Chap.3, analysis results and discussion will be provided. Finally, summary of this study will be described in Chap.4.

2. EQUILIBRIUM CORE OPTIMIZATION

In this study, many equilibrium cores must be generated assuming different radial peaking factor limitations. Since the objective of this study is comparison of fuel cycle costs, the equilibrium cores should be well optimized to obtain an accurate result.

An equilibrium core is defined as a steady state loading pattern with the fixed number of fresh fuel, feed enrichment, inventory of the burnable poison and fuel reloading between two consecutive cycles. So the core characteristics such as the discharge burnup and the cycle length do not change cycle by cycle; these characteristics are identical in every cycle. The equilibrium core can be attained through the repetition of cycle burnup calculations assuming an identical fuel reloading throughout consecutive cycles.

Most of loading pattern optimization methods are based on the shuffles of fuel assemblies(3); assemblies are directly swapped with each other to obtain a better solution. However, in an equilibrium core, the fuel assemblies cannot be swapped directly because the equilibrium core loading pattern is represented not by the fuel *loading* pattern but by the fuel *reloading* pattern. Though the equilibrium core optimization is more complicated than single cycle optimizations, there are several researches in this area(4) (5) (6).

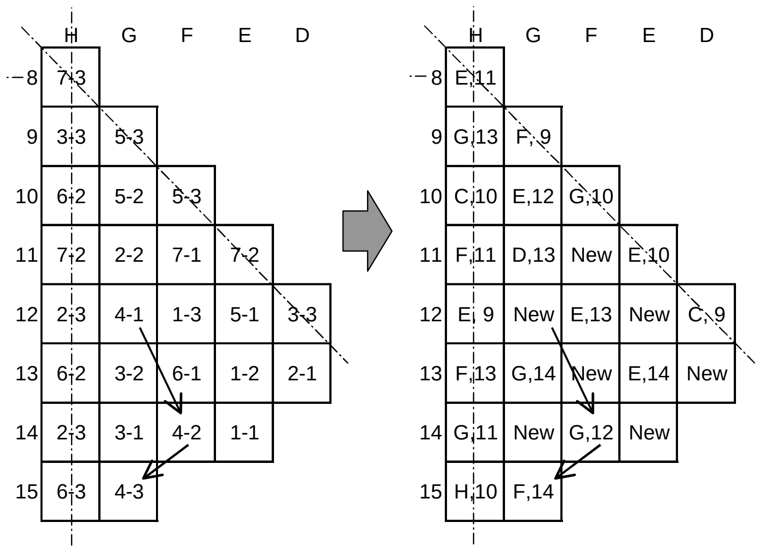
In this study, a loading pattern optimization code OPAL[6] was used to optimize the equilibrium cores. The OPAL code utilizes a concept of “fuel ID” to treat equilibrium cores as shown in Fig.3. Figure 3 shows an example of the fuel ID pattern and a “decoded” fuel reloading pattern. The fuel reloading pattern shown in Fig. 3(b) is decoded by tracking the cycle by cycle movement of the fuel assembly on the fuel ID pattern shown in Fig. 3(a).

The loading pattern optimization is performed on the basis of the fuel ID pattern shown in Fig. 3. In other words, a candidate of the fuel ID pattern is generated using an optimization method, and the candidate is decoded into a fuel reloading pattern. After that, iterative burnup calculations to obtain the equilibrium core are performed using the identical fuel reloading throughout consecutive cycles. From preliminary calculations, approximately five iterations were required to attain an equilibrium state when the two dimensional core calculation was utilized to evaluate the core characteristics.

Example of fuel ID for the equilibrium loading pattern optimization

Serial No.	Number of Assemblies	Irradiated Cycle		
		1	2	3
1	8	1-1	1-2	1-3
2	8	2-1	2-2	2-3
3	8	3-1	3-2	3-3
4	8	4-1	4-2	4-3
5	8	5-1	5-2	5-3
6	8	6-1	6-2	6-3*)
7	8	7-1	7-2	7-3**)

*) Only four out of eight fuel assemblies are loaded in the third cycle.
**) Only one out of eight fuel assemblies is loaded in the third cycle.



(a) The fuel ID pattern consisted of the fuels shown in the above table. The arrows corresponding to an example of the fuel reloading history. The fuel of serial No. 4 shown in the above table has been loaded at "G,12" as fresh fuel. This fuel has been reloaded successively to "F,14" and "G,15" in the consecutive two

(b) The fuel reloading pattern decoded from the fuel ID pattern. The fuel reloading can be identified through the trajectory of the fuel assembly. For example, the fuel loaded at "G,15" has been reloaded from "F,14".

Figure 3. Concept of the fuel ID adopted in the equilibrium core optimization by the OPAL code.

The simulated annealing method[3] was adopted in this study because of its affinity with the fuel ID treatment described above. Note that the simulated annealing, the direct search[7], the enumerated binary exchange[8], the rotational search[8] and any combination of these optimization methods can be used in the OPAL code. A permutation of the loading pattern, which is performed by successive fuel swaps, is directly performed on the fuel ID pattern and the reloading pattern of the candidate is generated through the decode procedures in Fig.3. The computational procedures of the equilibrium cycle optimization in this study are shown in Fig. 4. The capability of the OPAL code has been confirmed through a comparison with successive multi-cycle analyses[6].

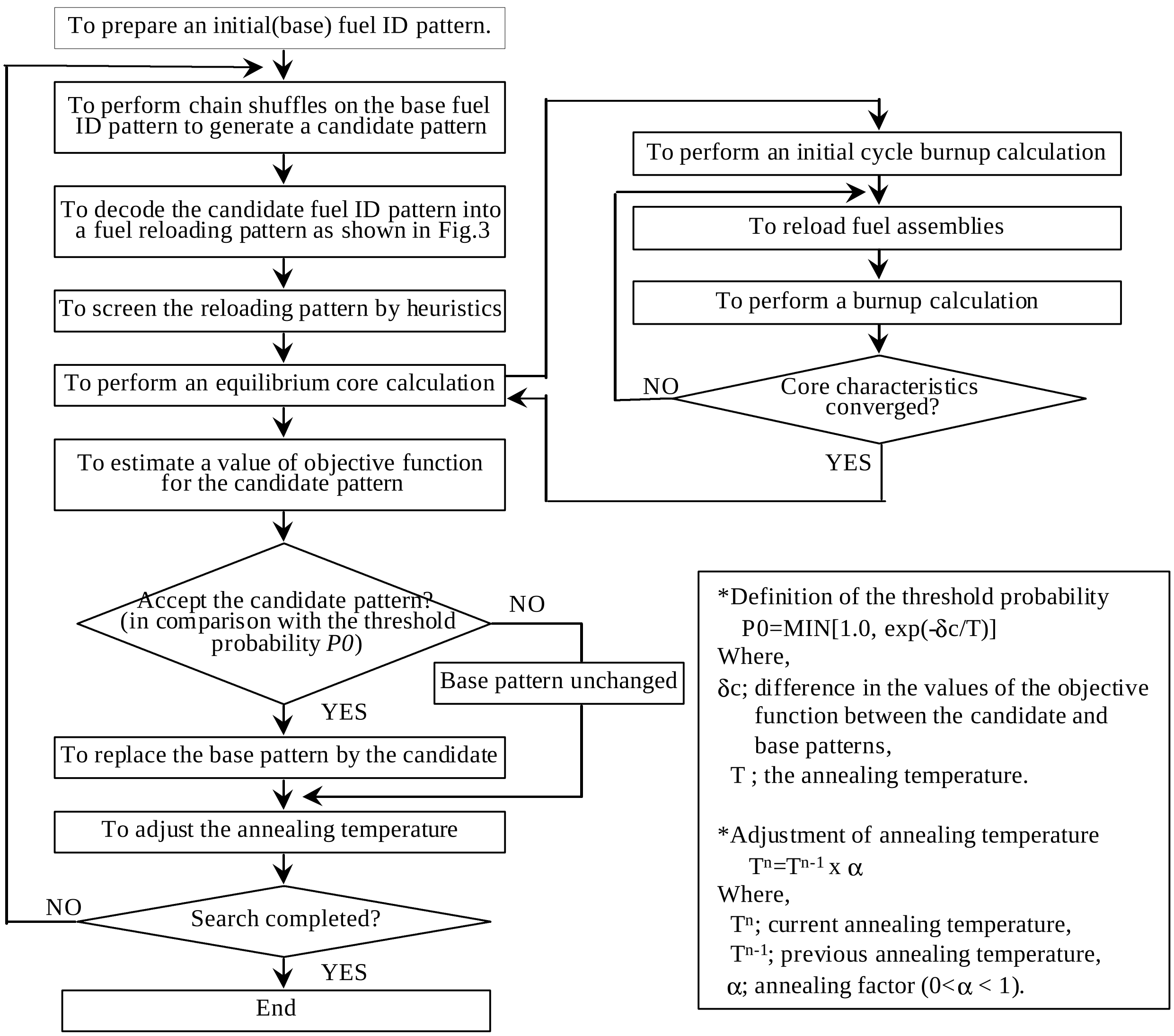


Figure 4. Flow of equilibrium core optimization code, OPAL.

The OPAL code can treat various limitations on core characteristics via an objective function derived by weighted sum of penalties; cycle length, fuel dependent maximum burnup, radial peaking factor, radial power tilt, moderator temperature coefficient, location dependent fuel burnup, location dependent power density and so on. The OPAL code also has various heuristics that make equilibrium core optimization more efficient. Because of the above features, the OPAL code can automatically generate suitable loading patterns for different limitations of the radial peaking factor.

3.ANALYSIS AND DISCUSSION

3.1 DEFINITION OF A PROBLEM

Two different reactor types that are shown in Table I were used in this study to evaluate reactor size effect.

Table I. Specifications of target reactors

Type	Fuel assembly	Number of assembly in core	Note
2 loop type PWR	14x14	121	Westinghouse type, 570MWe
3 loop type PWR	17x17	157	Westinghouse type, 870MWe

For these reactor types, different cycle lengths and fuel types were assumed in the calculations as shown in Table II. To cover typical cycle length for PWR, 13 EFPM and 18EFPM operations were assumed. For feed enrichment, 4.1wt% and 4.8wt% were used, which correspond to the current and the next generation fuel design, respectively. Number of feed assemblies was defined to satisfy the target cycle length and was fixed in each case as shown in Table II.

In general, optimum concentration of Gadolinia and number of Gadolinia bearing fuel rods depends on cycle length. However, since main objective of this study is evaluation of impact of core calculation accuracy on fuel cycle cost, optimization of Gadolinia fuel design is considered to be less important. Furthermore, a design of Gadolinia bearing fuel is not changed in each reload in Japan mainly due to licensing restrictions. Therefore, the same fuel design were used for different cycle length.

Table II. Cycle length and fuel specifications

Type	Target cycle length (EFPM)	Feed enrichment (wt%)	Number of feed assembly	Concentration(wt%)/ Number of Gadolinia bearing fuel rods in assy.
2 loop type PWR	~13	4.1	40(20)*)	6.0/12
	~13	4.8	36(16)	10.0/16
	~18	4.8	52(32)	10.0/16
3 loop type PWR	~13	4.1	56(32)	6.0/16
	~13	4.8	44(20)	10.0/20
	~18	4.8	64(40)	10.0/20

*) Number in parenthesis shows number of Gadolinia bearing fuel assemblies. For example, 36(16) means 20 assemblies without Gadolinia and 16 assemblies with Gadolinia were used as feed assemblies.

3.2 OPTIMIZATION CALCULATIONS

Equilibrium core optimization calculations were carried out using the OPAL code. Five different limitations for radial peaking factor were assumed in each case; 1.40, 1.45, 1.50, 1.55 and 1.65. Note that previous design target of the radial peaking factor in Japanese PWRs is close to 1.40 and the current design target is nearly 1.45. Current limitation of the radial peaking factor is generally 1.48, which is close to 1.50. In the near future, limitation of the radial peaking factor will be relaxed to around 1.55 by improving a DNBR evaluation method.

The other restrictions used in the calculations are listed below:

-the octant symmetric of a loading (reloading) pattern should be satisfied,
-feed assembly without Gadolinia should not be placed core inboard,
-feed assembly with Gadolinia should not be placed side by side; they should not be placed in adjacent position,
-feed assembly with Gadolinia should not be placed at core periphery,

Loading patterns that do not satisfy the above heuristic rules are immediately abandoned before the core calculation; the heuristic rules were used as "hard constraints".

During optimization calculations, cycle length maximization was performed. Note that cycle length maximization is somewhat different from discharge burnup maximization in single cycle optimization, but they are identical in the equilibrium core optimization since the discharge burnup is proportional to the cycle length in the equilibrium core[6].

Objective function of the optimization was defined by;

$$F^{obj} = \text{Cycle length(GWd/t)} - 100.0 * \max[0, Fxy^{cal} - Fxy^{lim}] \quad (1)$$

Where

F^{obj} : Value of objective function
Fxy^{cal} : Calculated maximum radial peaking factor throughout a burnup cycle
Fxy^{lim} : Limitation of radial peaking factor

In order to evaluate the isolated impact of the radial peaking factor limitation, other safety parameters such as the maximum burnup or the moderator temperature coefficient was not taken into account in the objective function.

In the simulated annealing optimizations, the annealing factor was set to 0.9 and the Malkov length of an annealing stage was set to 75. These values are somewhat too small for detailed single cycle optimizations[7], but they are compromised by the calculation time. About 7,000 equilibrium cores were evaluated in each optimization calculations by the simulated annealing. Since iterative core depletion calculations are required to obtain converged characteristics of equilibrium core, calculation time of the equilibrium core optimization becomes much longer than that of the single cycle optimization. However, thanks to quick two-dimensional core calculation using the advanced nodal method with the pin-power reconstruction capability, a typical optimization completes about 20 hours using a HP-C180 workstation.

Due to stochastic characteristics of the simulated annealing optimization, a final loading pattern inevitably depends on an initial random seed. Therefore, three independent optimizations using different random seeds were performed in each case. Consequently, 2(reactor types)*3(cycle lengths and/or fuel types)*5(peaking factor limitations)*3(random seeds)=90 equilibrium cores were optimized in the course of this study.

3.3 RESULTS AND DISCUSSION

Summary of calculation results is shown in Table III and in Fig.5. The loading patterns with minimum radial peaking factor and maximum cycle length in each case are shown in Fig.6~Fig.11 for reference.

In all cases, the discharge burnup increases with the calculated radial peaking factor. Gain in the discharge burnup due to relaxation of the radial peaking factor limitation are different among calculation cases, but they are almost within 2~3GWd/t.

In the 3loop ~13EFPM 4.8wt% case, calculated radial peaking factors significantly deviate from constraints when the limitation is 1.40. Since the radial peaking factor of this case is higher than that of other cases as will be described later, such lower limitation (~1.40) cannot be satisfied.

Sensitivities of gain in discharge burnup to change in calculated radial peaking factor, which is defined by Eq.(2), lie between 0.2~0.4 as shown in Table IV. Note that relative gain in discharge burnup and relative change in calculated radial peaking factor is estimated from Fig. 5.

$$S = \textit{Relative gain in discharge burnup/Relative change in radial peaking factor} \qquad (2)$$

Where

S : Sensitivities of gain in discharge burnup to change in calculated radial peaking factor

If the design margin of radial peaking factor can be redueced by 1.0%, the fuel cycle cost can be reduced by 0.4% when the value of sensitivity S is 0.4. Here, reduction of the fuel cycle cost is assumed to be proportional to improvement in discharge burnup. The 0.4% reduction in fuel cycle cost is equivalent to about 40 million Yen/year/reactor when the fuel cycle cost, reactor type and capacity factor are 1.5 Yen/kWh, 3 loop type and 90%, respectively. Since considerable impact on fuel cycle cost was found, the above results provide a strong motivation to improve accuracy of in-core fuel management methods.

Table IIIa. Summary of calculation results for 2 loop type PWR

Reactor type	Target cycle length (EFPM)	Feed enrichment (wt%)	Number of feed assembly	Fxyn Limit	Random seed	Calculated cycle length (GWd/t)	Calculated Fxyn	Discharge burnup (GWd/t)
2 loop type	~13	4.10	40	1.40	1	13.777	1.3995	41.675
				1.40	2	13.808	1.3998	41.769
				1.40	3	13.797	1.3992	41.736
				1.45	1	14.013	1.4470	42.389
				1.45	2	13.932	1.4486	42.144
				1.45	3	13.845	1.4460	41.881
				1.50	1	14.160	1.4977	42.834
				1.50	2	14.062	1.4965	42.538
				1.50	3	14.099	1.4922	42.649
				1.55	1	14.296	1.5481	43.245
				1.55	2	14.415	1.5469	43.605
				1.55	3	14.321	1.5451	43.321
				1.65	1	14.420	1.6458	43.621
				1.65	2	14.423	1.6349	43.630
				1.65	3	14.461	1.6376	43.745
2 loop type	~13	4.80	36	1.40	1	14.509	1.3956	48.766
				1.40	2	14.584	1.4335	49.018
				1.40	3	14.366	1.4045	48.286
				1.45	1	14.602	1.4428	49.079
				1.45	2	14.650	1.4422	49.240
				1.45	3	14.556	1.4103	48.924
				1.50	1	14.742	1.4999	49.550
				1.50	2	14.706	1.4958	49.429
				1.50	3	14.887	1.4972	50.037
				1.55	1	15.114	1.5447	50.800
				1.55	2	15.067	1.5460	50.642
				1.55	3	14.995	1.5436	50.400
				1.65	1	15.412	1.6488	51.801
				1.65	2	15.412	1.6483	51.801
				1.65	3	15.350	1.6491	51.593
2 loop type	~18	4.80	52	1.40	1	18.969	1.3985	44.139
				1.40	2	18.960	1.3997	44.118
				1.40	3	18.889	1.4000	43.953
				1.45	1	19.553	1.4467	45.498
				1.45	2	19.522	1.4476	45.426
				1.45	3	19.520	1.4458	45.422
				1.50	1	19.705	1.4986	45.852
				1.50	2	19.719	1.4987	45.885
				1.50	3	19.705	1.4947	45.852
				1.55	1	19.799	1.5091	46.071
				1.55	2	19.753	1.5333	45.964
				1.55	3	19.841	1.5210	46.168
				1.65	1	19.895	1.5411	46.294
				1.65	2	19.876	1.6322	46.250
				1.65	3	19.895	1.5411	46.294

Note1:Fxyn represents maximum radial peaking factor through burnup cycle

Note2:Target cycle length was used to set number of feed assemblies. Cycle length maximization was performed in optimization calculations

Table IIIb. Summary of calculation results for 3 loop type PWR

Reactor type	Target cycle length (EFPM)	Feed enrichment (wt%)	Number of feed assembly	Fxyn Limit	Random seed	Calculated cycle length (GWd/t)	Calculated Fxyn	Discharge burnup (GWd/t)
3 loop type	~13	4.10	56	1.40	1	15.161	1.4419	42.505
				1.40	2	15.004	1.4188	42.065
				1.40	3	15.062	1.4116	42.227
				1.45	1	15.289	1.4498	42.864
				1.45	2	15.336	1.4486	42.996
				1.45	3	15.245	1.4469	42.740
				1.50	1	15.504	1.4997	43.467
				1.50	2	15.427	1.4996	43.251
				1.50	3	15.389	1.4981	43.144
				1.55	1	15.527	1.5459	43.531
				1.55	2	15.526	1.5483	43.528
				1.55	3	15.551	1.5421	43.598
				1.65	1	15.681	1.6440	43.963
				1.65	2	15.671	1.6365	43.935
				1.65	3	15.683	1.6432	43.968
3 loop type	~13	4.80	44	1.40	1	14.622	1.4552	52.174
				1.40	2	15.217	1.5232	54.297
				1.40	3	14.667	1.4584	52.335
				1.45	1	14.622	1.4552	52.174
				1.45	2	15.217	1.5232	54.297
				1.45	3	14.667	1.4584	52.335
				1.50	1	15.074	1.4992	53.787
				1.50	2	15.217	1.5232	54.297
				1.50	3	15.048	1.4998	53.694
				1.55	1	15.178	1.5497	54.158
				1.55	2	15.301	1.5429	54.597
				1.55	3	15.271	1.5450	54.490
				1.65	1	15.435	1.6498	55.075
				1.65	2	15.386	1.6480	54.900
				1.65	3	15.504	1.6176	55.321
3 loop type	~18	4.80	64	1.40	1	19.912	1.4117	48.847
				1.40	2	19.940	1.4032	48.915
				1.40	3	19.888	1.4102	48.788
				1.45	1	20.110	1.4497	49.332
				1.45	2	20.116	1.4453	49.347
				1.45	3	20.206	1.4471	49.568
				1.50	1	20.310	1.4988	49.823
				1.50	2	20.271	1.4936	49.727
				1.50	3	20.189	1.4991	49.526
				1.55	1	20.369	1.5469	49.968
				1.55	2	20.315	1.5476	49.835
				1.55	3	20.376	1.5403	49.985
				1.65	1	20.500	1.6008	50.289
				1.65	2	20.501	1.6011	50.292
				1.65	3	20.399	1.6158	50.041

Note1:Fxyn represents maximum radial peaking factor through burnup cycle

Note2:Target cycle length was used to set number of feed assemblies. Cycle length maximization was performed in optimization calculations

From Table IV, estimated sensitivity *S* much depends on the cycle length or the fuel types. However, it less depends on reactor core size; sensitivities for 2 loop and 3 loop type PWR are similar when the cycle length and the fuel type are consistent.

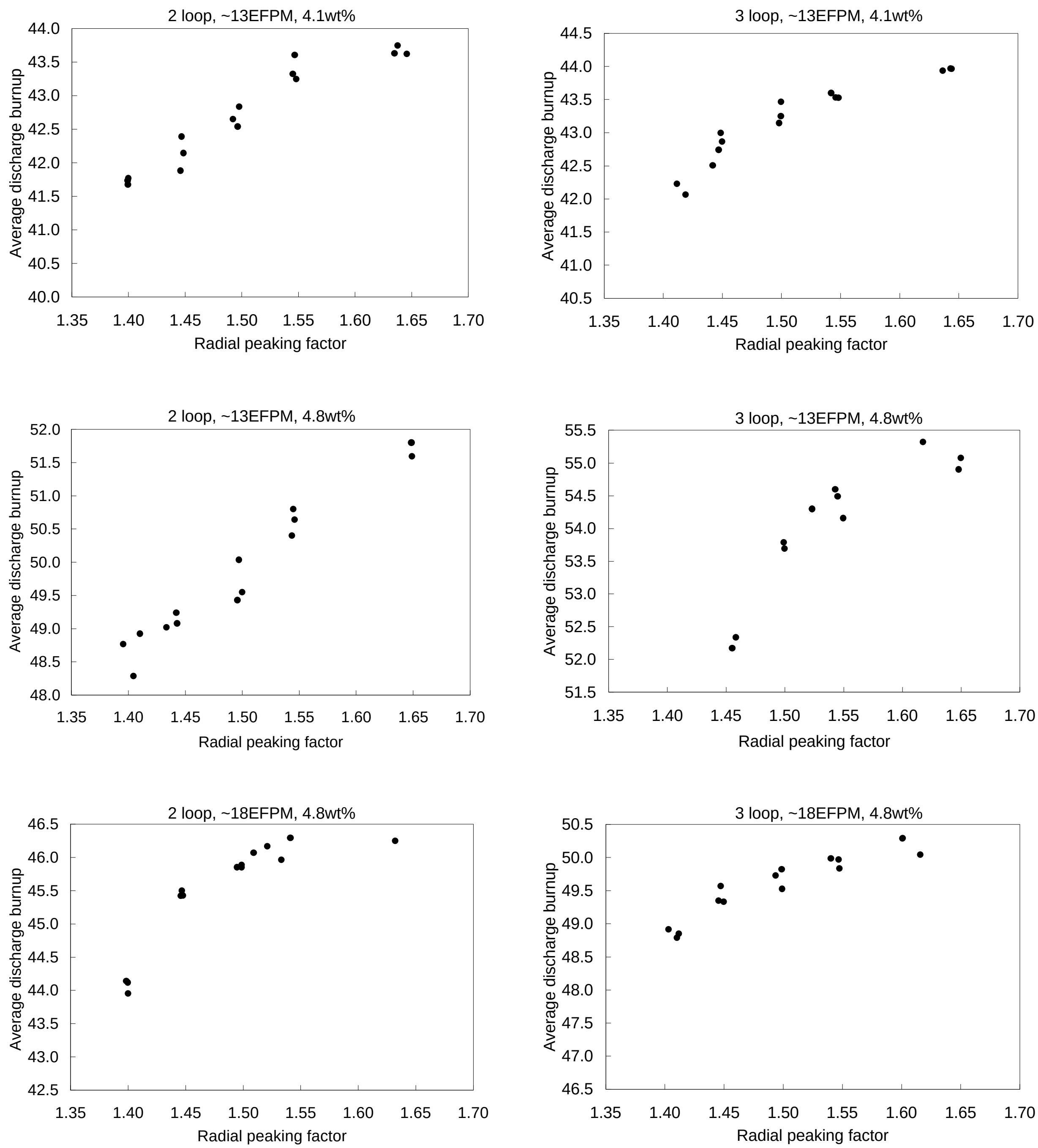


Figure 5. Relationship between calculated radial peaking factor and average discharge burnup

	7	8	9	10	11	12	13
G	35.2 47.3	26.9 40.7	Gd 17.0 32.3	23.1 38.1	26.9 40.9	Gd 32.3 44.4	0.0 12.0
H	26.9 40.7	12.0 28.2	Gd 31.4 44.9	Gd 14.3 30.4	Gd 15.2 31.4	Gd 0.0 15.2	0.0 10.1
I	Gd 17.0 32.4	Gd 31.4 45.0	Gd 0.0 17.0	Gd 30.4 44.0	10.1 26.9	10.1 23.0	
J	23.1 38.1	Gd 14.3 30.5	Gd 30.5 44.1	23.0 36.8	Gd 0.0 14.3	0.0 10.2	
K	26.9 41.0	Gd 15.2 31.4	10.1 26.9	Gd 0.0 14.3	28.2 35.2		
L	Gd 32.3 44.4	Gd 0.0 15.2	10.2 23.1	0.0 10.2			
M	0.0 12.0	0.0 10.1					

--Fuel type: Gd means Gadolinia bearing fuel
--Burnup at beginning of cycle(GWd/t)
--Burnup at end of cycle(GWd/t)

	7	8	9	10	11	12	13
G	44.4 58.5	Gd 0.0 20.3	Gd 23.9 41.4	27.4 44.4	8.8 27.4	33.4 45.1	0.0 8.8
H	Gd 0.0 20.3	Gd 23.9 41.5	15.4 34.7	Gd 0.0 20.8	Gd 20.8 37.3	0.0 14.9	Gd 37.3 42.1
I	Gd 23.9 41.4	15.3 34.7	Gd 20.3 38.4	14.9 33.4	Gd 0.0 17.3	34.7 42.9	
J	27.4 44.4	Gd 0.0 20.8	14.9 33.4	33.4 47.2	0.0 15.4	Gd 17.3 23.9	
K	8.8 27.4	Gd 20.8 37.2	Gd 0.0 17.2	0.0 15.3	Gd 38.4 44.5		
L	33.4 45.0	0.0 14.9	34.7 42.9	Gd 17.2 23.8			
M	0.0 8.8	Gd 37.3 42.0					

--Fuel type: Gd means Gadolinia bearing fuel
--Burnup at beginning of cycle(GWd/t)
--Burnup at end of cycle(GWd/t)

(a)Minimum radial peaking factor(1.3992) (b)Maximum cycle length(14.461GWd/t)

Figure 6. Loading patterns of equilibrium cycle(2 loop, ~13EFPM, 4.1wt%)

	7	8	9	10	11	12	13
G	46.6 60.1	24.6 41.4	30.6 46.5	Gd 31.4 46.5	13.6 30.7	Gd 34.0 47.0	0.0 13.6
H	24.6 41.5	24.6 41.9	Gd 16.5 34.0	Gd 14.5 31.4	42.3 55.4	Gd 0.0 14.5	0.0 11.2
I	30.6 46.7	Gd 16.5 34.1	Gd 31.4 46.7	26.6 42.3	Gd 0.0 16.5	11.2 24.6	
J	Gd 31.4 46.5	Gd 14.5 31.4	26.7 42.4	Gd 34.0 47.7	11.4 26.6	0.0 11.4	
K	13.6 30.7	42.4 55.4	Gd 0.0 16.5	11.4 26.7	41.4 48.3		
L	Gd 34.0 47.0	Gd 0.0 14.5	11.2 24.6	0.0 11.4			
M	0.0 13.6	0.0 11.2					

--Fuel type: Gd means Gadolinia bearing fuel
--Burnup at beginning of cycle(GWd/t)
--Burnup at end of cycle(GWd/t)

	7	8	9	10	11	12	13
G	50.4 65.3	10.9 32.2	32.2 50.3	Gd 28.3 46.2	36.3 51.7	Gd 36.8 49.7	0.0 10.9
H	10.9 32.2	Gd 36.8 53.8	Gd 0.0 21.3	17.2 38.0	17.3 36.3	0.0 17.3	38.0 44.1
I	32.1 50.3	0.0 21.3	Gd 28.3 46.8	Gd 0.0 20.3	Gd 20.3 36.8	44.2 52.8	
J	Gd 28.3 46.3	17.2 38.0	Gd 0.0 20.3	36.3 51.8	0.0 17.3	Gd 21.2 28.3	
K	36.3 51.7	17.3 36.3	Gd 20.3 36.8	0.0 17.2	51.8 58.2		
L	Gd 36.8 49.7	0.0 17.3	44.2 52.8	Gd 21.2 28.3			
M	0.0 10.9	38.0 44.1					

--Fuel type: Gd means Gadolinia bearing fuel
--Burnup at beginning of cycle(GWd/t)
--Burnup at end of cycle(GWd/t)

(a)Minimum radial peaking factor(1.3956) (b)Maximum cycle length(15.412GWd/t)

Figure 7. Loading patterns of equilibrium cycle(2 loop, ~13EFPM, 4.8wt%)

	7	8	9	10	11	12	13
G	35.1 53.8	Gd 19.0 40.5	Gd 19.0 40.9	Gd 23.2 43.6	Gd 22.6 42.7	15.5 35.1	Gd 23.3 34.6
H	Gd 19.0 40.5	Gd 22.6 43.9	Gd 0.0 23.3	29.3 49.3	Gd 19.5 40.1	Gd 0.0 19.0	0.0 12.5
I	Gd 19.0 40.8	Gd 0.0 23.2	36.4 55.2	Gd 0.0 22.6	14.4 36.5	12.5 29.3	
J	Gd 23.2 43.6	29.3 49.3	Gd 0.0 22.6	36.5 54.2	Gd 0.0 19.5	0.0 14.4	
K	Gd 22.6 42.7	Gd 19.5 40.1	14.4 36.5	Gd 0.0 19.5	0.0 15.5		
L	15.5 35.1	Gd 0.0 19.0	12.5 29.3	0.0 14.4			
M	Gd 23.3 34.6	0.0 12.5					

--Fuel type: Gd means Gadolinia bearing fuel
--Burnup at beginning of cycle(GWd/t)
--Burnup at end of cycle(GWd/t)

	7	8	9	10	11	12	13
G	38.5 56.1	Gd 24.5 45.2	Gd 24.4 46.6	Gd 26.0 47.6	Gd 26.0 46.7	Gd 26.6 44.5	0.0 13.5
H	Gd 24.5 45.2	Gd 19.8 42.5	Gd 0.0 26.0	21.9 45.9	Gd 0.0 24.5	0.0 21.9	45.9 52.9
I	Gd 24.4 46.5	Gd 0.0 26.0	Gd 19.8 44.6	Gd 0.0 26.7	13.1 36.7	36.7 49.6	
J	Gd 26.0 47.6	21.9 45.9	Gd 0.0 26.6	13.5 38.5	Gd 0.0 19.9	0.0 13.1	
K	Gd 26.0 46.7	Gd 0.0 24.4	13.1 36.6	Gd 0.0 19.8	Gd 26.7 37.0		
L	Gd 26.6 44.5	0.0 21.9	36.6 49.5	0.0 13.1			
M	0.0 13.5	45.9 52.9					

--Fuel type: Gd means Gadolinia bearing fuel
--Burnup at beginning of cycle(GWd/t)
--Burnup at end of cycle(GWd/t)

(a)Minimum radial peaking factor(1.3985) (b)Maximum cycle length(19.895GWd/t)

Figure 8. Loading patterns of equilibrium cycle(2 loop, ~18EFPM, 4.8wt%)

	H	G	F	E	D	C	B	A
8	Gd 26.4 39.5	24.4 38.6	28.2 43.3	24.4 40.3	Gd 18.2 34.6	Gd 18.2 34.1	Gd 16.4 31.8	Gd 16.4 26.5
9	24.4 38.6	28.2 42.9	Gd 0.0 18.9	Gd 19.0 35.8	Gd 17.8 34.1	29.4 44.1	Gd 0.0 16.4	0.0 10.6
10	28.2 43.4	Gd 0.0 19.0	Gd 34.1 48.6	11.7 29.5	Gd 35.8 49.6	Gd 0.0 18.2	10.6 24.4	
11	24.4 40.3	Gd 19.0 35.9	11.7 29.4	Gd 34.0 48.0	Gd 0.0 17.8	11.8 28.2	0.0 11.7	
12	Gd 18.2 34.6	Gd 17.8 34.0	Gd 35.8 49.6	Gd 0.0 17.8	Gd 34.0 46.0	0.0 11.8		
13	Gd 18.2 34.1	29.4 44.1	Gd 0.0 18.2	11.8 28.2	0.0 11.8			
14	Gd 16.4 31.8	Gd 0.0 16.4	10.6 24.4	0.0 11.7				
15	Gd 16.4 26.4	0.0 10.6						

--Fuel type: Gd means Gadolinia bearing fuel
--Burnup at beginning of cycle(GWd/t)
--Burnup at end of cycle(GWd/t)

(a)Minimum radial peaking factor(1.4116)

	H	G	F	E	D	C	B	A
8	Gd 37.1 50.9	Gd 19.4 37.1	Gd 19.3 38.5	26.8 44.2	29.9 45.9	Gd 31.7 45.8	37.6 48.6	37.6 43.8
9	Gd 19.4 37.0	Gd 19.0 38.1	Gd 0.0 22.7	17.1 37.6	9.0 29.9	Gd 0.0 19.4	0.0 17.1	0.0 9.0
10	Gd 19.3 38.5	Gd 0.0 22.7	26.8 46.0	Gd 0.0 22.3	Gd 22.3 40.1	Gd 22.6 37.8	16.0 26.8	
11	26.8 44.3	17.0 37.6	Gd 0.0 22.3	29.9 47.0	Gd 0.0 19.0	0.0 16.0	Gd 40.1 45.1	
12	29.9 45.9	9.0 29.9	Gd 22.3 40.1	Gd 0.0 19.0	Gd 19.0 31.7	Gd 37.8 43.6		
13	Gd 31.7 45.7	Gd 0.0 19.3	Gd 22.6 37.8	0.0 16.0	Gd 37.8 43.5			
14	37.6 48.6	0.0 17.0	15.9 26.8	Gd 40.1 45.1				
15	37.6 43.7	0.0 9.0						

--Fuel type: Gd means Gadolinia bearing fuel
--Burnup at beginning of cycle(GWd/t)
--Burnup at end of cycle(GWd/t)

(b)Maximum cycle length(15.683GWd/t)

Figure 9. Loading patterns of equilibrium cycle(3 loop, ~13EFPM, 4.1wt%)

	H	G	F	E	D	C	B	A
8	Gd 46.8 56.7	41.2 53.0	46.9 59.5	Gd 32.1 46.8	41.2 54.8	46.9 59.1	Gd 33.7 45.1	47.1 53.4
9	41.2 53.0	Gd 0.0 16.4	13.3 31.5	Gd 16.2 33.8	Gd 14.7 32.5	14.2 32.4	Gd 0.0 14.7	0.0 9.8
10	46.9 59.4	13.3 31.5	47.1 59.8	Gd 32.5 46.6	24.7 41.2	31.5 47.1	9.8 24.7	
11	Gd 32.1 46.7	Gd 16.2 33.7	Gd 32.5 46.6	Gd 33.7 47.0	32.4 46.9	Gd 0.0 16.2	0.0 13.3	
12	41.2 54.8	Gd 14.7 32.6	24.7 41.2	32.4 46.9	Gd 16.4 32.1	0.0 14.2		
13	46.9 59.1	14.2 32.4	31.5 47.1	Gd 0.0 16.2	0.0 14.2			
14	Gd 33.7 45.1	Gd 0.0 14.7	9.8 24.7	0.0 13.3				
15	47.1 53.4	0.0 9.8						

--Fuel type: Gd means Gadolinia bearing fuel
--Burnup at beginning of cycle(GWd/t)
--Burnup at end of cycle(GWd/t)

(a)Minimum radial peaking factor(1.4552)

	H	G	F	E	D	C	B	A
8	Gd 51.1 63.0	Gd 20.0 36.6	Gd 37.9 53.4	Gd 38.1 53.2	42.8 57.3	Gd 36.6 51.1	42.8 55.6	47.1 54.6
9	Gd 20.0 36.6	Gd 37.9 53.2	11.6 32.6	Gd 0.0 20.5	18.1 37.9	Gd 0.0 18.9	0.0 19.6	0.0 11.6
10	Gd 37.9 53.4	11.6 32.6	Gd 38.1 54.3	28.8 47.1	Gd 18.9 37.9	37.9 52.3	32.6 42.8	
11	Gd 38.1 53.2	Gd 0.0 20.5	28.8 47.0	Gd 0.0 20.0	Gd 20.5 38.1	0.0 18.1	52.3 57.6	
12	42.8 57.3	18.1 37.9	Gd 18.9 37.9	Gd 20.5 38.1	47.1 57.9	19.6 28.8		
13	Gd 36.6 51.1	Gd 0.0 18.9	37.9 52.2	0.0 18.1	19.6 28.8			
14	42.8 55.6	0.0 19.6	32.6 42.8	52.3 57.6				
15	47.1 54.6	0.0 11.6						

--Fuel type: Gd means Gadolinia bearing fuel
--Burnup at beginning of cycle(GWd/t)
--Burnup at end of cycle(GWd/t)

(b)Maximum cycle length(15.504GWd/t)

Figure 10. Loading patterns of equilibrium cycle(3 loop, ~13EFPM, 4.8wt%)

	H	G	F	E	D	C	B	A
8	Gd 43.4 57.2	Gd 35.5 51.9	Gd 23.6 44.5	Gd 22.8 44.3	36.3 55.6	Gd 20.2 41.6	Gd 20.2 39.7	Gd 22.8 35.5
9	Gd 35.4 51.9	Gd 23.7 43.4	Gd 0.0 23.7	Gd 23.0 44.9	Gd 0.0 23.7	Gd 23.7 44.7	Gd 0.0 20.2	0.0 14.2
10	Gd 23.6 44.5	Gd 0.0 23.6	34.2 54.2	17.5 40.5	40.5 59.0	Gd 0.0 23.0	16.8 34.2	
11	Gd 22.8 44.2	Gd 23.0 44.9	17.5 40.4	34.3 53.8	Gd 0.0 22.8	14.2 36.3	0.0 16.8	
12	36.3 55.6	Gd 0.0 23.7	40.4 59.0	Gd 0.0 22.8	36.3 53.3	0.0 17.5		
13	Gd 20.2 41.6	Gd 23.7 44.7	Gd 0.0 23.1	14.2 36.3	0.0 17.5			
14	Gd 20.2 39.7	Gd 0.0 20.2	16.8 34.3	0.0 16.8				
15	Gd 22.8 35.4	0.0 14.2						

--Fuel type: Gd means Gadolinia bearing fuel
--Burnup at beginning of cycle(GWd/t)
--Burnup at end of cycle(GWd/t)

(a)Minimum radial peaking factor(1.4032)

	H	G	F	E	D	C	B	A
8	Gd 43.8 60.4	Gd 23.2 44.7	Gd 24.4 47.6	Gd 24.4 47.6	Gd 25.8 48.0	Gd 26.4 47.0	Gd 26.4 43.8	Gd 42.3 51.2
9	Gd 23.2 44.6	Gd 23.2 46.0	Gd 0.0 27.0	20.8 46.1	Gd 0.0 25.8	23.0 45.6	13.1 34.2	0.0 13.1
10	Gd 24.4 47.6	Gd 0.0 27.0	Gd 25.8 49.7	Gd 0.0 26.4	34.2 55.3	Gd 0.0 24.4	0.0 20.8	
11	Gd 24.4 47.6	20.8 46.1	Gd 0.0 26.4	Gd 27.0 48.8	Gd 0.0 23.2	0.0 23.0	45.6 54.1	
12	Gd 25.8 48.0	Gd 0.0 25.8	34.2 55.3	Gd 0.0 23.2	Gd 27.0 42.2	46.1 53.9		
13	Gd 26.4 46.9	23.0 45.6	Gd 0.0 24.4	0.0 23.0	46.1 54.0			
14	Gd 26.4 43.8	13.1 34.2	0.0 20.8	45.6 54.1				
15	Gd 42.3 51.2	0.0 13.1						

--Fuel type: Gd means Gadolinia bearing fuel
--Burnup at beginning of cycle(GWd/t)
--Burnup at end of cycle(GWd/t)

(b)Maximum cycle length(20.501GWd/t)

Figure 11. Loading patterns of equilibrium cycle(3 loop, ~18EFPM, 4.8wt%)

Table IV. Sensitivities of gain in discharge burnup to change in calculated radial peaking factor

Reactor type	Target cycle length (EFPM)	Feed enrichment (wt%)	Relative gain in discharge burnup	Relative change in calculated peaking factor	Sensitivity *S* from Eq.(2)
2 loop PWR	~13	4.1	0.046	0.171	0.266
	~13	4.8	0.068	0.179	0.380
	~18	4.8	0.048	0.164	0.290
3 loop PWR	~13	4.1	0.040	0.163	0.247
	~13	4.8	0.056	0.138	0.404
	~18	4.8	0.033	0.143	0.230

For both reactor types, the values of *S* in the ~13EFPM 4.8wt% cases are larger than those of other cases. In these cases, reactivity difference among fuel batches is larger than that of other cases and number of Gadolinia bearing fuels is fewer. Therefore, the calculated radial peaking factor has tendency to be higher. Consequently, the impact of the radial peaking factor limitation on average discharge burnup becomes large.

On the other hand, when the cycle length becomes longer, reactivity difference among fuel batches becomes smaller and number of Gadolinia bearing fuels becomes larger. These make in-core power distribution less distorted and the impact of the radial peaking factor limitation on discharge burnup becomes lower.

An alternate approach to obtain the “trade-off surface” observed in Fig.5 is the multi-objective optimization[(8)(9)]. Incorporation of the multi-objective capability to the equilibrium core optimization is attractive and considered as one of future improvements in the OPAL code.

4. CONCLUSIONS

Impact of core calculation accuracy, especially effect of prediction accuracy of the radial peaking factor on fuel cycle cost was examined assuming different reactor types, cycle lengths and fuel types. Equilibrium cores were generated by the OPAL code assuming different radial peaking factor limitations, which correspond to the design margins due to uncertainty caused by limited accuracy of a calculation model. The OPAL code utilizes the simulated annealing method for optimization engine and can generate suitable equilibrium core under provided constraints.

The calculation results quantitatively revealed that the improvement on prediction accuracy of the radial peaking factor considerably contributes the improvement on the fuel cycle cost. The result obtained in this study is a strong motivation to improve accuracy of in-core fuel management method.

Similar investigations about other core characteristics are desired to grasp importance of these prediction accuracy on fuel cycle cost.

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