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COMPUTATIONAL STUDY ON THE BUCKLING-REACTIVITY CONVERSION FACTOR IN LIGHT WATER MODERATED UO_2 CORE

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Computational Study on the Buckling-Reactivity Conversion Factor in Light Water Moderated UO_2 Core

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The buckling-reactivity conversion factor (K-value) which is used in the water level worth method is one of the most important constants of the Tank-type Critical Assembly (TCA) of Japan Atomic Energy Research Institute. The K-value has been considered a constant value regardless of the core configurations. Computational study on the K-value was performed by means of two-dimensional transport perturbation theory to investigate how much the K-value varies among various core configurations in light water moderated and reflected UO_2 cores. The calculation indicates that the K-value varies by 5% within the limits of this investigation. The varience of the K-value components of fuel cell and other regions cancel out each other, which makes the varience of the K-value over various core configurations relatively small.

Keywords: Water Level Worth Method, Buckling-reactivity Conversion Factor, Low Enriched Uranium, Light Water Moderator, Transport Perturbation Theory, TCA

軽水減速UO_2炉心でのバックリング－反応度換算係数に関する解析的研究

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(1993年8月11日受理)

日本原子力研究所の軽水臨界実験装置TCAでの実験で水位差法に用いられるバックリング－反応度換算係数（K値）は，TCAの実験上，非常に重要な定数である。今まで，この定数は炉心形状等によって変化しないものとされてきた。本報では，このK値が軽水減速材，反射体を持つUO_2炉心で，炉心形状等の変化によってどの程度変動するかを調べるため，二次元の輸送摂動論を用いて解析的に研究した。その結果，検討した範囲では，K値は炉心により5％程度変化することが分かった。また，K値の燃料セル領域と他の領域の変動成分は相殺し合う。このためK値の炉心毎の変動は比較的小さくなる。

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Contents

目　　次

1. Introduction

The Tank-type Critical Assembly (TCA)(1) of Japan Atomic Energy Research Institute ordinarily uses no control rods. This reactor is operated in a way that water level is lower than the effective length of fuel rod. Reactivity is controlled by the level of light water moderator, which can be applied to the reactivity measurement method. When a certain perturbation is added to TCA core, there are some cases where the reactivity effect of this perturbation must be measured. In order to measure this reactivity, the perturbed or unperturbed core is made critical by controlling the water level and measuring this level. Multiplying the difference of vertical buckling of each critical core by the buckling-reactivity conversion factor, the reactivity effect caused by a perturbation can be obtained. According to the modified one group theory, the buckling-reactivity conversion factor is the ratio of migration area to infinite multiplication factor. Hence, it can be inferred that this buckling-reactivity conversion factor does not change regardless of the number of fuel pins or horizontal configuration of the core as far as water-fuel volume ratio of a unit cell consisting of the core is fixed, or the added perturbation is small.

The buckling-reactivity conversion factor of the core can be obtained experimentally by the following procedure. The water level of a critical core is raised up slightly and the subsequent positive reactivity is measured by the positive period method. By dividing the reactivity by the difference of the vertical buckling, the buckling-reactivity conversion factor can be obtained. Errors in measured reactivity and vertical buckling, however, make this factor inaccurate. Hence, an alternative method which correlates the reactivity with the vertical buckling over a wide range of water levels has been adopted. By changing the number of fuel rods or the configuration of the core, critical water level varies and a positive reactivity measurement by the positive period method can be performed at several critical water levels. Therefore, the correlation between the water level and reactivity which can be easily converted to the buckling-reactivity conversion factor can be obtained over a wide range of water levels. This buckling-reactivity conversion factor has been used in order to evaluate the reactivity effect of a perturbation added to the core, such as the insertion of absorber material or temperature change of the moderator. This methodology is based on the assumption that this factor is a constant value regardless of the number of fuel rods, the configuration of the core, or perturbation. This assumption, however, has not been confirmed in detail. In order to obtain accurate reactivity effects experimentally, it is essential that the variance of this factor be evaluated for various core configurations. The objectives of this paper are to (a) evaluate the buckling-reactivity conversion factor of several core configurations by a computational method, (b) clarify the variances of this factor, and (c) discuss the relationships between the core configuration and the buckling-reactivity conversion factor.

2. Theory

2.1 Experimental Method to Evaluate the Buckling-reactivity Conversion Factor

According to the modified one group theory, the effective multiplication factor is given by

$$k_{eff} = \frac{k_\infty}{1+M^2B_g^2} \tag{1}$$

where k_∞: Infinite multiplication factor

M^2: Migration area

B_g^2: Geometrical buckling.

When geometrical buckling changes to $B_g^{2'}$, this change results in the reactivity $\rho(=1/k_{eff}-1/k'_{eff})$ expressed by

$$\rho = \frac{M^2}{k_\infty}(B_g^2-B_g^{2'}), \tag{2}$$

on the condition that M^2/k_∞ does not change. Several fuel rods are added to a critical core with critical water level Hc, and the water level changes to Hc'. The reactivity effect of this added fuel rod can be estimated as follows:

$$\rho = K\left(\left(\frac{\pi}{H_C+\lambda_z}\right)^2-\left(\frac{\pi}{H'_C+\lambda_z}\right)^2\right) \tag{3}$$

tion that this factor is a constant value regardless of the number of fuel rods, the configuration of the core, or perturbation. This assumption, however, has not been confirmed in detail. In order to obtain accurate reactivity effects experimentally, it is essential that the variance of this factor be evaluated for various core configurations. The objectives of this paper are to (a) evaluate the buckling-reactivity conversion factor of several core configurations by a computational method, (b) clarify the variances of this factor, and (c) discuss the relationships between the core configuration and the buckling-reactivity conversion factor.

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on the condition that M^2/k_∞ does not change. Several fuel rods are added to a critical core with critical water level Hc, and the water level changes to Hc'. The reactivity effect of this added fuel rod can be estimated as follows:

$$\rho = K\left(\left(\frac{\pi}{H_c+\lambda_z}\right)^2-\left(\frac{\pi}{H_c'+\lambda_z}\right)^2\right) \tag{3}$$

where K: Buckling-reactivity conversion factor (M^2/k_∞),

λ_z: Vertical extrapolated length.

A certain perturbation is added to a critical core and if the K-value can be considered to be constant regardless of this perturbation, the reactivity can be obtained by Eq.(3). This method of measuring the reactivity is called "the water level worth method".

In order to evaluate the buckling-reactivity conversion factor, the K-value, the differential water-level worths $d\rho/dH$ are fitted by the least squares method to an equation$^{(1)}$,

$$\frac{d\rho}{dH} = 2K\frac{\pi^2}{(H+\lambda_z)^3}\,. \tag{4}$$

As stated in Chap.1, the differential water-level worth is obtained by dividing the reactivity measured by the positive period method by the increment of water level from critical water level.

2.2 Calculational Method

A method to calculate the K-value based on the diffusion perturbation theory was derived in Ref.(2). In this paper, the K value was calculated by the transport perturbation theory. The well-known system of multigroup transport equation of X-Y geometry is written$^{(3)}$ as

$$\begin{aligned}&\vec{\Omega}\cdot grad\ \Phi^g(\vec{r},\vec{\Omega})+\left(\Sigma_t^g(\vec{r})+\frac{1}{3\Sigma_t^g(\vec{r})}B_z^2\right)\Phi^g(\vec{r},\vec{\Omega}) = \\ &\sum_{g'=1}^{G}\int_{4\pi}\Sigma_s^{g'\to g}(\vec{r},\vec{\Omega}'\to\vec{\Omega})\Phi^{g'}(\vec{r},\vec{\Omega}')d\vec{\Omega}'+\frac{1}{k_{eff}}\frac{\chi^g}{4\pi}\sum_{g'=1}^{G}\nu\Sigma_f^{g'}(\vec{r})\int\Phi^{g'}(\vec{r},\vec{\Omega}')d\vec{\Omega}'\end{aligned} \tag{5}$$

where B_z^2: Z-direction buckling,

$\Sigma_t^g(\vec{r})$: Total cross section for g-group at $\vec{r}$,

The adjoint equation with Z-direction buckling $B_z^{2'}$ to Eq.(5) is written as

$$\begin{aligned}&-\vec{\Omega}\cdot grad\ \Psi^g(\vec{r},\vec{\Omega})+\left(\Sigma_t^g(\vec{r})+\frac{1}{3\Sigma_t^g(\vec{r})}B_z^{2'}\right)\Psi^g(\vec{r},\vec{\Omega}) = \\ &\sum_{g'=1}^{G}\int_{4\pi}\Sigma_s^{g\to g'}(\vec{r},\vec{\Omega}\to\vec{\Omega}')\Psi^{g'}(\vec{r},\vec{\Omega}')d\vec{\Omega}'+\frac{1}{4\pi k'_{eff}}\nu\Sigma_f^g(\vec{r})\sum_{g'=1}^{G}\chi^g\int\Psi^{g'}(\vec{r},\vec{\Omega}')d\vec{\Omega}'\end{aligned} \tag{6}$$

where $\Psi^g(\vec{r},\vec{\Omega})$: Adjoint angular flux,

k'_{eff}: Effective multiplication factor corresponding to buckling $B_z^{2'}$.

Constants except for vertical buckling do not change.
Taking the inner product of Eq.(5) with $\Psi^g(\vec{r},\vec{\Omega})$, and of Eq.(6) with $\Phi^g(\vec{r},\vec{\Omega})$, and subtracting gives$^{(4)}$

$$\rho(=1/k_{eff}-1/k'_{eff})=\frac{\sum_{g=1}^{G}\int_V d\vec{r}\int_{4\pi}d\vec{\Omega}\,\frac{1}{3\Sigma_t^g(\vec{r})}\,\Phi^g(\vec{r},\vec{\Omega})\Psi^g(\vec{r},\vec{\Omega})}{\int_V d\vec{r}\sum_{g'=1}^{G}\chi^{g'}\int_{4\pi}d\vec{\Omega}'\,\Psi^{g'}(\vec{r},\vec{\Omega}')\sum_{g=1}^{G}\frac{\nu\Sigma_f^g}{4\pi}\int_{4\pi}d\vec{\Omega}\Phi^g(\vec{r},\vec{\Omega})}(B_z^2-B_z^{2'}) \tag{7}$$

The buckling-reactivity conversion factor, the K-value, is defined by this equation. When $B_z^{2'}\to B_z^2$, the K-value defined by Eq.(7) is the buckling-reactivity conversion factor at a water level corresponding to the buckling B_z^2.

3. Calculations

By use of the method derived in Chap.2.2, the K-values of the various Tank-type Critical Assembly(TCA) core configurations were calculated. In this paper, 2.6wt% enriched UO_2 fuel rods with 14.2mm O.D., which have been utilized for almost all the experiments at TCA, were chosen. The fuel rods are arrayed with 19.56mm square lattice whose water-to-fuel volume ratio is 1.83. The group constants with 10 energy groups of this unit cell were calculated by the cell calculation of the SRAC code system$^{(5)}$ with the library based on JENDL-2. The angular flux and adjoint flux with 10 energy groups were calculated by using S_n transport code TWOTRAN-II$^{(3)}$. The critical vertical buckling was investigated in this S_n calculation. This calculation was performed by S_8 calculation with a 30cm-thick water reflector. The K-values of Eq.(7) were calculated by using the total cross-section and angular flux and adjoint angular flux obtained above.

(1) K-value in regular rectangular fuel lattice

The calculated K-values of n × m rectangular fuel lattice illustrated in Fig. 1 are shown in Table 1. Suzaki$^{(6)}$ measured the K-value for 17 × 17 core by pulsed neutron source method and obtained K=31.2 ± 0.2cm^2. The calculation overestimates the K-value by 1.2%. But it is where $\Psi^g(\vec{r},\vec{\Omega})$: Adjoint angular flux,

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$$\rho(=1/k_{eff}-1/k'_{eff})=\frac{\sum_{g=1}^{G}\int_V d\vec{r}\int_{4\pi}d\vec{\Omega}\,\frac{1}{3\Sigma_t^g(\vec{r})}\,\Phi^g(\vec{r},\vec{\Omega})\Psi^g(\vec{r},\vec{\Omega})}{\int_V d\vec{r}\sum_{g'=1}^{G}\chi^{g'}\int_{4\pi}d\vec{\Omega}'\Psi^{g'}(\vec{r},\vec{\Omega}')\sum_{g=1}^{G}\frac{\nu\Sigma_f^g}{4\pi}\int_{4\pi}d\vec{\Omega}\Phi^g(\vec{r},\vec{\Omega})}(B_z^2-B_z^{2'}) \qquad (7)$$

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(2) K-value in fuel lattice with water gap

In order to study the neutron interaction effect among coupled cores, many critical experiments have been performed for coupled cores where several cores are separated by the light water moderator(7) at TCA. The water gap makes the neutron spectrum and flux distribution around the water gap quite different from that of cores without water gap. Thus, it is expected that water gap produces a significant effect on the K-value. The core configurations for which K-values were calculated are illustrated in Figs. 2 and 3. Calculated K-values are shown in Table 2.

(3) K-value in fuel lattice with borated plates

Critical experiments on trap cores composed of four rectangular fuel lattices separated by a water gap and borated stainless steel plates, as shown in Fig. 4, were performed(8) at TCA. The reactivity effect of borated plates were estimated with the water level worth method. In this calculation, a plate with a thickness of 3.0mm and boron content of 0.7% was dealt with. Calculated K-values are shown in Table 3.

(4) K-value in fuel lattice with Gd_2O_3-UO_2 rods

A few Gd_2O_3-UO_2 rods were replaced with 2.6wt% enriched UO_2 rods in the 21 × 21 rectangular core lattice and reactivity effect and power distribution were measured(9) at TCA. The K-values of these lattices with several fuel rods containing 3wt% Gd_2O_3 were calculated. The core configurations are illustrated in Figs. 5(a), (b), and (c). Calculated K-values are shown in Table 4.

(5) K-value in fuel lattice with soluble boron in the moderator

Critical experiments on the fuel lattice with soluble boron in the moderator were performed(1),(10) at TCA. Calculations were carried out for a regular square lattice whose moderator contained 100, 350, and 600ppm soluble boron. Calculated K-values are shown in Table 5.

(6) K-value in fuel lattice with higher moderator temperature

The variations of the reactivity with temperature were measured for moderator temperatures ranging from 0 to 80°C at TCA(1),(10). The difference in the critical water level due to temperature was converted into reactivity by the water level worth method. The K-values were calculated for a 19 × 19 regular square lattice at 52 and 77°C. Calculated K-values are shown in Table 6.

4. Discussion

The numerator of Eq.(7) represents diffusion coefficient averaged over the whole core. The diffusion coefficient of water is smaller than that of fuel lattice. Therefore, the K-value decreases as the water reflector or water gap exerts more effect on the K-value. In addition, since total cross-section increases as the neutron energy decreases, it can be seen from Eq.(7) that the K-value increases as the neutron spectrum averaged over the whole region gets harder.

As seen from Table 1, the K-value for n × n cores increases with increasing n. This calculational result can be explained fairly well in the following. As the core size increases, the effect of the water reflector region on the diffusion coefficient averaged over the whole core decreases. By the same reasoning, the K-value of the fuel lattice with one or two lattice pitch water gap is smaller than that of the fuel lattice without water gap, as shown in Table 2. Since a higher moderator temperature makes the diffusion coefficient larger, this temperature rise can cause the K-value to increase.

Insertion of borated plate or Gd_2O_3-UO_2 rod, containing soluble boron in the moderator which makes neutron spectrum harder can cause the K-value to increase. Tables 3~6 show this tendency.

The K-value is calculated by integration over the whole energy and whole region. In order to clarify which factor dominates the K-value, the K-value is separated as

$$K = K_{T,C}+K_{T,W}+K_{E,C}+K_{E,W} \tag{8}$$

where

$$K_{T,C} = (\sum_{g\leq E_{th}} \int_{V\subset Cell} A_g(\vec{r})dV)/F,$$

$$K_{T,W} = (\sum_{g\leq E_{th}} \int_{V\not\subset Cell} A_g(\vec{r})dV)/F,$$

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$$A_g(\vec{r}) = \int_{4\pi} d\vec{\Omega}\,\frac{1}{3\Sigma_t^g(\vec{r})}\,\Phi^g(\vec{r},\vec{\Omega})\Psi^g(\vec{r},\vec{\Omega}),$$

$$F = \int_V d\vec{r} \sum_{g'=1}^{G} \chi^{g'} \int_{4\pi} d\vec{\Omega}'\,\Psi^{g'}(\vec{r},\vec{\Omega}') \sum_{g=1}^{G} \frac{\nu\Sigma_f^g}{4\pi} \int_{4\pi} d\vec{\Omega}\,\Phi^g(\vec{r},\vec{\Omega})$$

E_{th} = Thermal cut off energy (0.683ev).

By Eq.(8), the K-value is broken down into each component of two energy groups (thermal(<0.683ev), and epithermal) and two regions (fuel cell and others). The calculated components of the K-value are shown in Tables 7~11. Tables 7, 8, 9, 10, and 11 correspond to the representative cases of Tables 1, 2, 3, 4, and 5, respectively.

Although the component of fuel cell region varies from 26 to 31cm^2, that of other regions also varies so that the K-value lies between 30 and 32cm^2. Thus, the regional component of the K-value varies not a little among various core configurations. The variance of the K-value is, however, kept relatively constant, since the variance of regional components cancel each other out. The calculational result in Table 2 that the K-value of the core with more than three lattice pitch water gap between two rectangular cores is larger than that of single core seems to be doubtful, but it can be explained by Table 8. When the water gap is wider than three lattice pitches, the contribution of fuel cell region to the K-value is approximately constant regardless of the gap width and that of water gap region makes the K-value larger than the K-value of single core.

From Tables 1~6, the followings are remarkable;

(1) In the cores composed of fuel rod and light water moderator, the K-values lie between 30.2 and 31.2cm^2(Tables 1, 2). The K-value is confined to within about 3% variance.

(2) The insertion of the absorber material, such as borated plate, Gd_2O_3-UO_2 rod and soluble boron makes the K-value larger by 5% at most within the limits of this investigation.

(3) When temperature of light water moderator is raised up from room temperature to 77°C, the K-value increases by 4%.

The accuracy of the reactivity measured by water level worth method depends not only on the K-value, but also the water level, the accuracy of measured water level, differences between critical water levels and

the accuracy of vertical extrapolated length, as seen in Eq.(3). Hence, whether these variances of the K-value are significant or not is not covered in this paper.

5. Conclusion

The buckling-reactivity conversion factor (K-value) which is one of the most important factors at TCA was investigated for various core configurations. In general, as diffusion coefficient averaged over the whole core becomes larger, or neutron spectrum of the core gets harder, this value increases. Hence, when a perturbation which makes diffusion coefficient larger or makes neutron spectrum harder is added to the core, the K-value increases. Furthermore, as the number of fuel rods increases, the K-value increases. The variance of the K-value ranges within about 5% at most, since the variance of the K-value components of fuel cell and other regions cancel each other out. Though few examples of core configuration are described above, these are typical examples of core configurations encountered at TCA and it is sufficient to consider them only.

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Table 1 K-values of n×m rectangular lattice

n×m	K (cm²)
17×17	30.83
18×18	30.90
19×19	30.95
21×21	31.05
22×22	31.10
24×24	31.19
17×34	31.13
18×36	31.18

Table 2 K-values of fuel lattice with water gap

2-rectangular cores (Fig. 2)

Gap width (pitch)	K (cm²)
0 (18×36)	31.18
1	30.74
2	30.84
3	31.04
5	31.12
7	31.01
9	30.99
∞ (18×18)	30.90

4-rectangular cores (Fig. 3)

Gap width (pitch) G1	G2	K (cm²)
1	1	30.16
1	2	30.33

Table 3 K-values of fuel lattice with borated plates

4-rectangular cores (Fig. 4)		
Gap width (pitch)		K (cm^2)
G1	G2	
1	1	31.71
1	2	31.61

Table 4 K-values of fuel lattice with Gd_2O_3-UO_2 rods

21 ×21 rectangular cores	
Number of Gd_2O_3-UO_2 rods	K (cm^2)
1 (Fig. 5(a))	31.15
5 (Fig. 5(b))	31.46
9 (Fig. 5(c))	31.76

Table 5 K-values of fuel lattice with soluble boron in the moderator

Content of soluble boron (ppm)	K (cm^2)
100	31.27
350	31.70
600	31.82

Table 6 K-values of fuel lattice with higher temperature moderator

Temperature of moderator(°C)	K (cm^2)
27	30.95
52	31.49
77	32.16

Table 7 Component of the K-value of rectangular fuel lattice

Region	Energy	Component of the K-value(cm^2)	
		Rod array	
		18 ×18	24×24
Fuel cell	Epithermal($K_{E,C}$)	26.66	27.87
	Thermal ($K_{T,C}$)	2.44	2.45
Reflector	Epithermal($K_{E,W}$)	1.41	0.68
	Thermal ($K_{T,W}$)	0.39	0.18
	Total	30.90	31.18

Table 8 Component of the K-value of fuel lattice with water gap

Two rectangular cores (Fig. 2)

Region	Energy	Component of the K-value(cm^2)		
		Gap width(pitch)		
		1	5	∞
Fuel cell	Epithermal($K_{E.c}$)	26.23	26.60	26.66
	Thermal ($K_{T.c}$)	2.40	2.41	2.44
Reflector +Water gap	Epithermal($K_{E.w}$)	1.77	1.69	1.41
	Thermal ($K_{T.w}$)	0.34	0.42	0.39
	Total	30.74	31.12	30.90

Four rectangular cores (Fig. 3)

Region	Energy	Component of the K-value(cm^2)	
		G1 G2	G1 G2
		1 1	1 2
Fuel cell	Epithermal($K_{E.c}$)	24.30	23.77
	Thermal ($K_{T.c}$)	2.34	2.31
Reflector +Water gap	Epithermal($K_{E.w}$)	3.07	3.61
	Thermal ($K_{T.w}$)	0.46	0.64
	Total	30.17	30.33

Table 9 Component of the K-value of fuel lattice with borated plates

Region	Energy	Component of the K-value(cm^2)	
		G1 G2	G1 G2
		1 1	1 2
Fuel cell	Epithermal($K_{E,c}$)	26.60	26.06
	Thermal ($K_{T,c}$)	2.33	2.33
Reflector +Water gap +Borated plate	Epithermal($K_{E,w}$)	2.53	2.91
	Thermal ($K_{T,w}$)	0.25	0.31
	Total	31.71	31.61

Table 10 Component of the K-value of fuel lattice with 9 Gd_2O_3-UO_2 rods (Fig. 5(c))

Region	Energy	Component of the K-value(cm^2)
Fuel cell	Epithermal($K_{E,c}$)	27.90
	Thermal ($K_{T,c}$)	2.33
Reflector	Epithermal($K_{E,w}$)	1.20
	Thermal ($K_{T,w}$)	0.33
	Total	31.76

Table 11 Component of the K-value of fuel lattice with 600ppm soluble boron in the moderator

Region	Energy	Component of the K-value(cm^2)
Fuel cell	Epithermal($K_{E,c}$)	28.82
	Thermal ($K_{T,c}$)	2.34
Reflector	Epithermal($K_{E,w}$)	0.56
	Thermal ($K_{T,w}$)	0.10
	Total	31.82

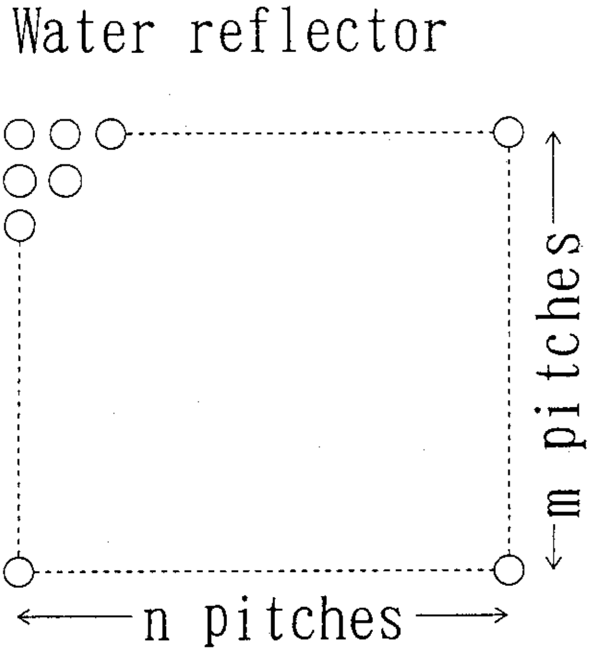

Fig. 1 Rectangular fuel lattice

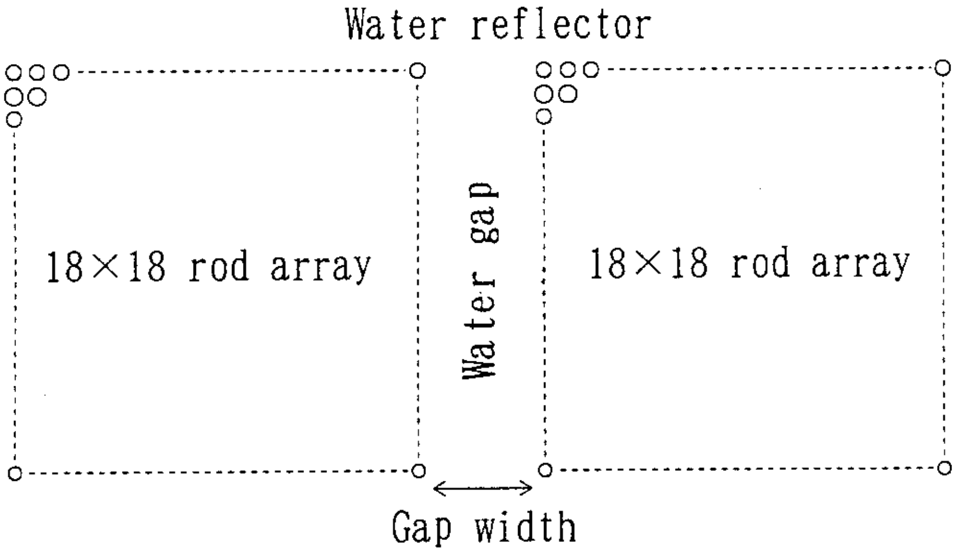

Fig. 2 Fuel lattice with water gap (two rectangular cores)

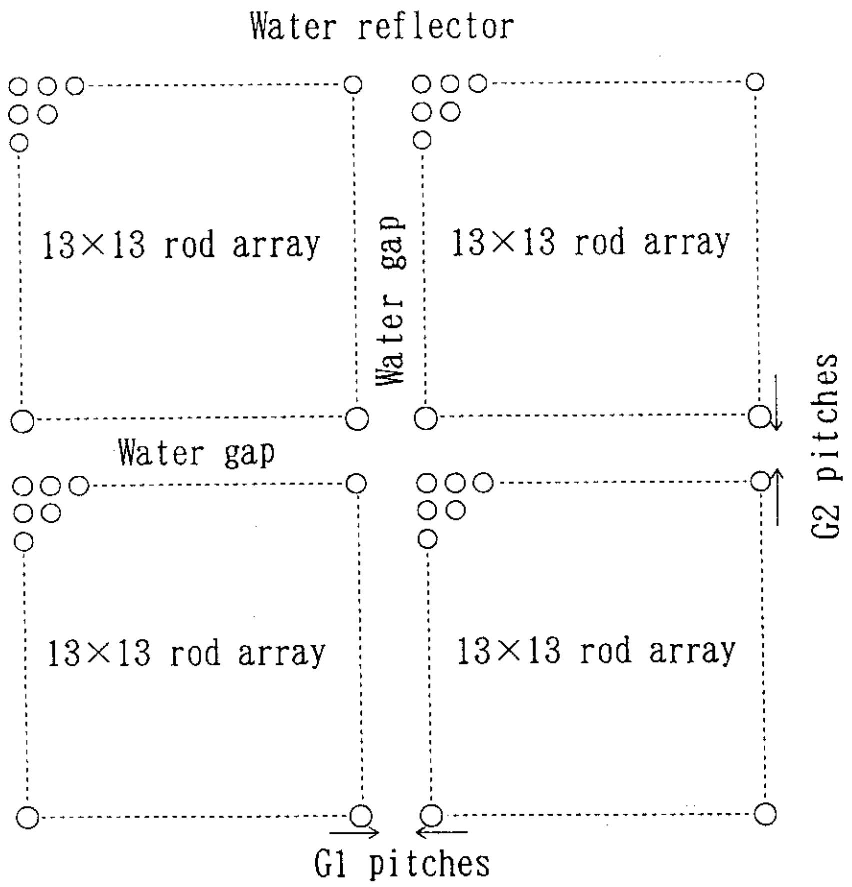

Fig. 3 Fuel lattice with water gap
(four rectangular cores)

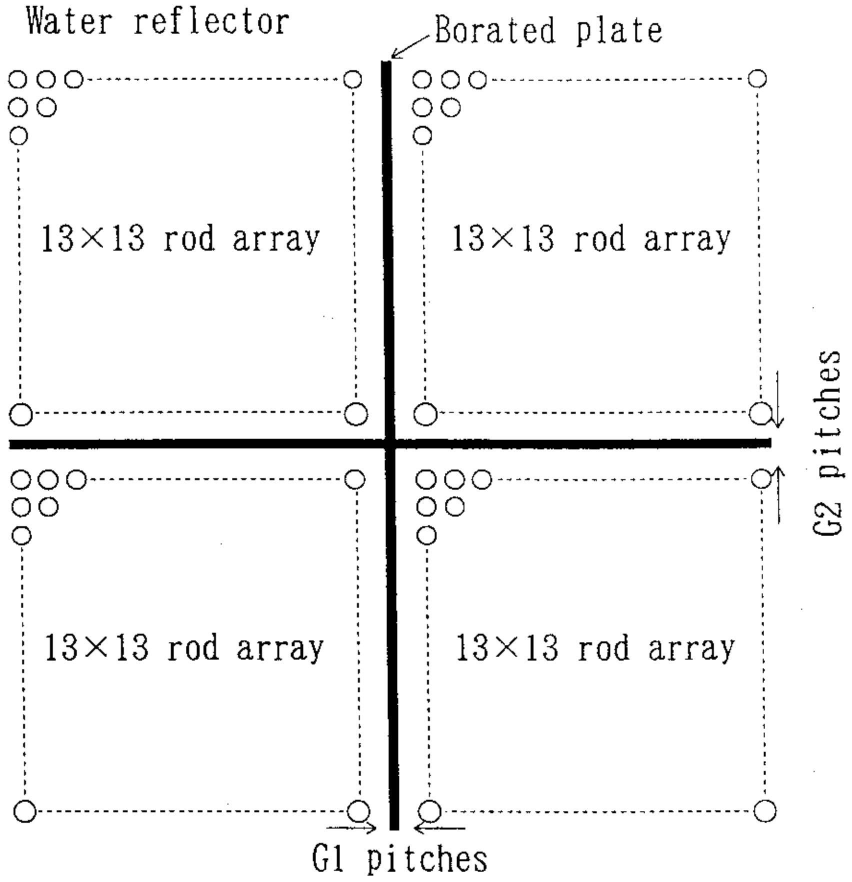

Fig. 4 Fuel lattice with borated plate

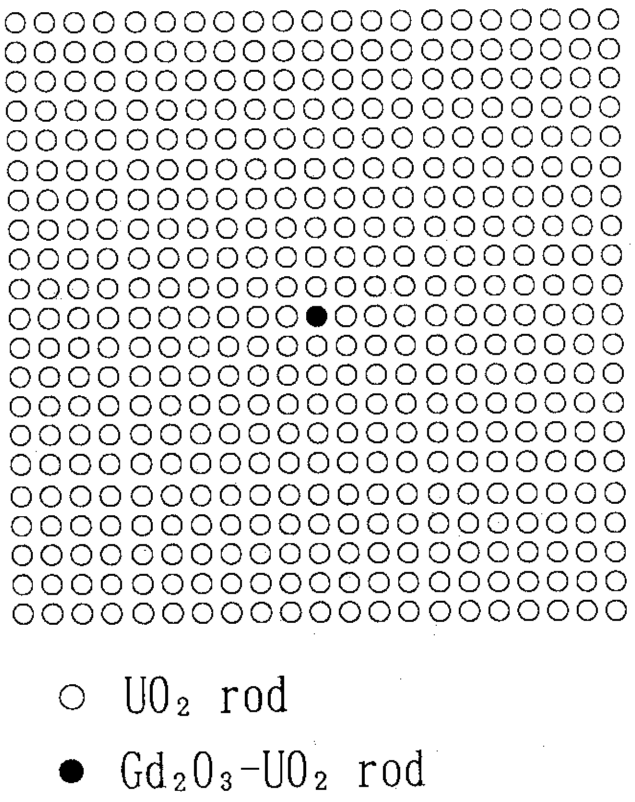

Fig. 5(a) Fuel lattice with Gd_2O_3-UO_2 rod

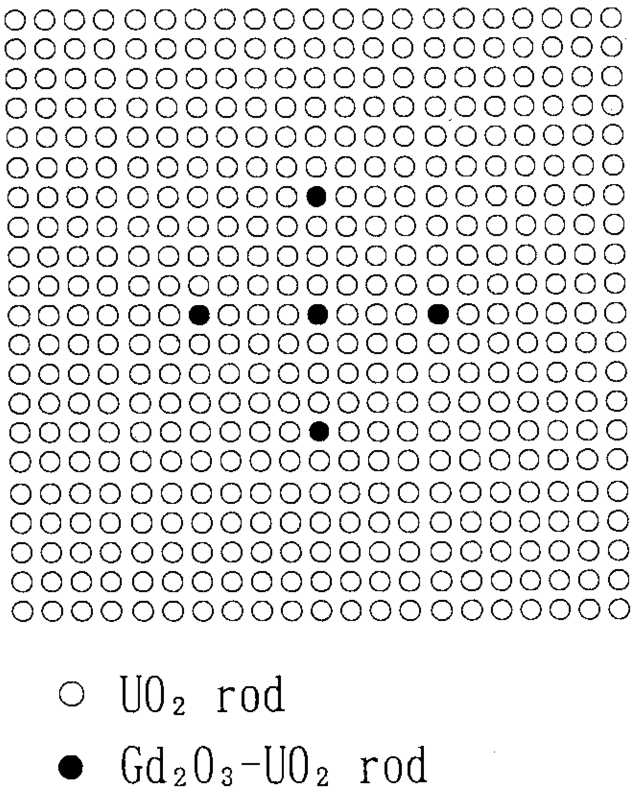

Fig. 5(b) Fuel lattice with Gd_2O_3-UO_2 rod

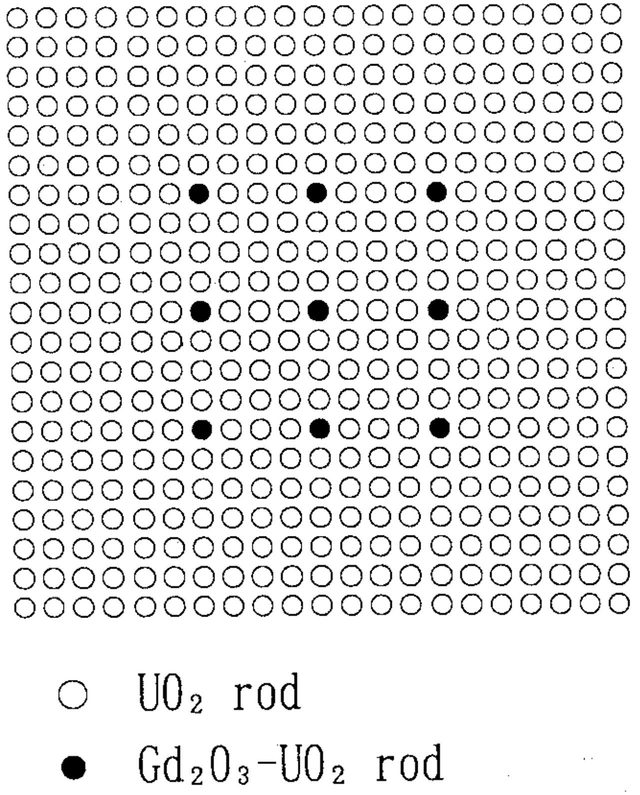

Fig. 5(c) Fuel lattice with Gd_2O_3-UO_2 rod