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A Proposed Heuristic Methodology for Searching Reloading Pattern

K.Y. Choi
Korea Institute of Nuclear Safety

Y.K. Yoon
Korea Advanced Institute of Science and Technology

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핵연료 재장전모형의 탐색을 위한 경험적 방법론의 제안

최기용
한국원자력안전기술원

윤용구
한국과학기술원

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Abstract

A new heuristic method for loading pattern search has been developed to overcome shortcomings of the algorithmic approach. To reduce the size of vast solution space, general shuffling rules, a regionwise shuffling method, and a pattern grouping method were introduced. The entropy theory was applied to classify possible loading patterns into groups with similarity between them. The pattern search program was implemented with use of the PROLOG language. A two–group nodal code MEDIUM–2D was used for analysis of power distribution in the core. The above mentioned methodology has been tested to show effectiveness in reducing of solution space down to a few hundred pattern groups. Burnable poison rods were then arranged in each pattern group in accordance with burnable poison distribution rules, which led to further reduction of the solution space to several scores of acceptable pattern groups. The method of maximizing cycle length(MCL) and minimizing power-peaking factor(MPF) were applied to search for specific useful loading patterns from the acceptable pattern groups. Thus, several specific loading patterns that have low power-peaking factor and large cycle length were successfully searched from the selected pattern groups.

요 약

재장전노심의 핵연료 장전모형 설계를 위한 기존의 알고리즘 탐색방법의 단점을 보완하기 위한 새로운 경험적 탐색방법을 개발하였다. 노심의 핵연료 장전모형으로 고려될 수 있는 수없이 많은 경우의 수를 줄이기 위하여 일반적 핵연료 배치규칙, 영역별 배치방법 그리고 장전모형의 집단화 방법을 이용하였다. 비슷한 장전모형을 모아서 집단화시키는 기준으로 엔트로피 이론을 이용하였

다. 또한 PROLOG언어를 이용하여 주어진 배치규칙에 따라 장전모형을 탐색하는 프로그램을 만들었다. 장전모형들의 노심내 출력분포 해석에는 2군 nodal코드인 MEDIUM-2D를 사용하였다. 이와같은 방법을 사용한 결과 수백개 정도의 장전모형 집단을 찾아낼 수 있었고, 여기에 가연성 독봉 배치규칙에 따라 가연성 독봉을 배치한 결과 장전모형 집단의 수를 수십개까지로 감소시킬 수 있었다. 이러한 장전모형 집단들로부터 실제로 이용 가능한 장전모형을 찾아내기 위하여, 주기길이 최대화방법과 첨두 출력 최소화방법을 사용하였다. 그 결과 고리 3호기 제·10주기의 예상 재장전모형보다 주기길이는 길고 첨두출력은 낮은 장전모형을 찾아낼 수 있었다.

1. Introduction

Optimization of fuel loading pattern is very important for reducing of the fuel cycle costs. However, since there exist so many available loading patterns in the solution space, it is difficult and complicate to find the optimum solution. The conventional method to search for the optimum loading pattern is based on an algorithmic optimization approach. Dynamic programming was used by Wall and Fenech,[1] and Stover and Sesonske.[2] Sauar[3] utilized linear programming to minimize the present worth weighted total fuel cost while imposing constraints on spatial region fuel loading. Federowicz and Stover[4] applied integer linear programming and a two-dimensional power shape. Naft and Sesonske[5] developed a direct search algorithm to optimize the fuel shuffling pattern and to minimize assembly power peaking with use of a simplified neutronics model. Chitkara and Weisman[6] related the movement of each assembly to fuel cycle cost by assuming an equilibrium cycle and applied direct search algorithm. Motoda[7] et al. combined linear programming with direct search of shuffling fuel within spatial regions for the boiling water reactor as part of a stagewise fuel cycle cost minimization. Chang and Sesonske[8] coupled a direct search algorithm with a nodal neutronics model to determine low-leakage loading patterns. Mingle[9] utilized the perturbation theory to predict how the core reactivity is affected by the change in fuel loading pattern. This method employs discrete burnup groups and a spatially zoned core with the objective of minimizing the fuel cycle cost. Then fuel assembly binary exchanges are attempted to minimize the power peaking. Hobson and Turinsky[10] utilized the first-order perturbation theory to determine effects of assembly shuffling on the core reactivity, power distribution, and end-of-cycle burnup. Monte Carlo integer programming was then used to determine a near-optimal loading pattern within a range of loading patterns near the reference case. The process was then repeated with a new loading pattern as a reference case and was terminated when no better loading patterns could be determined. Turney and Williamson[11] applied a variational techinque to minimize power peaking in the design of reload core. Ahn and Levine[12] applied the gradient projection method to calculate a priority shuffling scheme for maximizing reactivity in the three region core. Chao[13] et al. developed a backward diffusion calculation method which for a given power distribution solves the diffusion equation backwardly to estimate the reactivity distribution that will result in a given power distribution at the end of cycle(EOC). Sekimizu[14] proposed a hierarchy level scheme for quasi-optimum fuel assembly loading in boiling water reactors. The vast number of possible fuel assembly allocations were reduced by adopting the following two-step scheme : In the first step, an optimum allocation of fresh fuel assemblies was searched on the basis of proper criteria. Then in the second step, without moving the fresh fuel assemblies, allocation of reload fuel assemblies was determined to ascertain the required group property as closely as possible. Kim et al.[15] developed a two–step optmization procedure for a core reload design. Firstly, the end–of–cycle critical boron concentration was maximized to determine the best fuel allocation. A direct search scheme was then applied by a series of binary exchanges using the result of preliminary corewide sensitivity analysis. Secondly, the control poison requirements were established by use of excess reactivity and power peaking constraints.

The above mentioned algorithmic approaches, however, can not always guarantee a global optimum solution, and are highly dependent on the initial reference pattern.[6,8] The pattern obtained by these approaches is a near–optimal solution. For these reasons, the possibility of applying a heuristic search method was recently investigated.[16,17] Heuristic search methods are a well–developed branch of the computer science discipline known as artificial intelligence. The feasibility of utilizing a computerized heuristic search method for generation and optimization of fuel reload configuration was studied by Galperin and Nissan.[16] The heuristic knowledge was expressed modularly in the form of IF–THEN production rules. Elimination and preference rules were used to reduce so vast solution space. A set of 312 solutions were obtained within 20 minutes of generation time. Galperin et al.[17] also developed a knwoledge–based system for optimization of fuel reload configurations. This system was based on a heuristic search method and was implemented in a common Lisp programming language. The solution space was reduced, by the application of several rules, to a few hundreds of basic patterns each representing a family of potential solutions. Each family, however, contained a very large number of solutions. Only one member of each family was considered and compared to obtain an optimal solution. The essence of this approach is how to convince oneself that a specific configuration, arbitrarily selected from each family, represents the whole configurations in that family.

A new heuristic search method is developed to search for the optimum loading pattern. The solution space of heuristic search is so enormous that how to reduce its space to a reasonable level is the key point of the heuristic search method. Hence, reduction of solution space is performed in the present work by the application of general shuffling rules based on the experience of in–core fuel management. With only these general shuffling rules, however, it is still not possible to reduce the solution space to a reasonable level. Thus the regionwise shuffling and pattern grouping methods are applied in addition to general shuffling rules. For pattern grouping the entropy theory is applied. Burnable poison rods were then arranged in each pattern group in accordance with burnable poison distribution rules, which led to further reduction of the solution space to several scores of acceptable pattern groups. The methods of maximizing cycle length(MCL) and minimizing power–peaking factor(MPF) were applied to search specific useful loading patterns from the acceptable pattern groups.

2. Methodology

2.1. General Shuffling Rules

The total number of possible arrangements of fuel assemblies in the three–loop pressurized water reactor(PWR) is approximately 10^{210}. This number is so enormous that how to reduce the solution space is the main subject of the heuristic search method for optimization of fuel reloading. The general shuffling rules adopted in the first reduction stage of this heuristic search method are based on the following conditions :

(1) three batch modes shuffling(i.e., fresh, once–burned and twice–burned fuels)

(2) low–leakege loading pattern
(3) quasi–equilibrium core
(4) quarter core symmetry
(5) no assembly rotation in this stage
(6) single enrichment of the fresh fuel
(7) predetermined central fuel assembly

The possible number of fuel arrangements can be reduced to 10^{21} by applying of these shuffling rules. There are still too many configurations to search for the optimum solution. Hence, another elimination principles are necessary to reduce the number of loading patterns further.

2.2. Regionwise Shuffling Method

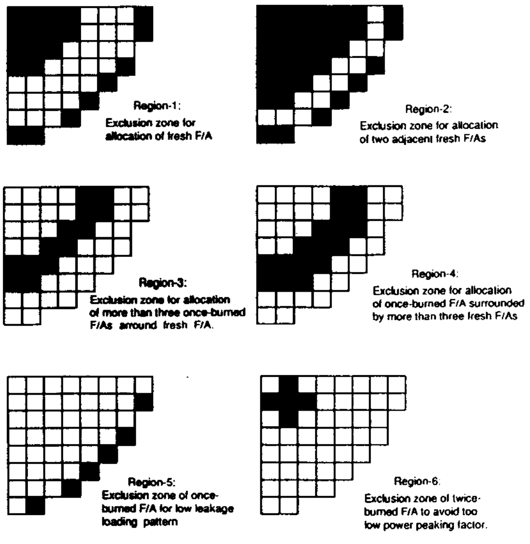
The regionwise shuffling method is utilized for further reduction of loading pattern space and exclusion of unacceptable ones. Fuel assembly position of each type having unacceptably high or low power peaking is excluded at this stage. The principles to determine forbidden regions(or exclusion zones) are as follows:

(1) Allocation of fresh fuel assemblies is avoided in the region having too high power peaking
(2) Allocation of twice–burned fuel assemblies is avoided in the region having too low power peaking.
(3) Allocation of fresh fuel assemblies adjacent to another fresh fuel assemblies is avoided in the region having too high power peaking.
(4) Allocation of too many once–burned fuel assemblies in the position adjacent to fresh fuel assemblies is prohibited to avoid localized power peaking.

Table 1. List of Reloading Fuel Assemblies

F/A Identity	Burnup (MWD/MTU)	F/A Identity	Burnup (MWD/MTU)
C00	32620	A01	14930
B01	31951	A02	14913
B02	30349	A03	14803
B03	30348	A04	14782
B04	28949	A05	14346
B05	28698	A06	14061
B06	27906	A07	14060
B07	27896	A08	13275
B08	27710	A09	13254
B09	27528	A10	13123
B10	27135	A11	11639
B11	27133	A12	11621
B12	26889	F01	0
B13	26592		
B14	25666		
B15	25697		

C00 : central fuel assembly
F01 : representative of fresh fuel assemblies
A05 : representative of once-burned fuel assemblies
B06 : representative of twice-burned fuel assemblies



Region-1: Exclusion zone for allocation of fresh F/A

Region-2: Exclusion zone for allocation of two adjacent fresh F/As

Region-3: Exclusion zone for allocation of more than three once-burned F/As around fresh F/A.

Region-4: Exclusion zone for allocation of once-burned F/A surrounded by more than three fresh F/As

Region-5: Exclusion zone of once-burned F/A for low leakage loading pattern

Region-6: Exclusion zone of twice-burned F/A to avoid too low power peaking factor.

Fig. 1. Types of Exclusion Zone or Forbidden Region.

The forbidden regions (or exclusion zones) are determined through analysis of core geometry and sensitivity study of fuel allocations to exclude extremely unreasonable loading patterns. Sensitivity analysis is performed for the quarter core of a typical 3–loop PWR core. Four kinds of fuel assembly groups are considered, namely, fresh fuel assemblies, once–burned fuel assemblies, twice–burned fuel assemblies and an arbitrary twice–burned fuel assembly which was assigned to the core center. Each fuel group is assumed to have identical charateristics to simplify sensitivity analysis. All fresh fuel assemblies are assumed to be identical. One fresh assembly is selected among the fresh fuel assemblies. One once–burned and one twice–burned fuel assemblies having the nearest average burnup of each fuel assembly group are selected as a representative fuel assembly of each fuel group, respectively. In this work fresh fuel F01, once–burned fuel A05 with the burnup of 14,346 MWD/MTU and twice–burned fuel B06 with the burnup of 27,906 MWD/MTU were selected. Table 1 shows data of the fuel assemblies and selected representative fuel assemblies. Figure 1 shows exclusion zones applied. It is possible with this regionwise fuel loading to simplify the shuffling procedure and obtain more proper loading patterns. Solution space is reduced to approximately 10^9 loading patterns at this stage.

2.3. Pattern Grouping Method

More powerful methodology is necessary to prune solution space to prevent combinatorial expansion of the search space. It was attempted to reduce loading pattern search space by grouping the whole loading patterns according to similarity between each pattern. The optimization problem of comparing each individual loading pattern is transformed to the problem of comparing each pattern group. In comparing each pattern group, how to classify the groups and to select the representative pattern for each group are very important and difficult tasks.

There are three important criteria in grouping patterns :

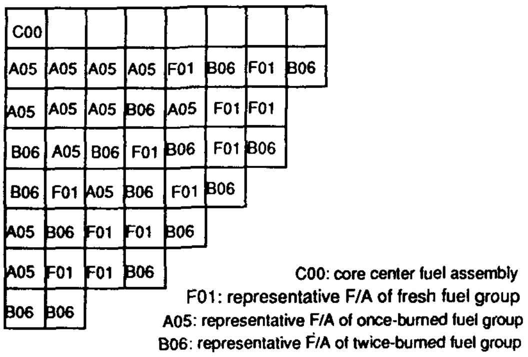
1. patterns in a group have similar characteristics(i.e., how many positions are allocated by the same batch of fuel assembly),
2. a representative pattern for each group can be selected, and
3. there must be clarity between groups.

In the present study the entropy theory is applied to classify pattern groups. If we use entropy as a measure for pattern grouping then criteria 1 and 2 above can be satisfied successfully. However, it is not straight foward to satisfy the criterion 3 but it is not so severe. For an example, in figure 3, groups A and B in cases of 1 and 2 have common part. But in case of 1, group B is much better then A and, in case of 2, both group A and B can be considered as candidated patterns. In case of 3, group B is apparently better then A. Therfore the main purpose of the pattern grouping method is to distinguish A and B in cases of 1 and 3.

10^9 patterns are so enormous to calculate entropies between them. At least $(10^{18}-10^9)/2$ times of calculations are necessary. To solve this problem the representative patterns allocated only with representative F/A of each fuel batch are selected. Then the whole solution space is classified with their entropies between representative patterns and specific patterns allocated with individual specific F/As of each fuel batch. The entropy represents quantatively the similarity of representative pattern and specific pattern. If the entropy is small then there is great similarity between two patterns. If it is large then there is much difference. If we grouping the specific patterns that allocated specific F/As of each fuel batch position of representative pattern then the patterns which have similarity with representative patterns are grouped automatically. The patterns in a group distributed in the 3–dimensional space constructed by power peaking, boron concentration and entropy.(Figure 3) All representative patterns are located on the plane of zero entropy surrounded with specific patterns of the group.

The entropy is measured by the following equation.18,19,20)

$$S_i^r = \sum_{k=1}^{K} \frac{|X_k^r - X_k^i|}{\sum_{k=1}^{K} |X_k^r - X_k^i|} \ln \left[\frac{|X_k^r - X_k^i|}{\sum_{k=1}^{K} |X_k^r - X_k^i|} \right]$$



C00							
A05	A05	A05	A05	F01	B06	F01	B06
A05	A05	A05	B06	A05	F01	F01	
B06	A05	B06	F01	B06	F01	B06	
B06	F01	A05	B06	F01	B06		
A05	B06	F01	F01	B06			
A05	F01	F01	B06				
B06	B06						

Fig. 2. Example of Representative Pattern Allocated by Only Representative F/As of Each Fuel Batch.

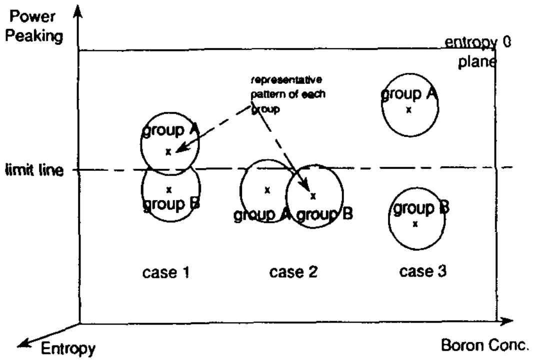


Fig. 3. Structure of Representative Pattern and Pattern Group.

where X_k^r are nuclear properties such as infinite multiplication factor and fuel assembly burnup of the representative pattern in k core position and X_k^i is that of pattern i. Representative patterns are allocated only by the representative for each fuel group in core positions instead of individual specific fuel assemblies. The difference between loading patterns in a same pattern group means mutual assembly exchanges only within the same fuel assembly batch. Measured entropies between representative pattern and all the loading patterns in a pattern group have nearly same values about with the order of 5. But the entropies between one representative pattern and a specific pattern of other pattern group, even if there is only one exchanges between once-and twice-burned fuel batch, is increased by the order of 10–20.

Total loading patterns that have to be considered are reduced to the level of 200–1000 pattern groups by applying this method.

2.4. Search for Specific Useful Loading Pattern From Each Pattern Group

2.4.1. Burnable Poison Distribution and Criteria

Burnable poison rods are then arranged to decrease power peaking in accordance with burnable poison distribution rules. Gadolinia is used as burnable poison in this work. Figure 4 shows the arrangement of burnable poison rods in a poisoned fuel assembly. The burnable poison distribution rules are as follows :

Rule 1 : distribute burnable poison rods only in fresh F/A

Rule 2 : use only 4 gadolinia rods to prevent power peaking at the end-of-cycle

Rule 3 : allocate burnable poison rods symmetrically

Rule 4 : allocate burnable poison rods from the highest fresh F/A until no benefit of power distribution

According to experiences, it is impossible to reduce power peaking factor more than 0.25 by

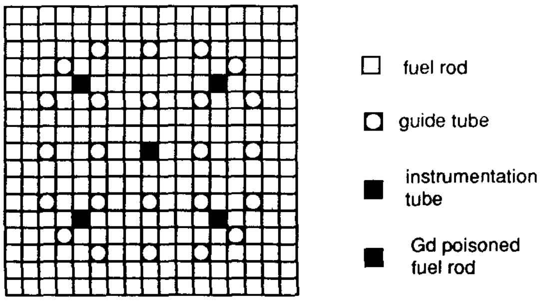


Fig. 4. Gadolinia Poisoned Fuel Assembly.

distribution of the gadolinia poisoned fuel assemblies. Power peaking factor that can be reducible after allocation of specific assemblies instead of each representative fuel assembly is also less than 0.08. The allowable maximum power peaking factor of the reload core design is 1.4350. Thus it is reasonable to treat pattern groups having peaking factors of less than 1.7650.

2.4.2. Search for Optimum Specific Loading Pattern

Now the key problem is how to search a specific loading pattern having lower power peaking factor and long cycle length that is located at the right lower corner of the pattern distribution diagram(Figure 5). Pattern groups are divided into two categories, namely, category 1 that has power peaking factor lower than 1.4750 and category 2 that has peaking factor greater than 1.4750.

The best loading pattern in category 1 is searched by the method of maximizing cycle length(MCL). The MCL method is to maximize cycle length by locating high burned fuels in the peripheral core positions. At first high burned fuels are allocated in the peripheral core position. The remaining fuel assemblies are allocated in the order of their burnup around fresh fuel position having a highest power peaking factor. More reasonable loading pattern is found by trial and error by tuning of some alternation of fuel assemblies only within each fuel batch.

The method of minimizing power peaking factor(MPF) is applied for category 2. This method is to minimiz power peaking factors by allocation of high burned fuels in inner core positions. Higher burned fuel assemblies are allocated arround fresh fuel assemblies in the order of their power peaking. The remaining fuel assemblies are arranged in peripheral core positions. The better loading pattern having high cycle length and low peaking factor is obtained with some alternations of fuel assemblies only within each fuel batch.

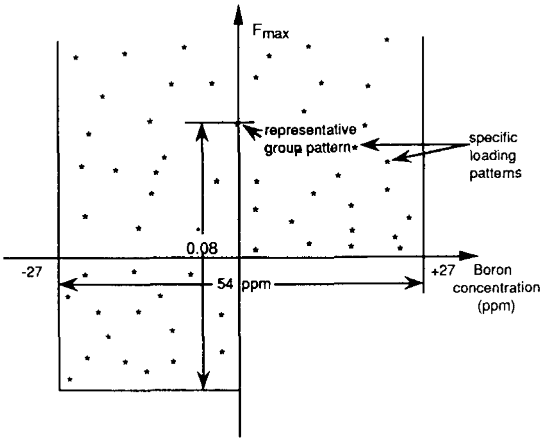


Fig. 5. Distribution Diagram of Specific Patterns in a Pattern Group.

3. Application of the Methodology

The equilibrium core of the three–loop PWR plant with annual/three batch modes, mamely, Korea's Kori–3 Cycle–10 was selected as a test problem to demonstrate the methodology developed in this work. This power plant is rated as 2775 MW thermal core power and its core consists of 157 fuel assemblies. The loading pattern search program is constructed by QUINTUS PROLOG installed in a SUN 3/280 computer system. The program is composed of the loading pattern search part and the burnable poison arrangement part.

3.1. Application of Shuffling Methods

Loading patterns are firstly searched by application of the fuel allocation rules without burnable poison. The core center position is assigned to the highest burned fuel assembly in the whole fuel assemblies. Three types of representative fuel assemblies are then allocated. Figure 2 shows one of these examples. The loading pattern that is allocated by only three types of representative fuel assemblies and central fuel assembly is a representative pattern containing many specific loading patterns with only minor alternations of fuel assemblies within each fuel batch. Loading patterns within a pattern group have nearly the same entropy between each pattern and representative pattern in comparison with other loading patterns of another pattern groups. Hence it becomes a simplified problem of comparing representative loading patterns rather than so vast specific loading patterns.

Representatives for fresh fuel assemblies are allocated to allowed core positions according to fresh fuel allocation rules. 62 fresh fuel pattern groups are obtained after the allocation of fresh fuel assemblies. Representatives of twice-burned fuel assemblies are assigned to core periphery positions for the low-leakage loading pattern. Remaining twice-burned representatives are allocated to core positions permitted by twice-burned fuel allocation rules. There remain 205 reference pattern groups after allocation of twice-burned representative fuel assemblies. Since once-burned representative fuel assemblies are automatically assignd to empty core positions, the remaining pattern groups are still 205. These 205 pattern groups are evaluated by the MEDIUM-2D code to check their power peaking factors with use of the Cyber computer.

3.2. Burnable Poison Distribution

Burnable poison rods are then arranged to decrease power peaking in accordance with burnable poison distribution rules. There are 142 pattern groups that meet burnable poison distribution criteria. Burnable poison rods are distributed in 142 pattern groups according to burnable poison distribution rules, and these pattern groups are evaluated again by the MEDIUM-2D. Pattern groups having power peaking factors greater than 1.510 are excluded because it is possible to decrease peaking factor by 0.08 at best with alloca-

Table 2. List of Pattern Groups that Have Peaking Factor Less than 1.5150 After Burnable Poison Distribution

Pattern No.	Peaking Factor without BP	Peaking Factor with BP	Initial Boron Concentration(ppm)
P003	1.6149	1.5019	1270
P005	1.6376	1.5145	1247
P006	1.6161	1.4841	1243
P010	1.6449	1.5115	1292
P011	1.6870	1.5109	1265
P014	1.6336	1.5058	1270
P017	1.5869	1.4803	1264
P041	1.6051	1.4711	1249
P043	1.6017	1.4862	1275
P046	1.6388	1.4818	1290
P048	1.5601	1.4984	1284
P052	1.5934	1.4682	1251
P056	1.5970	1.4972	1281
P071	1.6172	1.5096	1304
P074	1.5214	1.5014	1335
P083	1.6700	1.5083	1272
P084	1.6684	1.5045	1271
P086	1.7118	1.5031	1275
P088	1.7091	1.5060	1300
P098	1.5483	1.4580	1236
P099	1.5501	1.4700	1246
P106	1.6758	1.5085	1303
P115	1.6335	1.5039	1246
P118	1.6344	1.5122	1296
P128	1.6018	1.4904	1259
P129	1.6118	1.5023	1260
P130	1.5751	1.4573	1258
P131	1.6213	1.5103	1268
P132	1.6237	1.4853	1268
P135	1.7227	1.4872	1262
P138	1.7167	1.5066	1268
P139	1.5753	1.4728	1286
P140	1.6061	1.5029	1297
P142	1.5806	1.5041	1294
P152	1.5326	1.4435	1253
P153	1.5783	1.5025	1262
P154	1.6027	1.4939	1262
P168	1.6008	1.4947	1229
P170	1.5969	1.4947	1257
P171	1.5976	1.5041	1266
P175	1.6181	1.5130	1292
P176	1.5808	1.5113	1278
P201	1.5709	1.4685	1254
P202	1.6618	1.4912	1265
P203	1.5685	1.4802	1256

tion of specific fuel assemblies in core positions. Pattern groups that satisfy this criterion are 45 groups and they are shown in Table 2. These 45 pattern groups are representative patterns for each pattern family. Since each pattern group also contains many specific loading patterns one must search the best loading pattern among these pattern groups. The data shown in Table 2 are maximum power peaking factors of representative patterns and a critical boron concentration at the beginning of cycle with and without burnable poison. Effect of burnable poison (varied approximately 2–3ppm) on cycle length is negligible. Critical boron concentration without burnable poison could be used as a cycle length criterion in comparing pattern groups. The distribution range of peaking factors and cycle length of loading patterns for a representative pattern are shown in Figure 5.

Maximum reduction(0.08) of power peaking from the value of the group representative pattern can be realized when all of the high burned fuel assemblies are located in inner core positions and all of the less burned fuel assemblies are located in the core periphery. Critical boron concentration is approximately varied to the maximum of 54ppm from the value of the group representative pattern The maximum boron change occurs when almost high burned fuel assemblies are located in inner core positions and when less burned fuel assemblies are allocated in inner core positions. Since the cycle length must be shorten by lowering power peaking factor, it is impossible to lower power peaking factor and lengthen cycle length at the same time. The breakeven point, namely, no gain of cycle length compared to that of the group representative pattern, occurs to decrease the power peaking factor more than 0.04 from the value of the group representative pattern. The distribution ranges of 45 loading pattern groups are evaluated, and some examples are shown in Figure 6. This evaluation shows that case 130, case 139 and case 152 are recommendable loading pattern groups.

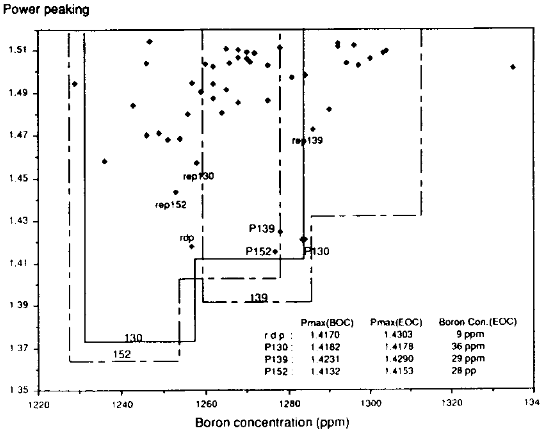


Fig. 6. Evaluation Results of 45 Representative Patterns and Reference Design Pattern(rdp).

3.3. Search for Optimum Specific Pattern

After distributing burnable poison rods, a specific loading pattern having lower power peaking factor and long cycle length which is located at the right lower corner of the pattern distribution diagram(Figure 5) was searched. Pattern groups are divided into two categories, namely, category 1 that has power peaking factor lower than 1.4750 and category 2 that has peaking factor greater than 1.4750.

Pattern group case 130 and case 152 are classified into category 1. The MCL method is used to find optimum specific loading pattern from each pattern group. After three to five changes of fuel assemblies from each initial starting loading pattern, case 130 and case 152 are obtained. Pattern group case 139 is classified into category 2. The MPF method is used to find optimum specific loading pattern from pattern group. After three to five Case 139 is obtained after several trials from the initial starting loading pattern. Figure 6 shows the evaluation results of 45 representative pattern groups and found three specific loading patterns

It is possible to search several specific loading patterns(P130, P139 and P152) which are better than the reference design pattern (rdp) which was designed to scope cycle 10 of Kori–3. If a designer who wants to obtain a loading pattern having long cycle length, the pattern group 130 is then suitable and a desiginer for whom to obtain low power peaking factor the pattern group 152 is suitable. Figure 7 shows the final specific loading patterns of reference design pattern, P130, P139 and P152.

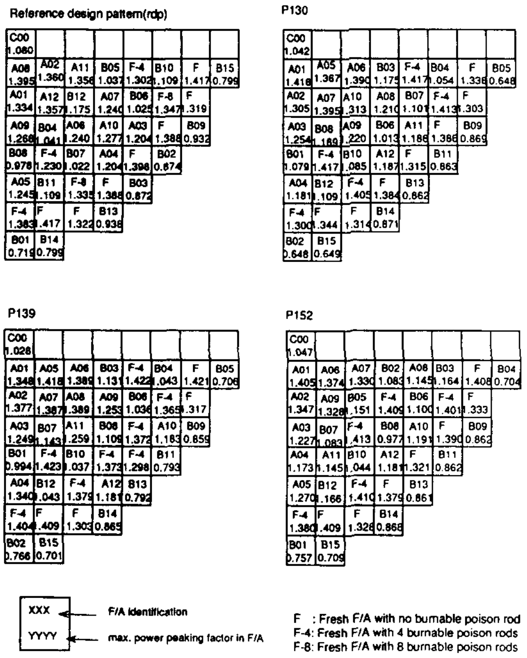


Fig. 7. The Final Specific Loading Patterns and Reference Design Pattern at BOC.

4. Conclusions

Three principles, namely, the general shuffling rules, regionwise shuffling method and pattern grouping method were applied to reduce solution space. With application of the general shuffling rules, the solution space was reduced from 10^{210} to the level of 10^{21} loading patterns. The loading pattern space was further reduced by use of the regionwise shuffling method to the level of 10^{9} patterns. With use of the pattern grouping method that classifies loading patterns in accordance with similarity between loading patterns, the loading pattern space was reduced to the number of 200–1000 representative patterns.

The entropy theory was applied as the criterion of pattern group classification. Pattern generation and burnable poison distribution programs are constructed by the QUINTUS PROLOG language, and power peaking factor was checked by use of the MEDIUM 2D computer code. 205 representative patterns without burnable poison distribution were initially generated by the pattern search program. They were ultimately reduced to 45 representative patterns with burnable poison by the limiting criteria and distribution rules for distribution of burnable poisoned fuel assemblies.

The MCL and MPF method were applied to find the best specific loading pattern in a representative pattern group. Case 130 and 152, a specific loading pattern of each representative pattern group, were obtained by the MCL method. The pattern group 152 is very good loading pattern having the lowest power peaking factor and large cycle length. MPF method was used to find case 139. It was successful to obtain the specific loading pattern after several trials with the initial starting loading pattern. Therefore, it is possible to search the loading pattern group and a specific loading pattern that meet a designer's purpose for reload core design.

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References

1. I. WALL and H. FENECH, "The Application of Dynamic Programming to Fuel Management Optimization," Nucl. Sci. Eng., 22, 285(1965).
2. R.L. STOVER and A. SESONSKE, "Optimization of BWR Fuel Management Using an Accelerated Exhaustive Search Technique," J. Nucl. Energy, 23, 673(1969).
3. T.O. SAUAR, "Application of Linear Programming to In-Core Fuel Management Optimization in Light Water Reactors," Nucl. Sci. Eng., 46, 274(1971).
4. A.J. FEDEROWICZ and R.L. STOVER, "Optimization of PWR Loading Patterns by Reference Design Perturbation," Trans. Am. Nucl. Soc., 17, 308(1973).
5. B.N. NAFT and A. SESONSKE, "Pressurized Water Reactor Optimal Fuel Management," Nucl. Technol., 14, 123(1972).
6. K. CHITKARA and J.WEISMAN, "An Equilibrium Approach to Optimal In-Core Fuel Management for Pressurized Water Reactors," Nucl. Technon., 24, 33(1974).
7. H. MOTODA, J.HERCEG, and A. SESONSKE, "Optimization of Refueling Schedule for Light Water Reactors," Nucl. Technol., 25, 497(1975).
8. Y.C. CHANG and A. SESONSKE, "Optimization and Analysis of Low-Leackage Core Management for Pressurized Water Reactors," Nucl. Technol., 65, 292(1984).
9. J.O. MINGLE, "In-Core Fuel Management Via Perturbation Theory," Nucl. Technol., 27, 248(1975).
10. G.H. HOBSON and P.J. TURINSKY, "Automatic Determination of Pressurized Water Reactor Core Loading Patterns That Maximize Beginning-of-Cycle Reactivity Within Power Peaking and Burnup Constraints," Nucl. Technol., 74, 5(1986).
11. W.B. TURNER and E.A. WILLIAMSON, Jr., "The Design of Reload Cores Using Optimal Control Theory," Nucl. Sci. Eng., 82 260(1982).
12. D.H. AHN and S.H. LEVINE, "Automatic Optimized Reload and Depletion Method for a Pressurized Water Reactor," Nucl. Technol., 71, 535(1985).
13. Y.A. CHAO, C.W. HU, and C.A. SUO, "A Theory of Fuel Management Via Backward Diffusion Calculation," Nucl. Sci. Eng., 93, 78(1986).
14. K. SEKIMIZU, "A Hierarchy Level Scheme for Quasi-Optimum Fuel Assembly Loading in Boiling Water Reactors," Nucl. Technol., 37, 296(1978).
15. Y.J. KIM, T.J. DOWNAR, and A. SESONSKE, "Optimization of Core Reload Design for Low-Leakage Fuel Management in Pressureized Water Reactors," Nucl. Sci. Eng., 96, 85(1987).
16. A. GALPERIN and E. NISSAN, "Application of Heuristic Search Method for Generation of Fuel Reload Configurations," Nucl. Sci. Eng., 99, 343(1988).
17. A. GALPERIN, S. KIMHI, and M. SEGEV, "A Knowledge-Based System for Optimization of Fuel Reload Configurations," Nucl. Sci. Eng., 102, 43(1989).
18. R. CHRISTENSEN, "Entropy Minimax Source Book Volume I : General Description," Entropy Limited, Lincoln, Massachusetts, 1981.
19. R. CHRISTENSEN, "Entropy Minimax Source Book Volume IV : Application," Entropy Limited, Lincoln, Massachusetts, 1981.
20. L. BRILLOUIN, "Science and Information Theory," Academic Press, New York, 1962.