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Comparison of WABA and Gd Burnable Absorbers Nuclear Characteristics and Optimal Allocation of Gd Rods in Fuel Assembly

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WABA및 가도리니움 독봉 집합체에 대한 핵특성 비교 및 집합체내 가도리니아봉 위치 최적 선정

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Abstract

Recent popular trends in pressurized water reactor(PWR) fuel management are to extend the cycle length and to employ the low-leakage core designs for the optimal utilization of the uranium resources. In control strategy incorporated with the fuel management, burnable absorbers are required to control the power peaking and to ensure a negative moderator temperature coefficient during reactor operation.

In this study, the nuclear characteristics and the optimal allocation of gadolinium-poisoned rods within the fuel assembly are considered using KWU SAV 79 A Code Package. First, analyses are carried out to compare the nuclear characteristics of the fuel assemblies containing WABA(Wet Annular Burnable Absorber) and Gadolinium burnable absorbers respectively. The analyses show that the gadolinium-bearing fuel assembly has peculiar depletion characteristics ensuing from the very large thermal neutron absorption cross section. Peculiar characteristics of gadolinium provide basis for the optimal allocation of Gd rods in fuel assembly. Second, the methodology of an optimal allocation of gadolinium-posioned rods within the fuel assembly is developed and applied to some nuclear designs.

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요 약

가압 경수로의 노심 설계에 있어서 제한된 우라늄 자원의 효율적인 이용을 위한 다양한 방안으로 장주기 운전, 고연소도 및 저누출 장전 모형 등을 강구하고 있는 추세이다. 이러한 노심들은 원자로 운전 주기 전반에 걸친 공간적 출력 분포 제어와 잉여 반응도 제어를 위해 가연성 독물질을 사용하고 있다. 이와 관련하여 가연성 독물질 관리의 최적화 연구가 다각도로 진행되고 있다.

본 연구에서는 1990년도부터 국내 가압 경수로에 국산 핵연료가 장전되기 시작하면서 가도리니아 독봉을 사용하고 있으며 장차 주된 가연성 독물질로 쓰일 예정이므로 이에 대해서 분석을 수행하였다. 분석 결과 가도리니아 독봉은 열중성자 흡수 단면적이 매우 큰데서 기인한 특이한 연소 특성을 보이고 있다. 특히 집합체 내에서의 가도리니아 독봉의 위치에 따라 매우 다양한 출력 분포를 보이고 있다. 이러한 다양한 출력 분포 중에서 노심의 반경 방향 첨두 출력을 가능한 낮게하는 집합체 내에서의 가도리니아봉 위치 최적 선정을 위한 방법론을 제시하였다.

1. Introduction

Large amount of excess reactivity is contained in the recent core designs such as the low leakage loading scheme, extended burnup and longer cycle. To control the power peaking and to ensure a negative moderator temperature coefficient(MTC), a number of burnable poisons are required in these core designs as compared with the existing. Therefore the research on the management of the burnable absorbers is receiving much attention.

Both boron and gadolinium(Gd) have properties that make them suitable for use as burnable poison. Boron has been fabricated in the form of discrete types such as Pyrex glass and Wet Annular Burable Absorber(WABA) and widely used in the PWR cores. Gadolinium was first used as burnable poison in the Boiling Water Reactor(BWR) cores and has been reported to offer several advantages over the use of boron.

In this study, brief comparison analyses are carried out to specify the different characteristics between the two fore-mentioned burnable poisons in qualitive or quantitative terms. Two absorber types such as WABA and Gd-poisoned rod are selected in this study.

Specially much attention is given to Gd-bearing fuel assembly. In general, Gd rod is fabricated in the form of integral type in which gadolinium is mixed with the fuel material. This integral concept enables the Gd rods to be inserted in the various fuel rod positions, and such flexibility in the insertion position has various potential problems. One of them is the various power distribution resulting from the flexibility in the insertion positions of Gd rods within the fuel assembly. Another is the sudden rise in the power peaking within the fuel assembly at higher burnup. In particular, the power peaking within the fuel assembly is strongly affected by the detailed allocations of the Gd rods. Thus various power distributions within the fuel assembly are observed for the various allocation types of the poisoned-rods. Based on the results of the study, attention is given to the optimal selection of allocation positions of Gd rods within the assembly which show as low a power peaking within the fuel assembly as possible over th wide range of burnup.

2. Model Description

In this study, SAV 79 A Code Package of Kraftwerk Union(KWU) Computer Procedure[1-12] is used for analyses of the fuel assemblies bearing burnable poison rods. SAV 79 A Code Package consists of two parts, a main nuclear design procedure containing FASER, MULTIMEDIUM, MEDIUM, and PINPOW and sub-procedure consisting of BADASA, NUKLAN, LIBED, WOFIT and WQAB codes.

Infinite multiplication factor and power distribution versus burnup within the unit fuel assembly bearing burnable poison rods are calculated with NUKLAN/FASER and MULTIMEDIUM codes for some pre-fixed calculation conditions. Other nuclear characteristic features such as the power peaking factor, residual poisoning effect and so on are analyzed with MEDIUM code which is a 2- or 3-Dimensional depletion calculation code followed by PINPOW code.

3. Analysis of WABA and Gd

The main objectives of the use of burnable poisons are to compensate for the excess reactivity of the reactor core at BOC and to control the power profile across the reactor core. Boron and gadolinium are the widely-used burnable poison material.

In this Section, typical KOrean Fuel Assembly-(KOFA) which consists of 264 fuel rods, 24 guide tubes and 1 instrumentation tube is considered as a reference. Typical KOFA in the assembly calculation has an enrichment of 3.5 w/o UO_2.

3.1. Analysis of Unit Assembly

The depletion behavior of the fuel assembly bearing burnable poisons is determined approximately by two factors, infinite multiplication factor(k-infinity) and intra-fuel assembly power distribution

Figure 1 and 2 show infinite multiplication factors calculated with NUKLAN/FASER code versus burnup. The variation of the change rate of k-infinity shows a smooth curve for WABA-bearing fuel assembly. But the change rate of k-infinity of the gadolinium-bearing fuel assembly shows an significant variation. Also the variations of the

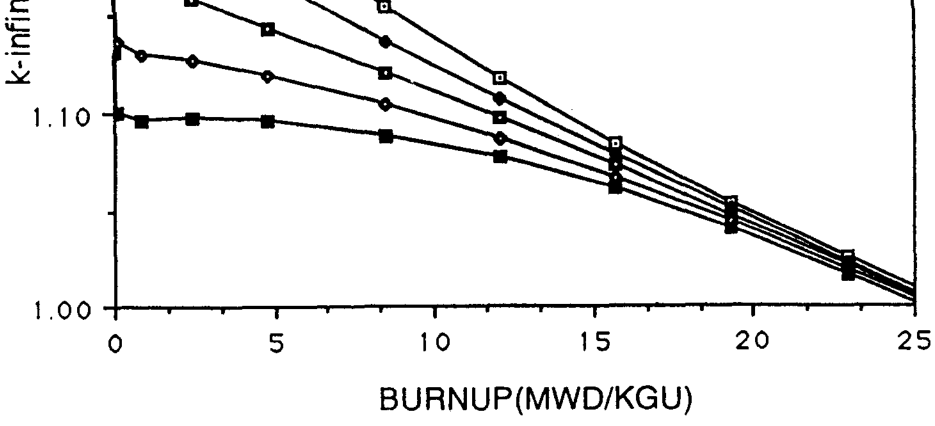


Figure 1. Infinite Multiplication Factor vs. Burnup (e.5 w/o U FA)

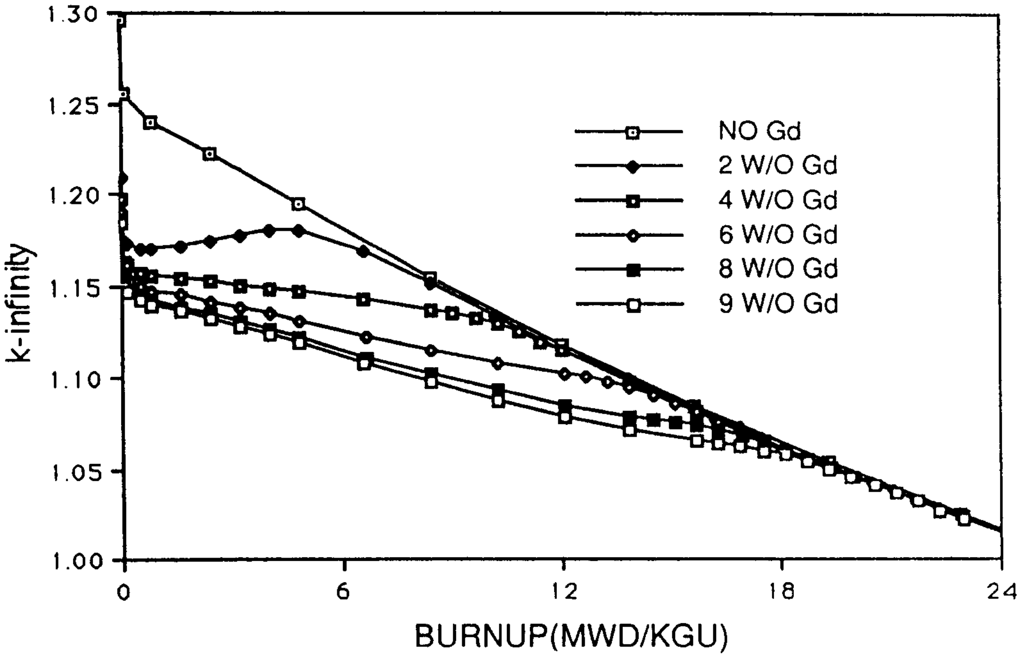


Figure 2. Infinite Multiplication Factor vs. Burnup
(8 Gd rods/FA, 3.5 w/o U)

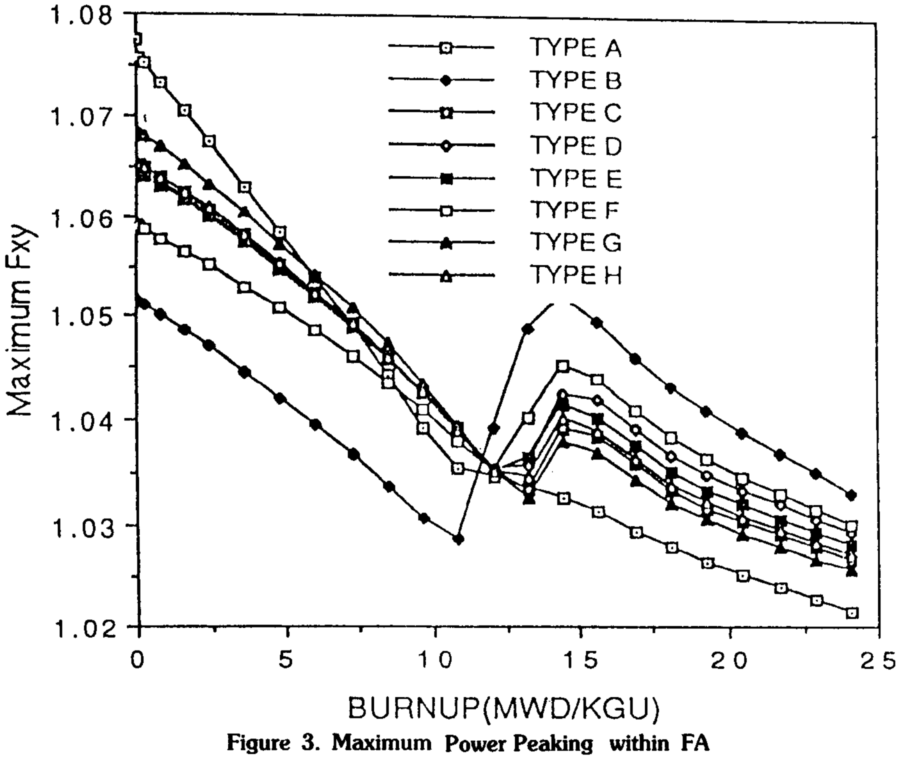


Figure 3. Maximum Power Peaking within FA
(4 Gd rods/FA, 3.5 w/o U, 9 w/o Gd)

change rate of k-infinity in the gadolinium-bearing fuel assembly are larger for smaller Gd enrichment. This characteristic is due to the large thermal absorption cross section. Namely, the depletion rate of gadolinium can be larger than that of the fuel material. Therefore the k-infinity of gadolinium-poisoned fuel assembly can increase and reach an equilibrium state for smaller gadolinium enrichment. At higher burnup after the rapid variation of the change rate of the k-infinity of the gadolinium-bearing fuel assembly, variation then becomes a nearly linear function of burnup for all cases. This means that the depletion of the fuel and burnable poisons reaches an equilibrium state after which the characteristics of the gadolinium-bearing fuel assembly are similiar with those of non-poisoned fuel assembly. This shows that the residual burnable poisons within the fuel assembly do not appreciably affect the k-infinity any longer and the effects of the residual fuel and fission products become dominant.

As can be predicted from the behavior of the k-infinity of unit fuel assembly, relative power peaking within the WABA-bearing fuel assembly is continuously decreasing versus burnup and significant rises of the power peaking are not shown. Unlike WABAs, the allocations of Gd rods within the fuel assembly are very flexible, but their allocation arrays are pre-selected subject to some requirements. The rapid rise of the relative power peaking within the fuel assembly is observed at the higher burnup for every case in Figure 3. The rapid rise of the relative power peaking in gadolinium-bearing fuel assembly corresponds to the rapid variation of the change rate of k-infinity. This characteristic is due to the different depletion behavior between the gadolinium-poisoned and non-poisoned rods ensuing from the very large thermal neutron absorption cross section of gadolinium which is about sixty-five times as large as that of boron. From the figure 3, power distributions in the fuel assembly are strongly affected by the allocation arrays of the Gd rods within the fuel assembly. The rapid rise in power peaking within the fuel assembly should be as low as possible over the wide range of burnup. Therefore appropriate allocation of Gd rods in the fuel assembly should be made to accomplish this objective.

Table 1. Results of Core Calculation

	Item	Gadolinia LP	WABA LP
12 month cycle	Crit. Boron Con.*	1404.3 ppm	1413.5 ppm
	Cycle Length (Burnup)	28.2 EFPD (11.7 MWD/KGU)	286.0 EFPD (11.6 MWD/KGU)
	React. Holddown**	138.4 pcm	282.8 pcm
18 month cycle	Crit. Boron Con.*	1983.4 ppm	1939.5ppm
	Cycle Length (Burnup)	440.9 EFPD (17.8 MWD/KGU)	439.3 EFPD (17.7 MWD/KGU)
	React. Holddown**	185.6 pcm	494.2 pcm

* :Critical Boron Concentration at BOC, No Xe.

**:Reactivity Holddown by the residual poisons at EOC.

3.2 Analysis of Core Calculation

As part of a study of brief nuclear characteristic comparisons for two typical burnable absorbers, i.e. WABA- and Gd-bearing fuel assemblies, core depletion analyses were carried out for two different burnup cycles such as 12 and 18 months. The loading patterns are shown in Figure 4.

Both the cores loaded with WABA- and gadolinium-bearing fuel assemblies considered in this study are made to have nearly same reactivity at BOC. In addtion, both cores for comparison have the same degree of neutron leakage (i.e. same loading pattern). What is specially note-worthy are that EOC is assumed to be the time when the critical boron concentration reaches 10 ppm and the reactivity hold down by the residual poisons in the core at EOC is calculated by setting the particle number density of all the burnable poisons to be zero.

Table 1 summarizes the results. The core loaded with Gd-bearing fuel assemblies is estimated to longer cycle length and advantage in residual poisoning effect than that loaded with WABA-bearing fuel assemblies. The values of the reactivity holddown shown in Table 1 are the reactivity suppressed by the residual poisons at EOC.

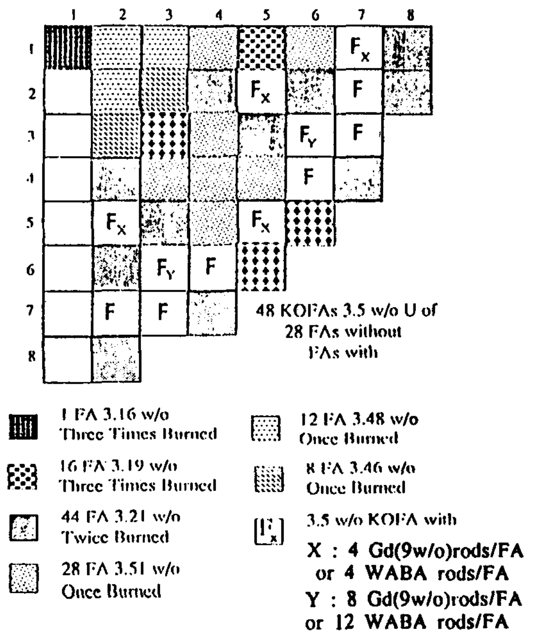
From the results of the depletion calculation, the core loaded with WABA-bearing fuel assemblies has behavior of continuously decreasing radial power peaking over the core burnup. In contrast, the core loaded with gadolinium-bearing fuel assemblies shows peculiar depletion behavior which is of second sudden rise in the radial power peaking factor at higher burnup. The latter result leads to potential difficulty in nuclear designs.

4. Gadolinium Positioning

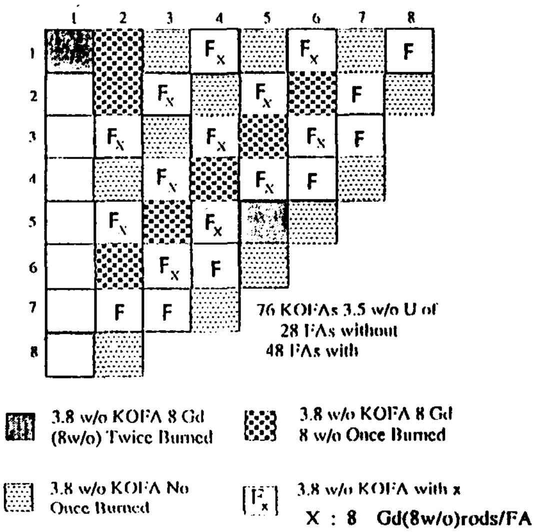
4.1. Background

A potential advantage of using Gd rods as burnable absorber is the flexibility in the insertion position in the fuel assembly. Namely, Gd rods are inserted in the fuel rod positions, not in the guide tubes, in the fuel assembly. Various allocation types of Gd rods in the fuel assembly are possible although the number of Gd rods in the fuel assembly is fixed. These various allocations of Gd rods in the fuel assembly strongly affect the power distributions within the fuel assembly. As shown in Figure 3, there are wide differences between the types of the allocation of Gd rods within the fuel assembly. In addition, gadolinium-bearing fuel assembly shows a sudden remarkable rise in the power peaking within the fuel assembly. This peculiar characteristic is closely related to the core-averaged radial power peaking factor. Sudden rise in the radial power peaking for the core loaded with gadolinium-bearing fuel assemblies can be briefly explained by the following descriptions. Generally, the assembly-averaged power of gadolinium-bearing fuel assembly increases with burnup as burnable poisons deplete out. Second rise in the relative power peaking within the gadolinium-bearing fuel assembly is combined with the increase in the assembly-averaged power. Consequently, core-averaged radial power peaking factor can jump at higher burnup. This is a potential disadventage in the core design. Based on this feature, it is important to control the core-averaged radial power peaking factor of the core loaded with the gadolinium-bearing fuel assemblies. In view of making the core-averaged radial power peaking as low as possible, it is important to select an allocation type of Gd rods within the fuel assembly which shows as low core-averaged radial power peaking as possible over the wide range of burnup. In this study, gadolinium positioning is defined to be the optimal selection of allocation positions of Gd rods within the fuel assembly which accomplishes this objective.

I.S. Jung studied the gadolinium positioning based on the unit assembly calculation[17]. He



12 Month cycle



18 Month cycle

Figure 4. Core Loading Pattern

used net zero current boundary conditions in the four sides of the fuel assembly. But calulation conditions used in his analysis were different from those of real core. This justifies the requirement that investigations should be carried out through the real core depletion calculation.

In this study, improved methodology considering the real core situation for gadolinium positioning is developed and applied to some nuclear designs. Improved methodology can be applied to the nuclear designs incorporated with the standard design procedure. In view of the optimal utilization of burnable poisons, different allocations of Gd rods within the fuel assembly are considered according to the detailed core loading position of poisoned-assemblies.

Peaking power is a critical factor in both the nuclear design and the nuclear safety. Reduction of peaking power provides sufficient design margins for the designers and improves the safety margins. From this point of view, it is very important to select the allocation type of Gd rods within the fuel assembly which leads to the reduction of peaking power. Newly-developed methodology can be applied to the optimal utilization of burnable poisons. Namely, different allocation types of Gd rods within the fuel assembly can be considered because new methodology requires only one depletion calculation.

4.2. Improved Methodology for Gd Positioning

In gadolinium positioning, improved methodology is based on the KWU standard design procedure[1-12]. Depletion calculations are carried out with MEDIUM code. The MEDIUM code uses assembly-averaged values as cross section data. Assembly-averaged cross section data are generated by NUKLAN/FASER code regardless of the detailed positions of Gd rods within the fuel assembly. Therefore 2-dimensional nodal calculation(one node per assembly) can be carried out only once for the loading pattern containing poisoned-assemblies which have different allocations of poisoned-rods in them. MEDIUM produces nodal values independent of the detailed allocation of Gd rods i the fuel assembly. The local effects of the poisoned-rods in the fuel assembly are combined in the subsequent procedure. This subsequent procedure called dehomogenization is to simply edit the nodal values by PINPOW code based on the modulation method[6]. Dehomogenization gives the detailed heterogeneous local values(neutron flux, power, etc.) within the fuel assembly determined by multiplying the assembly-averaged nodal values and the heterogeneous form functions(HFF) calculated by MULTIMEDIUM code in advance. HFF is a heterogeneous local (flux or power) distribution considering the local effects of Gd rods within the fuel assembly. Dehomogenization procedure requires much shorter computing time than the nodal calculation. What is specially note-worthy is that the detailed allocations of Gd rods within the fuel assembly has little effect on the assembly-averaged power used to determine the heterogeneous local power distribution in the dehomonization procedure. This fact was carefully checked in advance and the improved methodology for the optimal position selection of Gd rods within the fuel assembly has a clue to this logic.

Figure 5 shows the schematic logic diagram for this methodology. First, only one nodal calculation is carried out for the preliminary loading pattern. Second, heterogeneous local power distributions are calculated by applying the various allocation types of Gd rods within the fuel assembly to the nodal values as of the assembly-averaged power during the dehomogenization procedure with PINPOW code. One appropriate allocation of Gd rods which shows as low radial power peaking as possible over the wide range of burnup is chosen from the results of the dehomogenization calculation. Finally, assembly-averaged cross section data are modified for the selected allocation types of Gd rods. Assembly-averaged cross sections are nearly independent of the detailed allocation of Gd rods, but standard design procedure requires this stage.

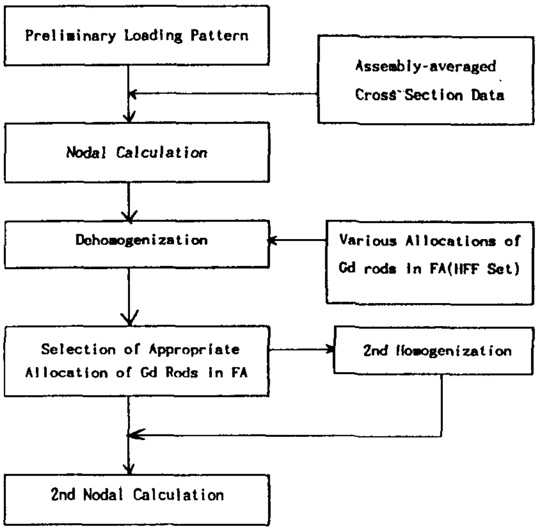


Figure 5. Schematic Logic for Optimal Position Selection

Improved feature of this methodology is that the calculations are carried out in the real core state. That is, combined effects of assembly-averaged power and the relative power distribution within the fuel assembly are reflected in the detailed core loading position of poisoned–assembly. In the past Gd positioning, appropriate selection of Gd rods in the fuel assembly was made only from the relative power peaking within the fuel assembly calculated by MULTIMEDIUM code.

4.3. Results

In this study, only symmetric allocation types of Gd rods within the fuel assembly are considered. New methodology was applied to the loading scheme considered in Section 3.

The results of gadolinium positioning are given in Table 2 with the type currently used in nuclear designs. Annual cycle pattern loaded with fuel assemblies bearing 4 or 8 Gd rods. Current designs use TYPE B as a poisoned-assembly bearing 4 Gd rods(4 Gd FA) and TYPE C as 8 Gd FA regardless of the cycle length. The results of applying the new methodology, all different types

Table 2 Results of Optimal Selection

	Existing Gd TYPE	Optimal Selection		
		Annual Cycle(12 Month)		18 Month Cycle
4Gd FA	TYPE B	7/1*	TYPE A(D,F)	——
		5/2*	TYPE C, G	
		5/5*	TYPE C,D,E,F,G,H	
8 Gd FA	TYPE C	6/3*	TYPE E, B	ALL TYPE E**

* :Position of poisoned–assembly in core loading pattern.

* *:Same Gd TYPE regardless of loading position of poisoned–assembly.

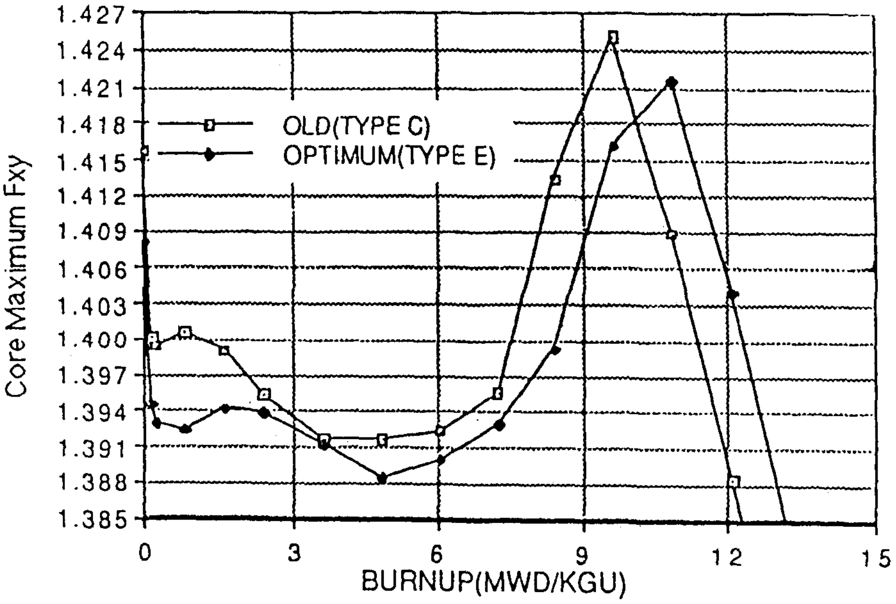


Figure 6. Core–averaged Radial Power Peaking (18 Month Cycle)

from the existing TYPE B are suggested according to the loading position in the core in case of annual cycle loading pattern. The use of different types according to the detailed loading position in the core is feasible in view of the optimal utilization of burnable poisons. The result for 18 month cycle loading pattern attracts attention. All the fuel assemblies bearing gadolinium can have the same allocation of Gd rods within the fuel assembly regardless of their detailed loading positions in the core. This means that gadolinium positioning can be accomplished regardless of the detailed core loading patterns in case of cores having many gadolinium-bearing fuel assemblies. Generally, when many poisoned-assemblies are loaded, they are apt to be scattered in the core. This fact can account for the above-mentioned result.

Core-averaged radial power peaking of 18 month cycle core is pictured in Figure 6 for the existing(TYPE C) and newly-selected(TYPE E) types of Gd-bearing assembly. The newly-selected gadolinium type results in lowering the core-averaged radial power peaking. Figure 7 shows the corresponding allocation type of Gd rods within the fuel assembly for the understanding of difference.

5. Conclusions

The following conclusions can be drawn:

1. Gadolinium–bearing fuel assembly has sudden variation in the change rate of infinite multiplication factor at higher burnup, but WABA-bearing fuel assembly has no appreciable rise and it has smooth variations over the wide burnup range.
2. Detailed allocations of the Gd rods within the fuel assembly strongly affect the power distribution within the fuel assembly.
3. Gadolinium-bearing fuel assembly has significant disadvantage in the core-averaged radial power peaking factor over the WABA-bearing fuel assembly.
4. Only one type of Gd assembly can be determined when a large amount of burnable poisons are required.

In view of the optimal utilization of burnable poisons, different allocations of Gd rods within the fuel assembly were considered according to the detailed core loading position of poisoned-assemblies although the number of Gd in the fuel assembly is fixed. But asymmetrical allocation of Gd rods within the fuel assembly can be considered based on the new methodology in the future.

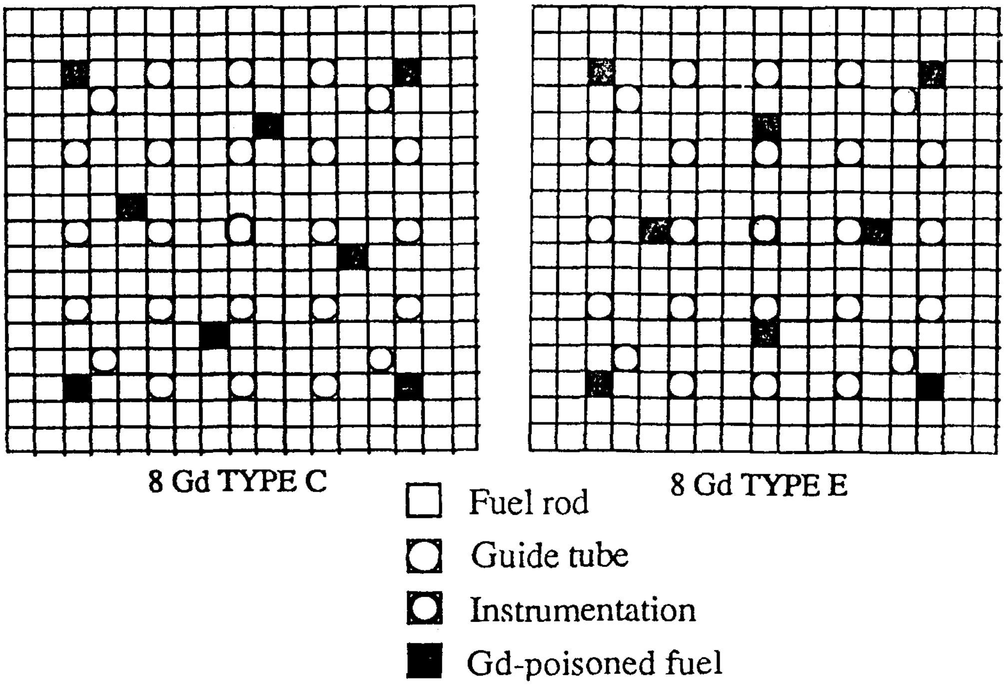


Figure 7. Allocation Type of Gd Rods within FA (18 Gd Rods/FA)

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