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EFFECTS OF VOLUME FRACTION
AND NON-UNIFORM ARRANGEMENT
OF WATER MODERATOR ON REACTIVITY

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Effects of Volume Fraction and Non-uniform Arrangement of Water Moderator on Reactivity

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From the viewpoint of nuclear criticality safety of fuel rod storage and transport, a series of critical experiments concerning effects of water hole size, water gap width, water-to-fuel volume ratio and non-uniform arrangement of water moderator have been performed at the Tank-type Critical Assembly (TCA) of Japan Atomic Energy Research Institute. In the present study, the effects of volume fraction and non-uniform arrangement of water moderator on reactivity are evaluated by the water level worth method and analyzed by the SRAC code. Error sources of experiments and calculations are discussed, especially for an energy group model. The calculation results of diffusion model with 17-group model show good agreement with the experiment results within a few dozen cents.

Keywords: Criticality Safety, TCA, Water Level Worth Method, Water Moderator, Water Gap, Water Hole, Water-to-fuel Volume Ratio, Non-uniform Arrangement, SRAC, Reactivity, Diffusion Model, Energy Group Model

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軽水減速材の体積比率及び非一様配置による反応度効果

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燃料棒の貯蔵と輸送に関する臨界安全性の観点から、日本原子力研究所の軽水臨界実験装置 TCA を用いて、水ホールの大きさ、水ギャップ幅、軽水対燃料体積比及び軽水減速材の非一様配置の反応度への影響を評価する実験が行われている。本研究では、軽水減速材の体積比率と非一様配置の反応度への影響を水位反応度差法により評価するとともに、SRAC コードを用いて解析評価した。実験値と解析値の持つ誤差、特に解析におけるエネルギー群モデルについて検討した。17 群モデルを用いた拡散計算による解析結果は実験結果と最大数十セント以内で良い一致を示した。

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1. Introduction

Light water plays an important role as a moderator in thermal nuclear reactors. The effective multiplication factor k_{eff} , is sensitive to the variation of water-to-fuel volume ratio (volume fraction of water). This effect becomes more complicated when it is accompanied by the temperature effect.

Nowadays we can obtain an optimal lattice pitch (or optimal water-to-fuel volume ratio) in reactor design for Nuclear Power Plant (NPP) according to safety and economical principles. However, for fuel storage tanks there are some special problems arising from the non-uniform fuel rod arrangement. To evaluate the reactivity of storage tank accurately in consideration of criticality safety, the further studies on the non-uniform arrangement effect should be carried out.

In the present research, based on a series of critical experiments performed at TCA, the effects of volume fraction and non-uniform arrangement of water moderator on reactivity are evaluated by the water level worth method and analyzed with the SRAC code. Meanwhile, error sources of experiment and calculation results are discussed, especially for an energy group effect.

2. Experimental Facility

2.1 Tank-type Critical Assembly (TCA)

As shown in Fig. 1, TCA consists of fuel rods, grid plates and a core tank (1.83m in diameter and 2.08m in height). The experimental lattices are built in the core tank. The moderator is light water. The reactor is operated by raising the water level from the bottom of the core tank by a feed water pump. No control rod is used for reactor operation. The detailed specifications of TCA are given in References 1 and 2.

The enrichment of ^{235}U is 2.6 wt.%. The 1.25-cm-diameter pellets are clad into an aluminum tube. The effective length of the fuel rod is 144.15 cm. Specification of the fuel rods is listed in Fig.2, Table 1 and Table 2.

2.2 Core patterns

TCA has flexible properties for constructing various pattern cores. The water-to-fuel volume ratio can be changed by replacing the grid plates with another set which has a different lattice pitch. The center-to-center rod spacing of the lattices ranges from 1.849 to 2.293cm, which corresponds to a water-to-fuel volume ratio ranging from 1.5 to 3.0. The names of cores are summarized in Table 3. The water hole size can be changed by withdrawing fuel rods from the core. The core patterns used in the present experiments are shown in Appendix A.

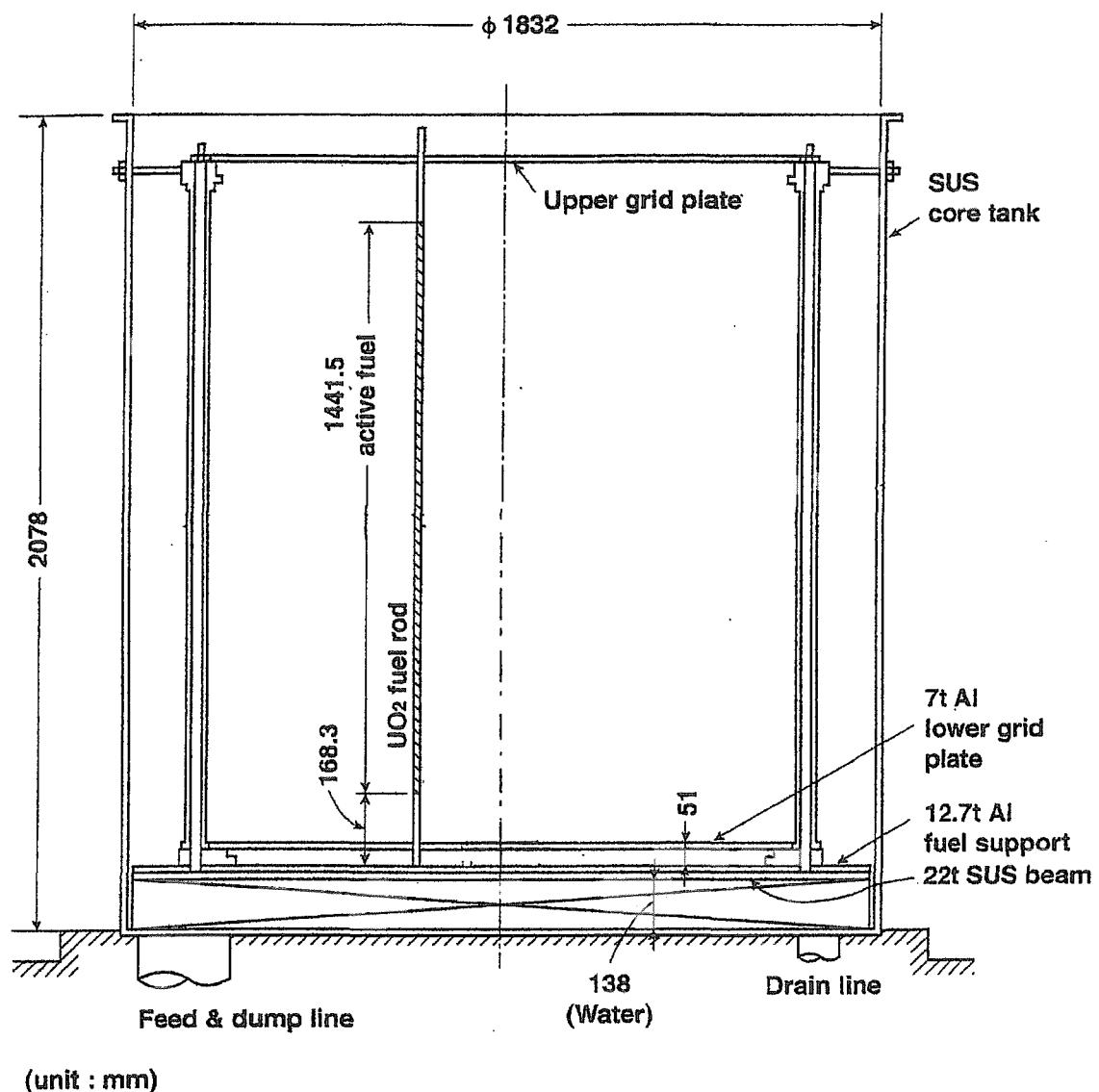


Fig. 1 Vertical cross-sectional view of TCA

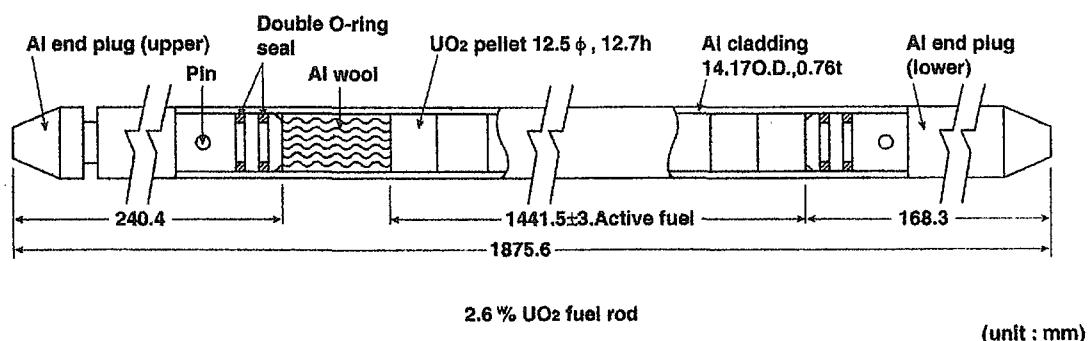


Fig. 2 2.6 wt.% UO₂ fuel rod

Table 1 Specification of fuel rod²⁾

Item	Value
Uranium composition	
²³⁴ U (wt.%)	0.021
²³⁵ U (wt.%)	2.596
²³⁸ U (wt.%)	97.383
UO ₂ pellet	
Diameter(cm)	1.25
Density (g/cm ³)	10.4
Height (cm)	1.27
Stack length (cm)	144.15
Aluminum Alloy cladding	
Inner diameter (cm)	1.265
Thickness (cm)	0.076

Table 2 Atomic number densities of cell composition²⁾

Region	Material	wt.%	Atom Density (10 ²⁴ atoms/cm ³)
Fuel	²³⁴ U	0.021	4.8872E-6
	²³⁵ U	2.596	6.0830E-4
	²³⁸ U	97.383	2.2531E-2
	O	-----	4.7214E-2
Cladding*	Aluminum	-----	5.5137E-2
Water	H	-----	6.6735E-2
	O	-----	3.3368E-2

* homogenized with air gap

Table 3 Names of cores²⁾

Core Name	Lattice Pitch (cm)	H/U
1.50U*	1.849	4.33
1.83U	1.956	5.28
2.48U	2.150	7.16
3.0U	2.293	8.65

* The figure gives the water-to-fuel volume ratio

3. Experiments and Calculations

3.1 Experiment and calculation methods

Experiment method^{1,3,4)}

Since there is no control rod in TCA, the reactivity is controlled by changing the level of water moderator. We treat a uniform core as a reference core. When a certain perturbation, such as water hole, is added to the TCA core, the reactivity effect of this perturbation can be obtained by the water level worth method.

We assume that H_{zc} and H_z represent the critical water levels of the reference and perturbed cores, respectively, and that B_{zc}^2 and B_z^2 are the vertical geometrical bucklings for the critical water levels of the reference and perturbed cores, respectively. For the reference core with the water level of H_z , according to the neutron balance equation, the neutron flux is governed by the following equation:

$$(-L_h - DB_z^2 + \frac{1}{k_{eff}} P) \Phi_s(x, y) = 0, \quad (1)$$

where L_h represents an operator of neutron loss except vertical neutron leakage, D a diffusion coefficient and P an operator of neutron production.

For a critical case with the water level of H_{zc} , Equation (1) can be changed to

$$(-L_h - DB_{zc}^2 + P) \Phi_b(x, y) = 0. \quad (2)$$

The adjoint equation of Equation (2) is expressed as

$$(-L_h^* - DB_{zc}^2 + P^*) \Phi_b^*(x, y) = 0. \quad (3)$$

Multiplying Φ_b^* to Equation (1) and Φ_s to Equation (3), integrating the products over the whole (x, y) space and subtracting, we can obtain the reactivity ρ_z added to the core just by changing water level of the reference core from H_{zc} to H_z .

$$\rho_z = 1 - \frac{1}{k_{eff}} = K(B_{zc}^2 - B_z^2), \quad (4)$$

where $K = \frac{(\Phi_b^*, D\Phi_s)}{(\Phi_b^*, P\Phi_s)}$ is a buckling-reactivity conversion factor. To obtain Equation (4), we apply the

following relation derived from the Green's theory and the boundary condition:

$$(\Phi_b^*, L_h \Phi_s) = (L_h^* \Phi_b^*, \Phi_s). \quad (5)$$

When a perturbation, such as water hole, is introduced to the reference core with the critical water level of the perturbed core H_z , the reactivity ρ_p added to the reference core can be given by the following formula:

$$\rho_p + \rho_z = 0, \quad (6)$$

where ρ_z represents the reactivity added to the core just by changing water level of the reference core from H_{zc} to H_z . Then,

$$\begin{aligned} \rho_p &= -\rho_z = -K(B_z^2 - B_{zc}^2) \\ &= K(B_z^2 - B_{zc}^2) \\ &= K\left(\left(\frac{\pi}{H_z + \lambda_z}\right)^2 - \left(\frac{\pi}{H_{zc} + \lambda_z}\right)^2\right), \end{aligned} \quad (7)$$

where λ_z is a sum of vertical extrapolated lengths at the upper and lower ends of core.

A K -value is treated as a constant regardless of the core configuration except a water-to-fuel volume ratio and can be obtained by the experimental method¹⁾. The newly evaluated K -values⁴⁾ used for the present study are listed in Table 4. Assuming that the K -value is constant regardless of the core configuration, we can easily and similarly obtain the same reactivity ρ_p added by the perturbation to the reference core with its critical water level as Equation (7).

The core water temperature is slightly changed around the room temperature 20°C. To get rid of the temperature effect on reactivity, we correct the critical water level at the experiment temperature to the one at the reference temperature 20°C by using the following quadratic function¹⁾ with the K -value :

$$\rho = A(T - T_0) + B(T^2 - T_0^2), \quad (8)$$

where T : the experiment temperature, and

T_0 : the reference temperature (20°C).

Parameters A and B obtained by the experimental method are listed in Table 4.

Table 4 Vertical extrapolated length¹⁾, buckling-reactivity conversion factor⁴⁾ and temperature effect factor¹⁾

Core Name	λ_z (cm)	K (\$·cm ²)	A ($\phi/^\circ\text{C}$)	B ($\phi/^\circ\text{C}^2$)
1.50U	12.6	4421	-0.11	-0.0136
1.83U	12.2	4288	-0.22	-0.0138
2.48U	11.3	3923	0.08	-0.0137
3.0U	11.1	3967	0.17	-0.0116

Calculation method

The experiment results are analyzed with the SRAC code⁵⁾ (the PIJ-CITATION option) with a cross section library based on JENDL-3.3. We select the PIJ code, a collision probability method code, for cell calculations and the CITATION code, a multi-dimensional diffusion code, for core calculations. The calculation scheme is shown in Fig. 3. For the core calculation, we adopt a horizontal two-dimensional model with introducing the vertical buckling. The thickness of the side water reflector is 30 cm.

We assume that $k_{eff,r}$ and $k_{eff,p}$ are calculated effective multiplication factors of the reference core and the perturbed core with a critical water level of the reference core, respectively, and that $\beta_{eff,r}$ represents the calculated effective delayed neutron fraction of the reference core. Then we can obtain the reactivity of the perturbed core relative to the reference core by the following formula:

$$\rho_p = \left[\left(1 - \frac{1}{k_{eff,p}} \right) - \left(1 - \frac{1}{k_{eff,r}} \right) \right] / \beta_{eff,r} \quad (9)$$

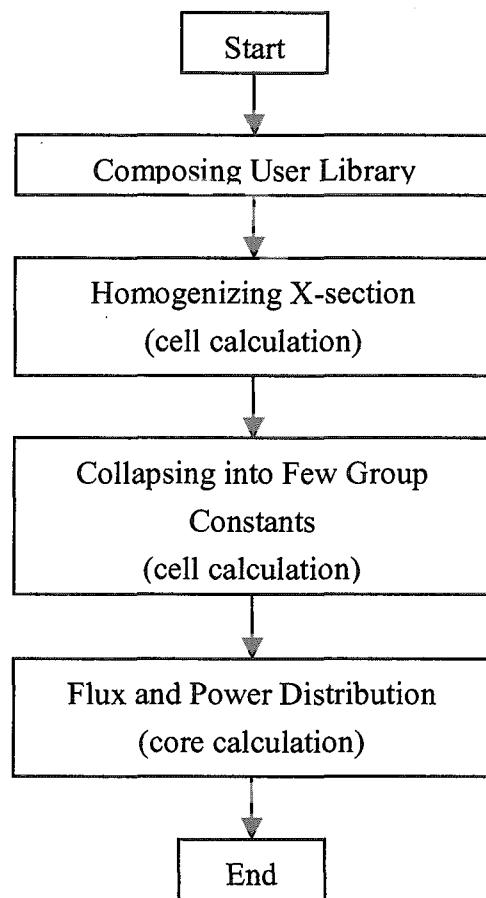


Fig. 3 Calculation scheme

3.2 Experiment I: water hole size effect

The reference core is constructed as a 19x19 rod square fuel array with a water-to-fuel volume ratio of 1.83. The water hole with different sizes (the different number and arrangements of water cells) are introduced to the reference core as perturbations, as shown in patterns 2 to 10 in Appendix A. The core parameters are listed in Table 5.

We choose 2-group, 4-group, 8-group, 10-group, 17-group and 25-group models as a benchmark calculation model to study the energy group effect on k-eff values. The calculated k-eff values for each critical core are shown in Fig. 4.

Figure 4 shows that the calculated k-eff values of the 8-group model are closer to unity than ones of the other group models. But we selected the 17-group model results as the benchmark calculation results owing to the calculation errors analysis made in Chapter 4.

Table 6 and Fig. 5 show that the reactivity introduced to the core is positive when the water hole size is chosen as one cell size (*i.e.*, one fuel rod withdrawn from the reference core) although the number of fuel rods decreases. The reason is that the core with the water-to-fuel volume ratio of 1.83 is operated in the under moderated condition. When a fuel rod is withdrawn, the local water-to-fuel volume ratio increases, which is beneficial for fission reaction. However, for the case of larger size water hole, the introduced reactivity is negative owing to much more decrease of fuel rods. In this experiment, if the water hole size is more than 21-cell-size, it is impossible to obtain the criticality because the critical water level will be beyond the effective fuel rod height 144.15 cm.

It should be noted that inserting the fuel rod in the center of larger water hole would introduce considerable positive reactivity to the core. For example, one fuel rod in the center of the 21-cell-size water hole will give a reactivity of about 150 ϕ from a comparison between Cases 9 and 10 because of the thermal flux peak in the center of water hole. The calculated flux distributions of the 20-cell-size water hole core are shown in Appendix B.

From Table 6, differences between calculation and experimental results are within about 25 ϕ .

Table 5 Summary of core parameters (Experiment I: Water Hole Size Effect)

Core Name	Case No.	Pattern No (no. of cells)	Measured Level* (cm)	Core Temperature (°C)	Critical Water Level at 20°C (cm)	Calculated β_{eff}
1.83U	1	1 (0)	60.60	15.9	60.734	0.007748
	2	2 (1)	60.43	15.9	60.563	0.007745
	3	3 (3)	61.00	16.0	61.133	0.007737
	4	4 (4)	60.80	16.2	60.926	0.007734
	5	5 (5)	62.65	16.1	62.789	0.007730
	6	6 (8)	65.00	16.2	65.149	0.007708
	7	7 (9)	70.00	16.2	70.180	0.007718
	8	8 (13)	78.03	16.3	78.262	0.007711
	9	9 (20)	103.03	16.6	103.478	0.007701
	10	10 (21)	140.64	16.5	141.720	0.007717

* Height from the lower end of the active fuel zone

Table 6 Reactivity relative to reference core (Experiment I)

Case No. (no. of cells)	Experiment results (ϕ)	Calculation results (17-group model) (ϕ)	Difference between calculation and experimental results (ϕ)
1 (0)	0.0	0.0	0.0
2 (1)	3.74	6.42	2.68
3 (3)	-8.64	-0.29	8.35
4 (4)	-4.17	4.93	9.10
5 (5)	-43.01	-29.73	13.28
6 (8)	-88.23	-69.12	19.11
7 (9)	-171.99	-148.86	23.13
8 (13)	-278.45	-254.85	23.60
9 (20)	-479.33	-454.02	25.31
10 (21)	-616.96	-603.60	13.36

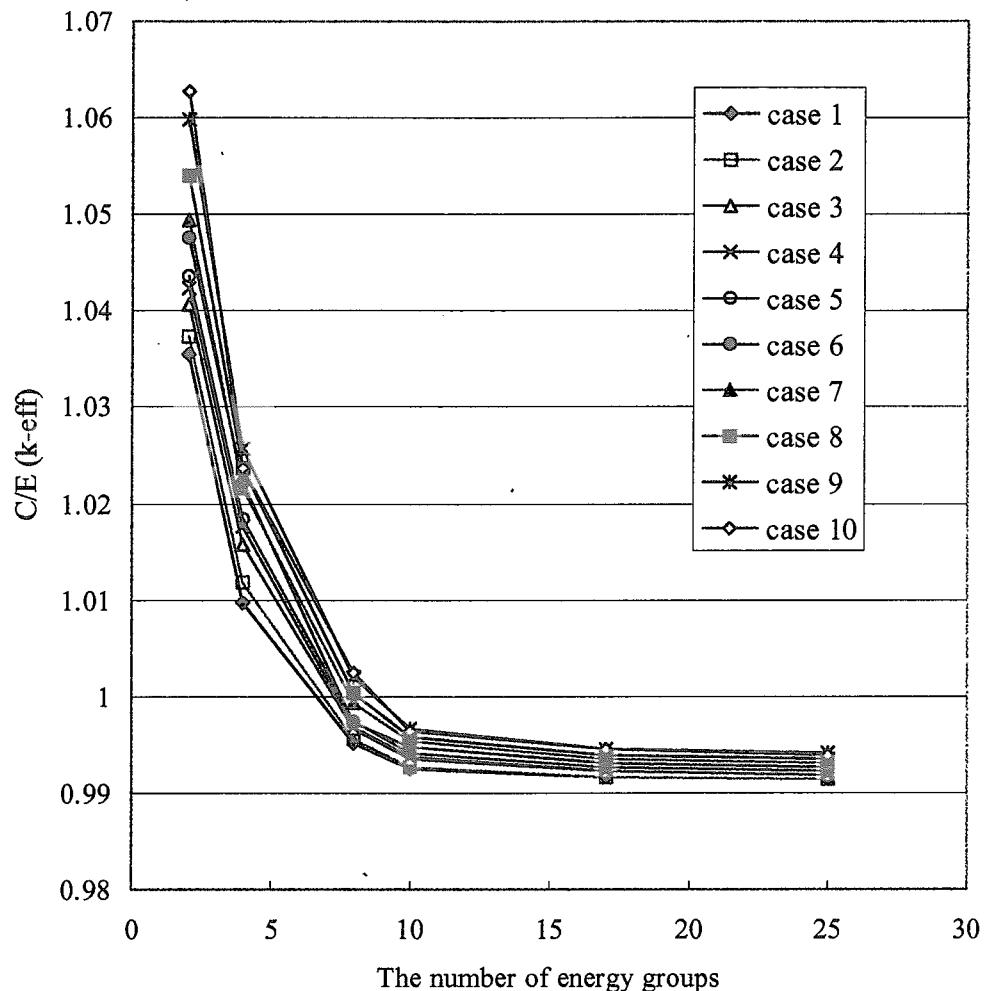


Fig. 4 Energy group effect

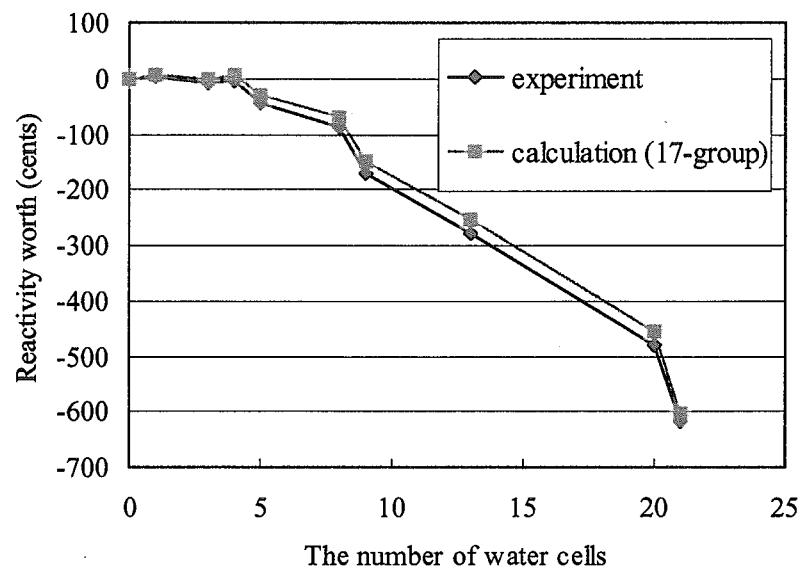


Fig. 5 Reactivity worth of water hole

3.3 Experiment II: water gap effect

The experiment core parameters are shown in Table 7¹⁾. Two cores are selected as the reference cores. One is a 24x24 fuel rod square array with a water-to-fuel volume ratio of 1.5 (pattern 11). The other is a 20x18 fuel rod rectangular array with a water-to-fuel volume ratio of 3.0 (pattern 17). The experiment and calculation results are listed in Table 8 and Fig. 6. Unlike Experiment I, the number of fuel rods is not changed while different size water gaps are introduced to the core as shown in patterns 12 to 20 except 17. Thus, the perturbation reactivity is only caused by the water gap effect. Positive reactivity effects are observed in Cases 12 and 16, which results from the increased moderation into the under-moderated system. On the other hand, a much larger water gap size leads to negative reactivity in the core because of the decrease of interaction effect between two regions divided by the water gap⁶⁾.

We should pay attention to the cross water gap core (Case 16). The one lattice pitch cross water gap introduces considerable positive reactivity (113.48 ‰ in the experiment results) to the core. This is caused by the increment of moderation by the water gaps. From Table 8, the maximum difference between calculation and experimental results is about 44 ‰ in Case 13.

Table 7 Summary of core parameters (Experiment II: Water Gap Effect)

Core Name	Case No.	Pattern No. (no. of gaps)	Measured Level (cm)	Core Temperature (°C)	Critical Water Level at 20°C (cm)	Calculated β_{eff}
1.50U	11	11 (0)	44.01	19.0	44.02	0.007817
	12	12 (1)	42.42	19.0	42.43	0.007765
	13	13 (2)	48.80	19.0	48.82	0.007733
	14	14 (3)	64.05	19.0	64.08	0.007751
	15	15 (4)	100.47	19.1	100.57	0.007812
	16	16 (1×2)	41.79	19.1	41.80	0.007718
3.0U	17	17 (0)	41.79	19.3	41.79	0.007668
	18	18 (1)	46.84	19.8	46.84	0.007628
	19	19 (2)	65.81	19.4	65.82	0.007639
	20	20 (3)	130.77	19.4	130.83	0.007712

Table 8 Reactivity relative to reference core (Experiment II)

Core Name	Case No. (no. of gaps and width(cm))	Experiment results (ϕ)	Calculation results (17-group model) (ϕ)	Differences between calculation and experimental results (ϕ)
1.50U	11 (0, 0.0)	0.0	0.0	0.0
	12 (1, 1.849)	79.83	91.00	11.17
	13 (2, 3.698)	-204.15	-160.13	44.02
	14 (3, 5.547)	-618.88	-588.37	30.51
	15 (4, 7.397)	-1020.2	-1007.03	13.17
	16 (1x2, 1.849x2)	113.48	139.98	26.50
3.0U	17 (0, 0.0)	0.0	0.0	0.0
	18 (1, 2.293)	-233.21	-199.69	33.52
	19 (2, 4.586)	-737.70	-721.22	16.48
	20 (3, 6.879)	-1205.08	-1237.46	-32.38

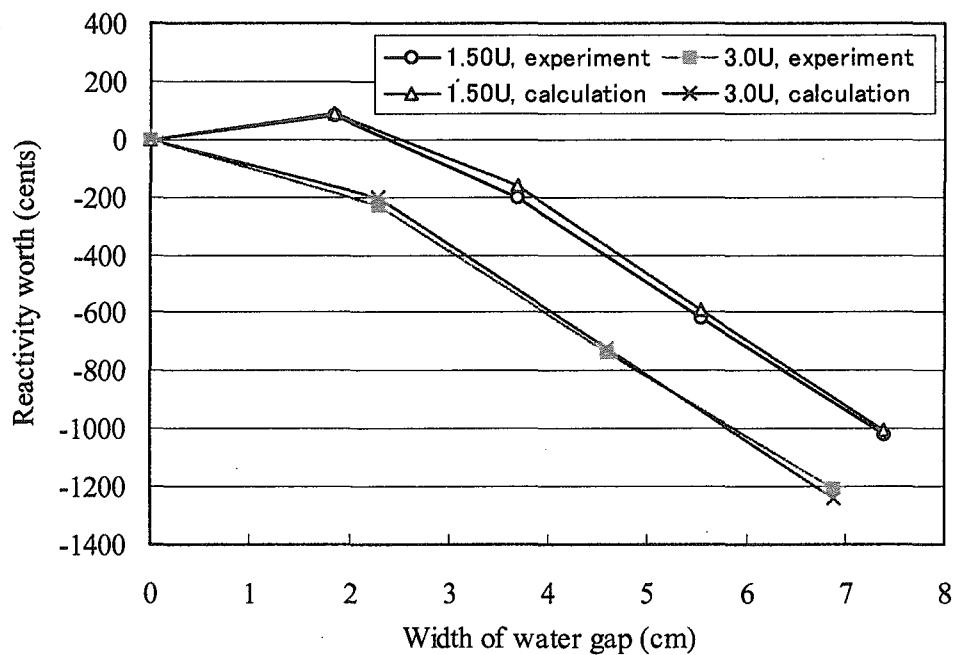


Fig. 6 Water gap reactivity worth

3.4 Experiment III: water-to-fuel volume ratio effect

The experiment core parameters^{1,2)} are listed in Table 9. The 1.50U core (water-to-fuel volume ratio 1.50) is selected as the reference core. The experiment and calculation results are shown in Table 10 and Fig. 7. In this experiments, cases of 1.50U (Case 21 and 24) are chosen as the reference cores and the K-value and the vertical extrapolated length of 1.50U are used for the evaluation of experimental reactivity effect.

The results show that the reactivity introduced to the core increases when the water-to-fuel volume ratio changes from 1.5 to 3.0 under the condition that the number of fuel rods is unchanged.

From Table 10, the maximum difference between calculation and experimental results is about 39 % in Case 26.

Table 9 Summary of core parameters^{1,2)} (Experiment III: Water to Fuel Volume Ratio Effect)

Core Name	Case No.	Pattern No.	Measured Level (cm)	Core Temperature (°C)	Critical Water Level at 20°C (cm)	Calculated β_{eff}
1.50U	21	1	99.98	15.1	99.45	0.007734
1.83U	1	1	60.12	17.0	60.38	0.007635
2.48U	22	1	44.51	15.5	44.55	0.007490
3.0U	23	1	41.51	16.5	41.54	0.007404
1.50U	24	21	72.86	14.2	73.73	0.007753
1.83U	25	21	51.57	17.6	51.65	0.007654
2.48U	26	21	40.41	15.5	40.44	0.007509

Table 10 Reactivity relative to the reference core (Experiment III)

Pattern No.	Case No. (water-to-fuel volume ratio)	Experiment results (ϕ)	Calculation results (17-group model) (ϕ)	Difference between calculation and experimental results (ϕ)
1	21 (1.50)	0.0	0.0	0.0
	1 (1.83)	471.71	465.12	-6.59
	22 (2.48)	988.41	954.05	-34.36
	23 (3.00)	1141.09	1114.1	-26.99
21	24 (1.50)	0.0	0.0	0.0
	25 (1.83)	471.54	456.91	-14.63
	26 (2.48)	965.55	929.66	-35.89

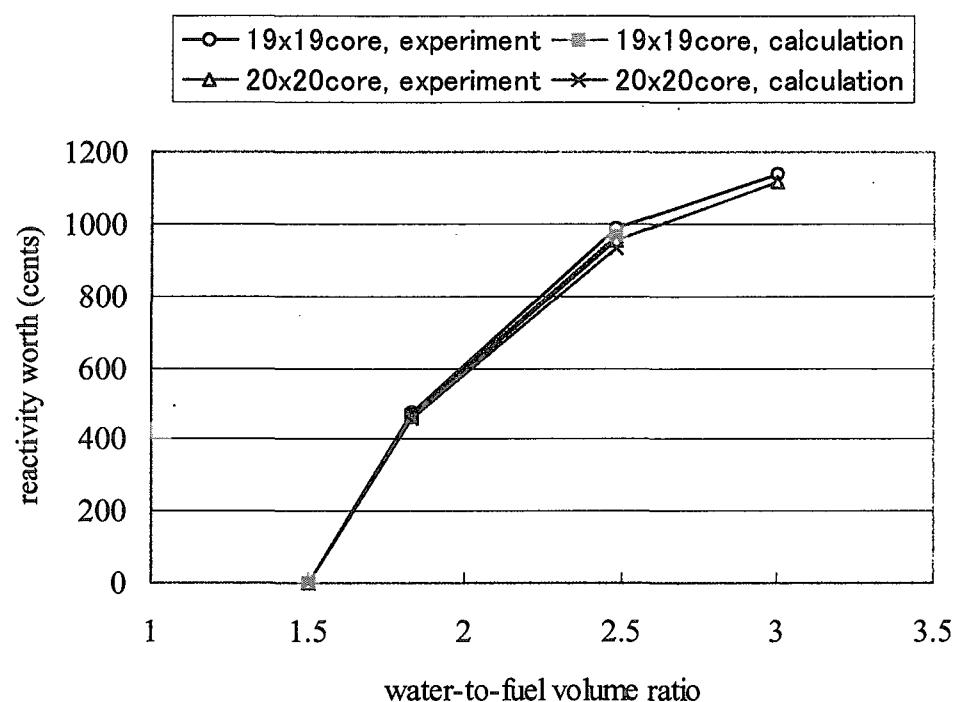


Fig. 7 Water-to-fuel volume ratio reactivity worth

3.5 Experiment IV: non-uniform arrangement effect

The experiment core parameters are listed in Table 11⁷⁾. The core is divided by two regions shown in Fig. 8: center region (region 1) and side region (region 2). The pattern 22 and pattern 23 show the typical experiment core configurations for average loading ratio of 5/6 and 2/3, respectively. No benchmark calculation is performed due to the complicated fuel rod arrangement for this experiment.

When we change the fuel rod loading ratio C_i and the x-directional dimension X_i of each region under the condition that the horizontal core dimensions (X and Y) and the total number of fuel rods are constant, the additional reactivity is introduced to the core owing to the non-uniform arrangement effect of water moderator. The experiment results are shown in Table 12, Fig. 9 and Fig. 10. The various arrangement of water cells in the core lead to the variation of reactivity because of the water cell position effect and the interaction effect among the water cells.

For further explanation, the calculations of one water cell position effect on reactivity are carried out. The reference core is shown in pattern 1 (Appendix A), where the figures show the position of water cell. The results are shown in Table 13 and Fig. 11. The water cell effect changes from positive to negative for the position change from the core center to periphery. This is one reason why the cores having water cells around the core center give a larger reactivity effect compared with those having water cells around the core periphery, as seen in Fig. 9. However, too many water cells in the central region result in a negative effect as seen in Fig. 10.

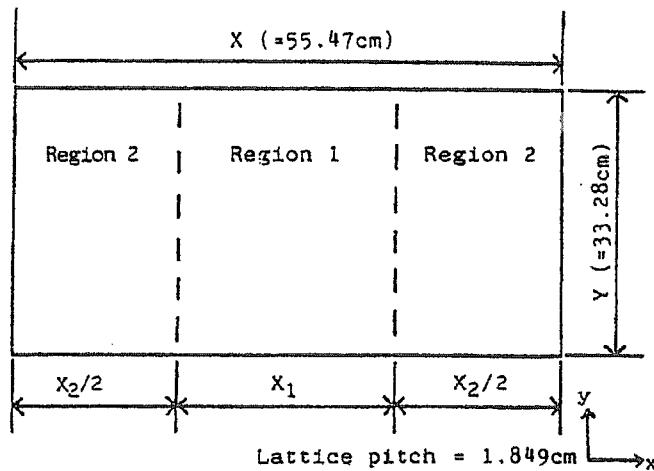


Fig. 8 General view of two-region core (Experiment IV)

Table 11 Summary of core parameters ⁷⁾ (Experiment IV: Non-uniform Arrangement Effect)

Core Name	Case No.	Pattern No.	C	C ₁	C ₂	X ₁ (cm)	X ₂ (cm)	Measured Water Level (cm)
1.50U	27	-	5/6	-	5/6	0	55.47	46.02
	28	-	5/6	1	4/5	9.25	46.22	46.78
	29	22	5/6	1	3/4	18.49	36.98	48.26
	30	-	5/6	1	2/3	27.74	27.73	50.06
	31	-	5/6	1	1/2	36.98	18.49	52.65
	32	-	5/6	1	3/8	40.68	14.79	55.56
	33	-	5/6	4/5	1	46.22	9.25	45.57
	34	-	5/6	3/4	1	36.98	18.49	45.91
	35	-	5/6	2/3	1	27.73	27.74	47.86
	36	-	5/6	1/2	1	18.49	36.98	54.67
	37	-	2/3	-	2/3	0	55.47	48.27
	38	-	2/3	1	3/5	9.25	46.22	51.33
	39	-	2/3	4/5	3/5	18.49	36.98	48.96
	40	-	2/3	1	1/2	18.49	36.98	55.53
	41	-	2/3	1	3/8	25.89	29.58	67.78
	42	-	2/3	3/5	1	46.22	9.25	51.90
	43	-	2/3	3/5	4/5	18.49	36.98	51.47
	44	23	2/3	1/2	1	18.49	36.98	60.89

C: Average loading ratio

C_i: Loading ratio of the i-th region (i=1, 2)X_i: x-directional core dimension of the i-th region (i=1, 2)

Table 12 Reactivity relative to reference core (Experiment IV)

Average loading ratio. C	Case No.	Experiment results (ϕ)
5/6	27(reference)	0.0
	28	-32.30
	29	-91.75
	30	-158.46
	31	-244.93
	32	-330.57
	33	19.72
	34	4.78
	35	-76.11
	36	-305.56
2/3	37(reference)	0.0
	38	-110.04
	39	-26.25
	40	-229.28
	41	-502.30
	42	-128.82
	43	-114.70
	44	-369.73

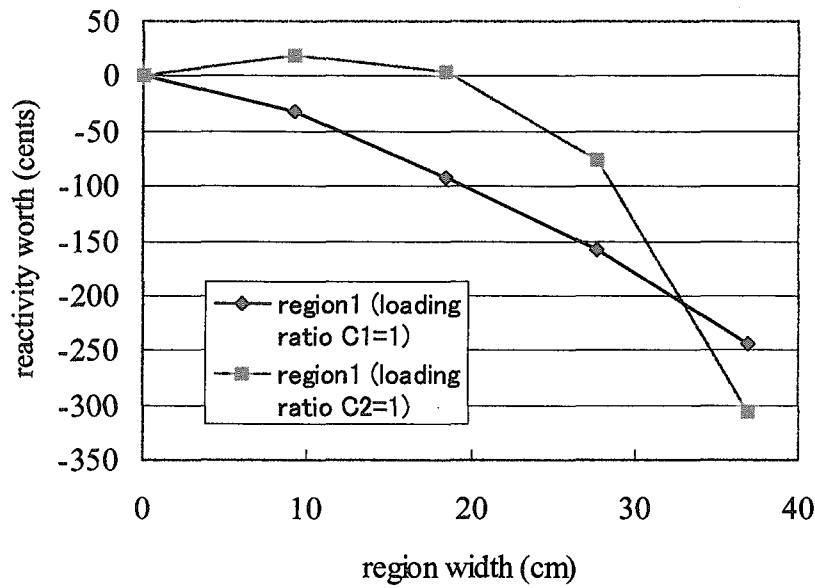


Fig. 9 Non-uniform arrangement effect vs. region width ($C=5/6$)

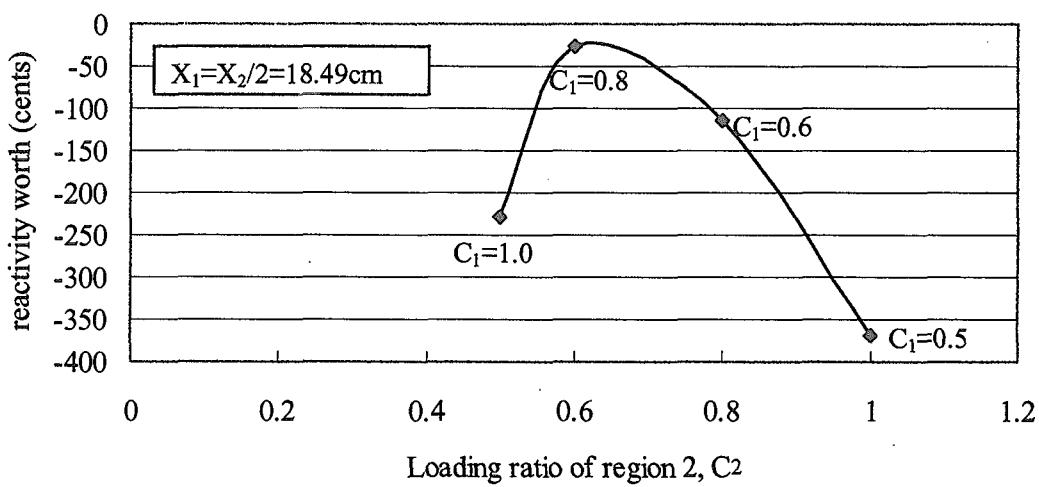


Fig. 10 Non-uniform arrangement effect vs. loading ratio of region 2 ($C=2/3$)

Table 13 Dependence of water cell worth on position
(Calculation Results)

Position	Reactivity $\rho_1 (\phi)$	Calculated β_{eff}
P0*	6.42	0.007748
P1	6.29	0.007748
P2	6.10	0.007747
P3	5.83	0.007747
P4	5.46	0.007748
P5	5.01	0.007748
P6	4.40	0.007748
P7	3.43	0.007749
P8	1.46	0.007749
P9	-4.73	0.007751

*The figure represents the distance from the core center by lattice pitch

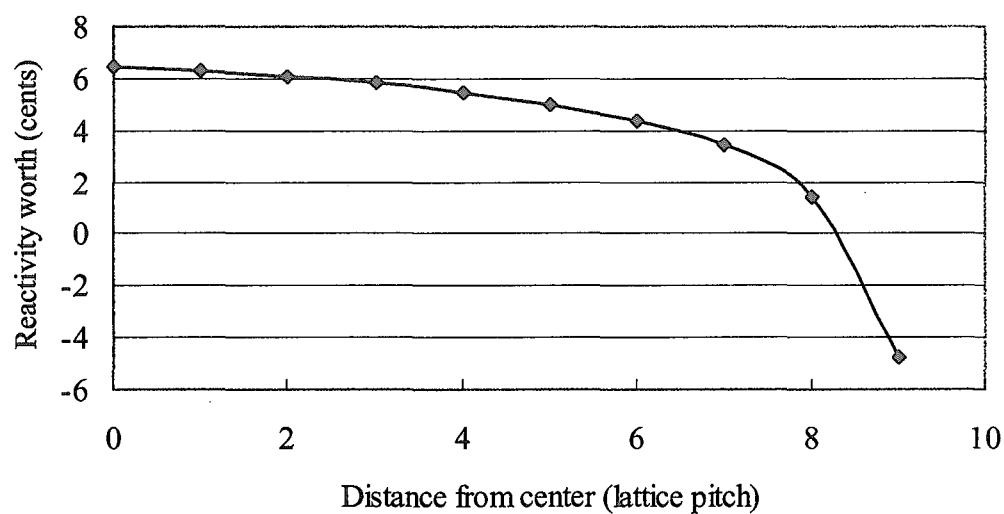


Fig. 11 Water hole reactivity worth vs. position

4. Discussions

As shown above, we study on the reactivity variation with the perturbation in the core by experiment and calculation methods. There are uncertainties or errors in the both methods^{2,8)}.

The main error sources of experiment results include the critical water level measurement uncertainty and K -value uncertainty. The effect of about 0.08% in critical core size measurement should be included as the uncertainty of k_{eff} value as Reference 2 reported. However, the uncertainty is limited within 0.01% for perturbation reactivity measurement by the water level worth method. We treat the buckling-reactivity conversion factor K as a constant at converting the variation of critical water level to reactivity. However, K -value has an error of about 1%⁴⁾ and will slightly change when some perturbations are introduced to the core, such as water holes, water gaps, etc.

The main error sources of calculation results include the uncertainties in nuclear data library, fuel rod characterization, benchmark model and calculation method. As reported in Reference 2, the effect of 0.16% by uncertainty of the fuel rod characterization should be included in the uncertainty of k_{eff} value. And the effect of about 0.20% is introduced to k_{eff} value owing to the uncertainty in the vertical extrapolated length²⁾ used in the two-dimensional model chosen in the present calculations. It is difficult to determine the uncertainty magnitude of nuclear data library and calculation method. The calculation results listed in Table 6 show that the converged k_{eff} value slightly underestimates the experimental one. This fact implies that the data library JENDL3.3 introduces negative systematic errors to the calculation results of present experiment core with 2.6 wt.% UO₂.

Concerning the calculation method errors, we study the energy group effect on the k_{eff} value. Table 6 and Fig. 4 show that the fewer group model introduces higher positive errors to the results. We can understand the fact that the 8-group model results are closer to critical k_{eff} value, unity, because the positive errors of energy group model and the negative errors of data library are partly canceled out. In this report, we treat the converged results of 17-group model as the benchmark calculation results. It is popular in reactor design and fuel management of NPP to choose the 2-group diffusion method which is accurate enough to meet need of nuclear engineering. However, as shown in Table 6 and Fig. 4, the calculation results of 2-group diffusion model are not satisfactory for a small size core such as TCA because the space dependent effect is considerable.

In the spectrum calculation at homogenization, the effect of finite medium should be taken into account. According to the age theory⁹⁾, the neutron flux spatial distribution does not depend on the energy of neutrons in the bare critical reactor, but in the reflected system such as the TCA core, it is difficult to separate the space and energy distribution of neutron fluxes. However, if the region is sufficiently large and far from the boundaries, the neutron energy spectrum is space independent. As an example, the calculated flux distributions of the 19x19 core with 20 water cells in each energy group are presented in Appendix B. In the present calculation, we select the one-point bare reactor model to provide the neutron spectrum for collapsing the cross sections into fewer-group ones which are applied to the core calculation.

This kind of collapsing into 2-group cross sections cannot serve the space dependent spectrum to produce the satisfactory results in the core calculation. But the situation is quite different for the model with more than 17 energy groups. The neutron spectrum used for collapsing has slight effect on the results. For TCA, the 17-group diffusion model is acceptable as the benchmark calculation model and shows a good agreement with the experimental results within a few dozen cents in reactivity effect of volume fraction and non-uniform arrangement of water moderator.

5. Conclusions

According to above experiment and calculation results, the followings are summarized:

- (1) The positive reactivity can be introduced to the core operated in the under-moderated condition when water cells or water gaps are formed by withdrawing fuel rods.
- (2) The considerable positive reactivity can be introduced to the core by inserting fuel rods in the center of larger water hole.
- (3) When a lattice pitch of the core is enlarged with keeping the total number of fuel rods, a considerably large positive reactivity can be introduced.
- (4) Mainly due to the positive reactivity effect of water regions, the non-uniform arrangement effects on the reactivity are complicated and remarkable. It is important to determine the tendency of reactivity variation when withdrawing or inserting fuel rods, by considering the positive effect of water moderator in the concerning cores.
- (5) The 17-group diffusion model is acceptable for TCA benchmark calculations.

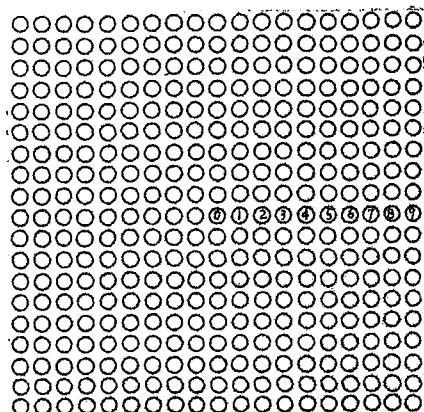
Acknowledgement

The first author would like to thank Dr. Takamasa Mori and Mr. Takenori Suzuki for continued encouragement and support. Thanks are due to Mr. Keisuke Okumura and Dr. Ken Nakajima for valuable discussions and suggestions. Thanks are also due to all members of the TCA Laboratory for kind help during the research at JAERI.

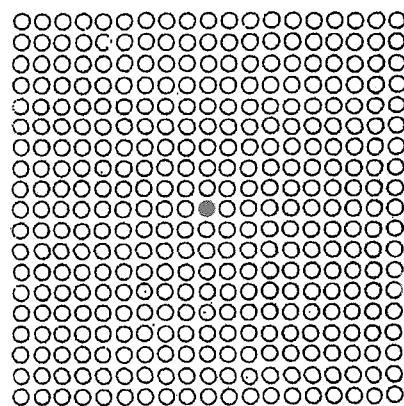
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- 1) H. Tsuruta, et al., "Critical size of light-water moderated UO₂ and PuO₂- UO₂ lattices", JAERI 1254, (1978).
- 2) Y. Miyoshi, et al., "Critical arrays of low-enriched UO₂ fuel rods with water-to-fuel volume ratio ranging from 1.5 to 3.0", International criticality safety benchmark evaluation project (ICSBEP), NEA/NSC/DOC/(95)03/VI, LEU-COMP-THERM-006, Sept. 2002 edition, (2002)..
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- 4) T. Suzuki, et al., "Precise determination of β_{eff} for water-moderated U and U-Pu cores by a method using buckling coefficient of reactivity", Proc. ICNC' 99, Versailles, France, p386 (1999).
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- 9) Allan F. Henry, "Nuclear-reactor analysis", the MIT Press, USA, (1975).

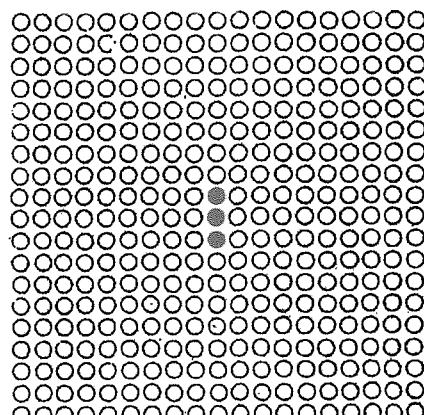
Appendix A Core Patterns



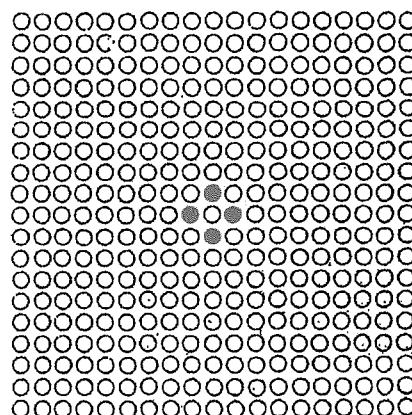
1 (19x19)



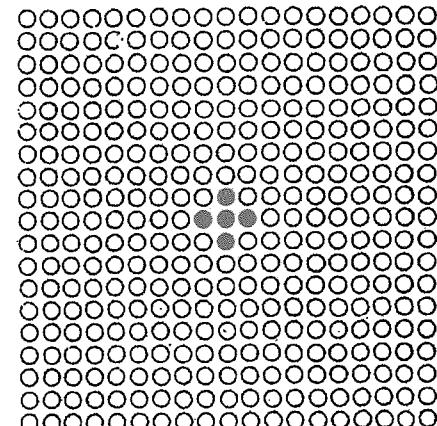
2 (19x19 one water cell)



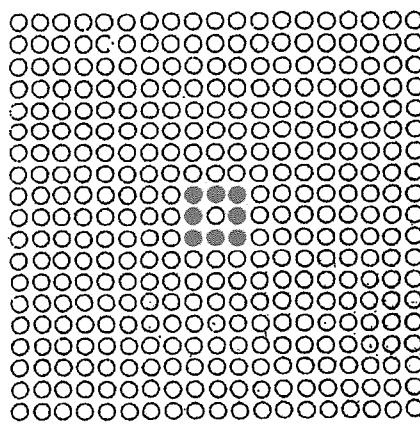
3 (19x19 3 water cells)



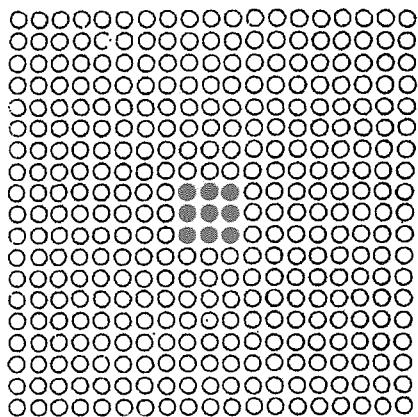
4 (19x19 4 water cells)



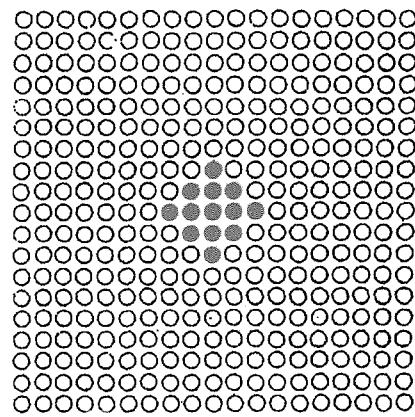
5 (19x19 5 water cells)



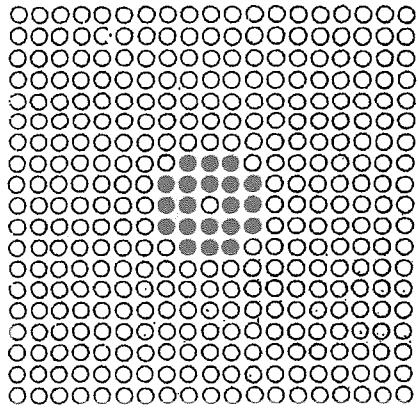
6 (19x19 8 water cells)



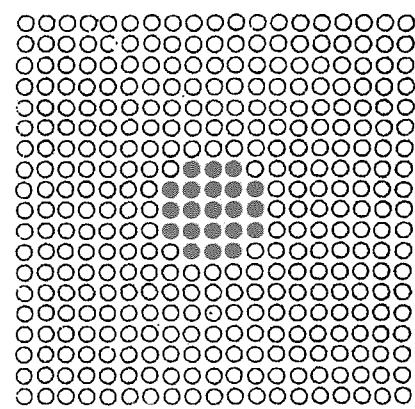
7 (19x19 9 water cells)



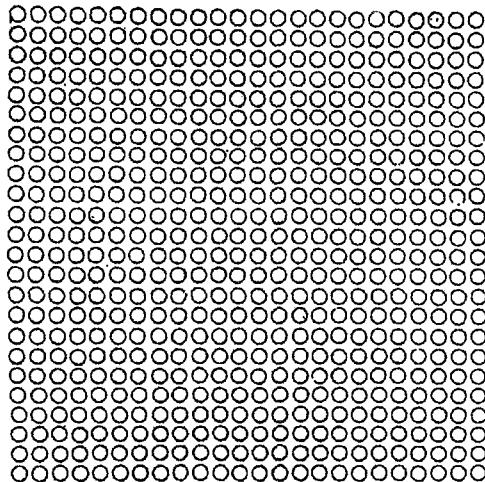
8 (19x19 13 water cells)



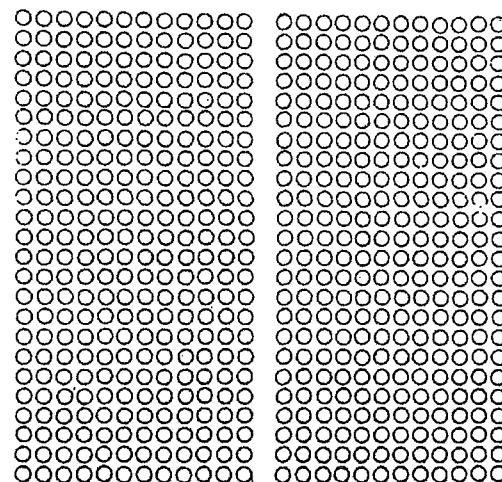
9 (19x19 20 water cells)



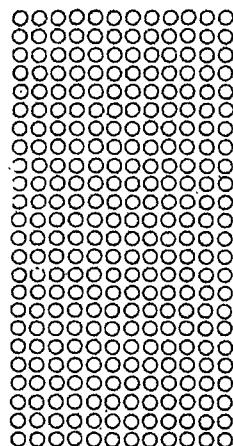
10 (19x19 21 water cells)



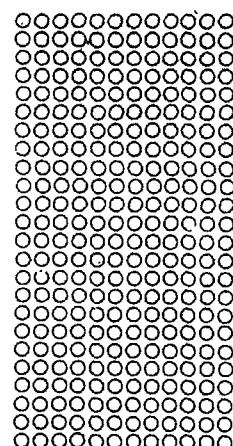
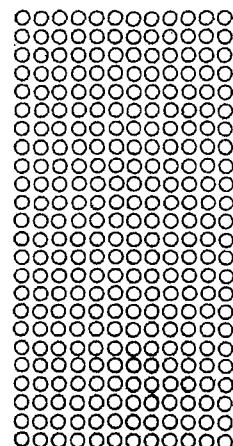
11 (24x24)



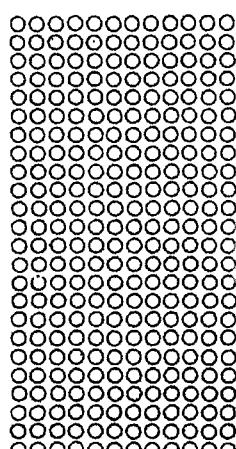
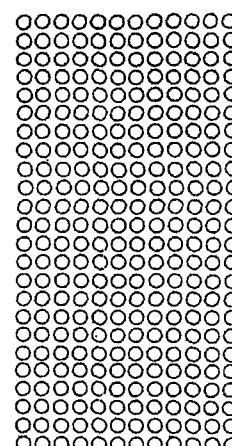
12 (24x24 one pitch water gap)



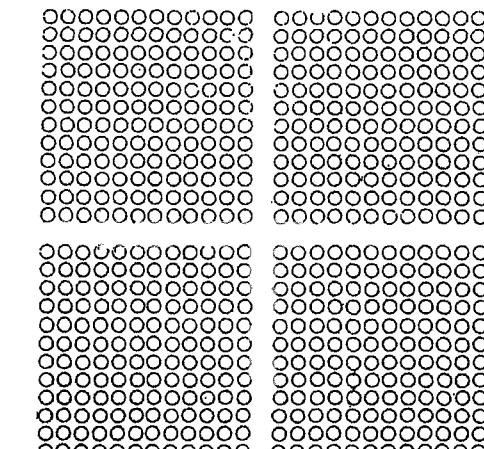
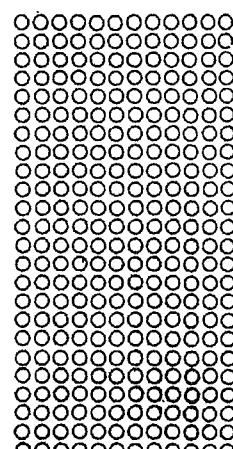
13 (24x24 2 pitch water gap)



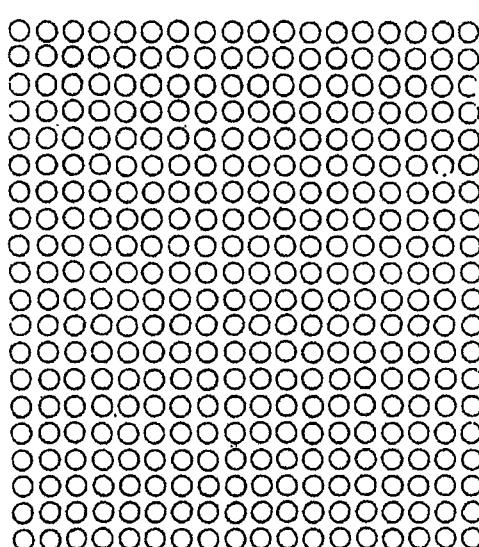
14 (24x24 3 pitch water gap)



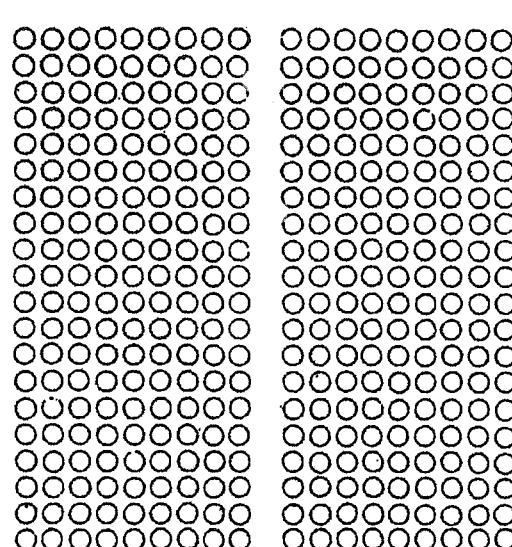
15 (24x24 4 pitch water gap)



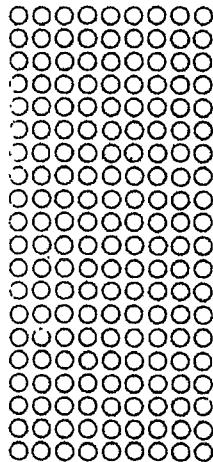
16 (24x24 one pitch cross water gap)



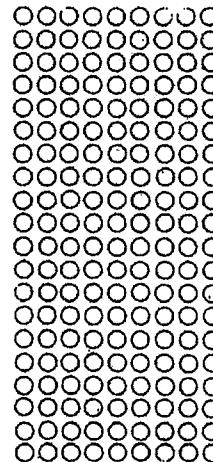
17 (20x18)



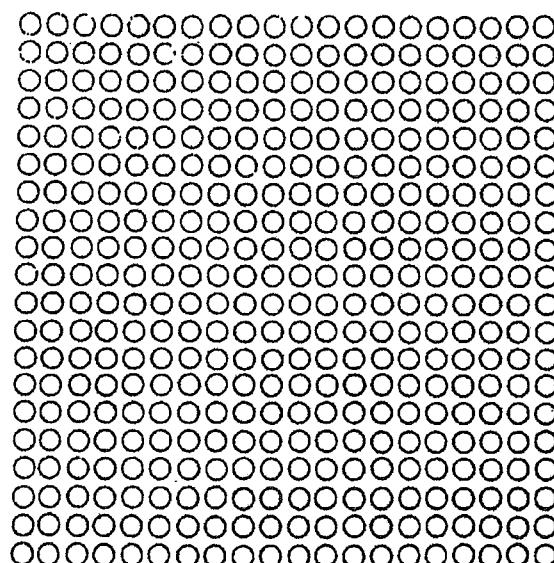
18 (20x18 one pitch water gap)



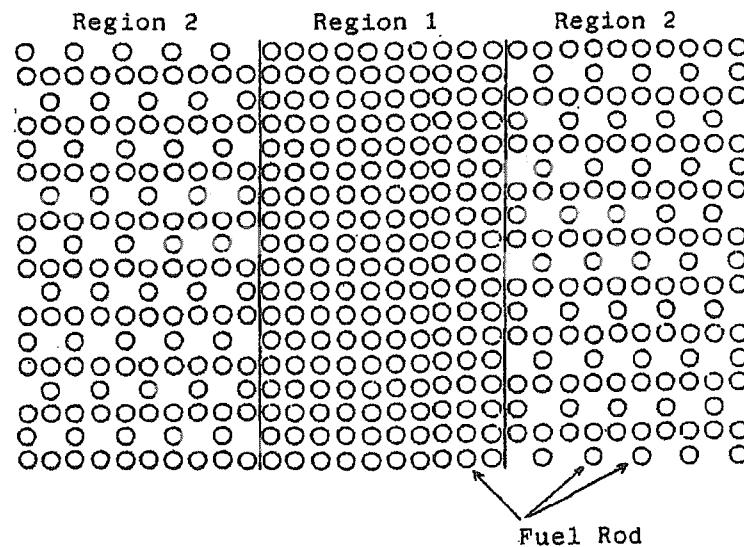
19 (20x18 2 pitch water gap)



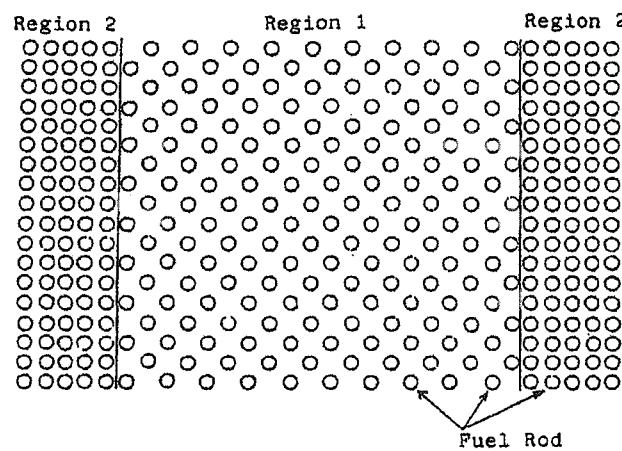
20 (20x18 3 pitch water gap)



21 (20x20)

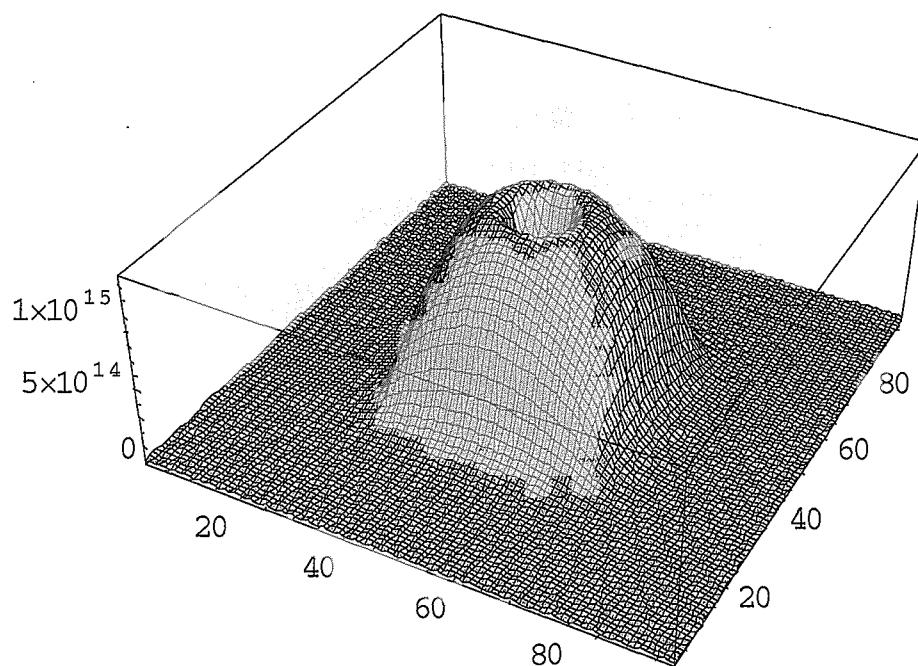


22 (from Reference 7)

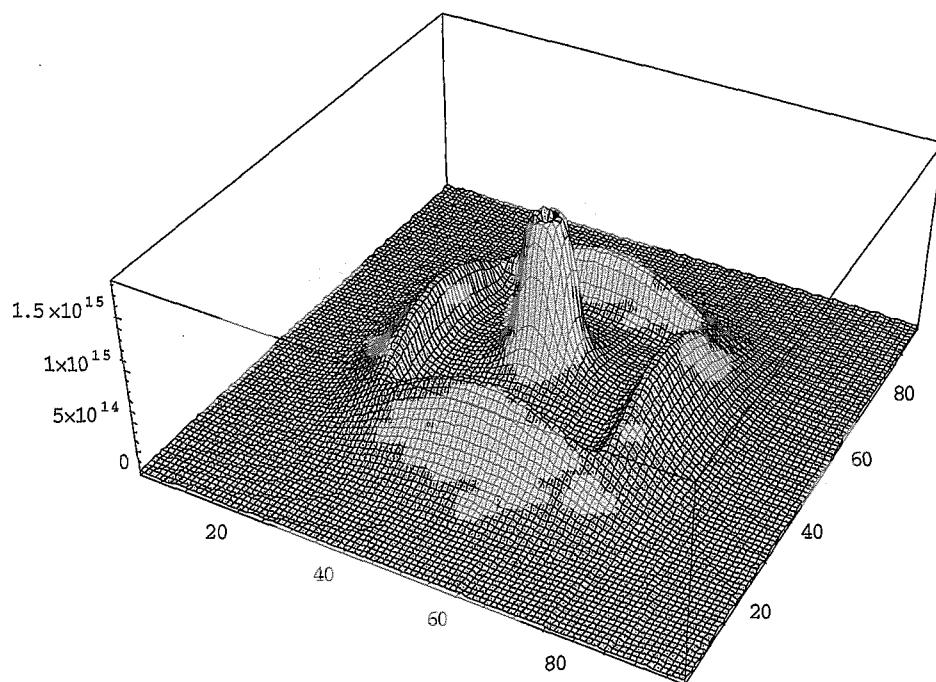


23 (from Reference 7)

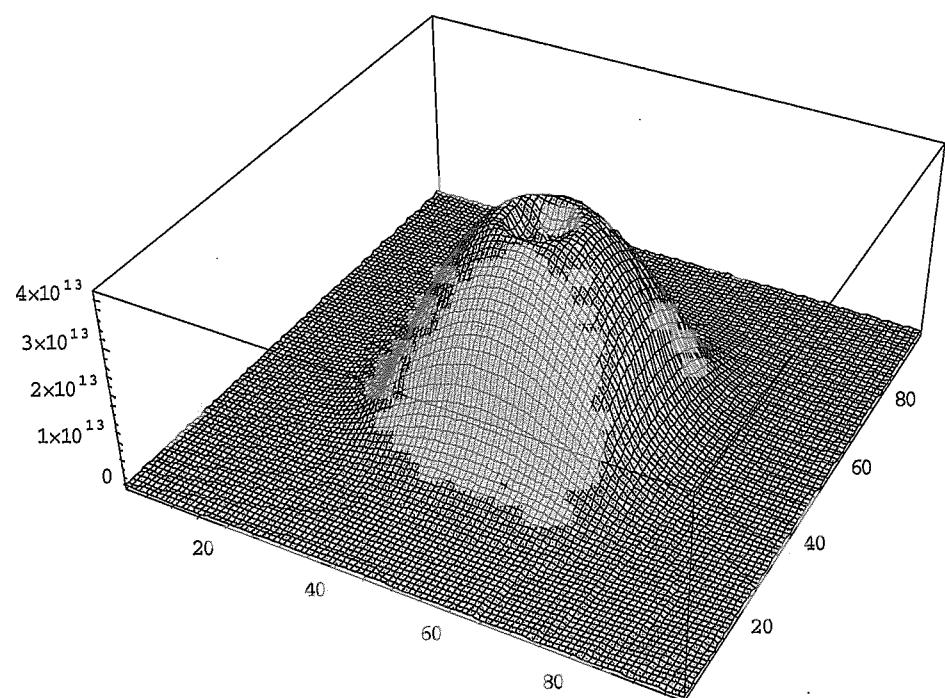
**Appendix B Calculated Flux Distribution
(19x19 core with 20 water cells, core pattern 9)**



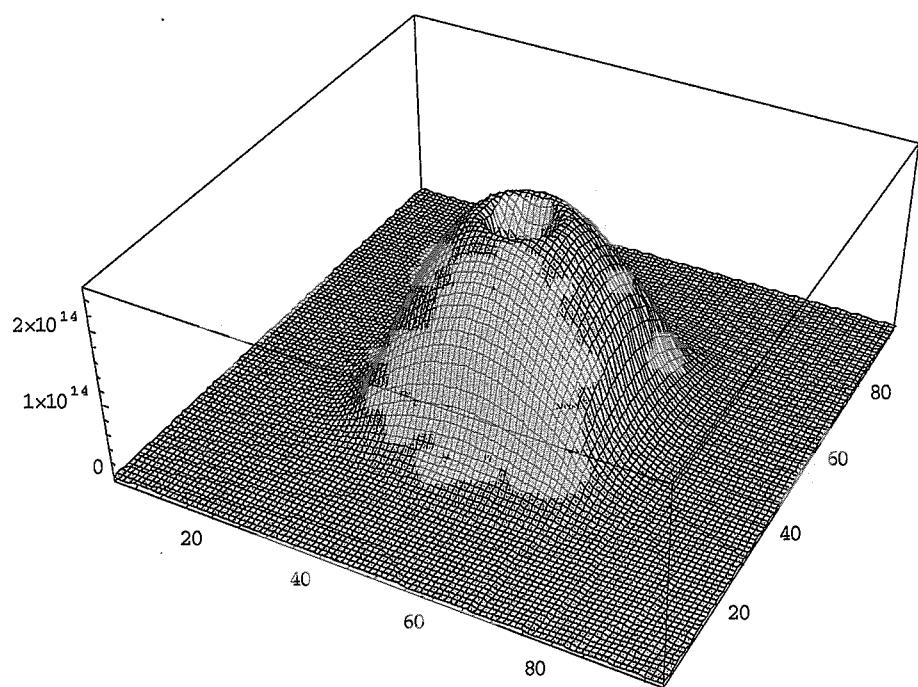
2-energy-group model (first group)



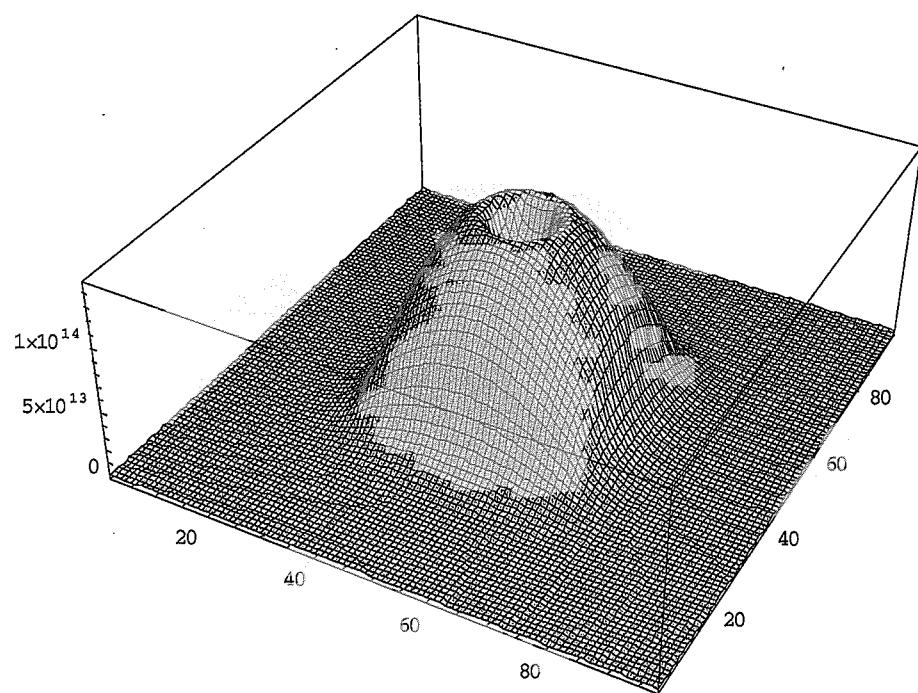
2-energy-group model (second group)



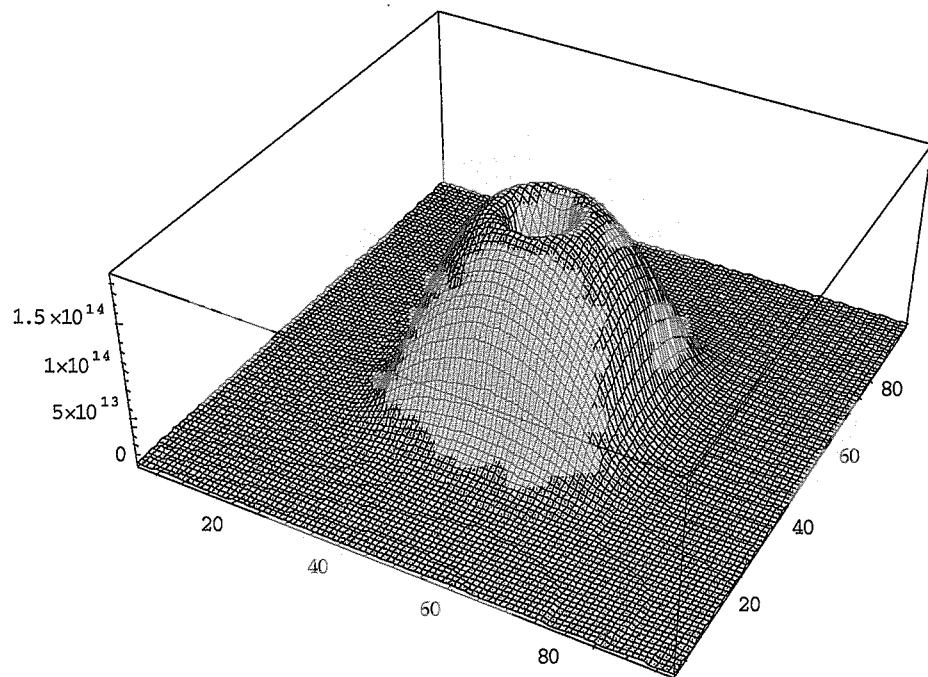
17-energy-group model (first group)



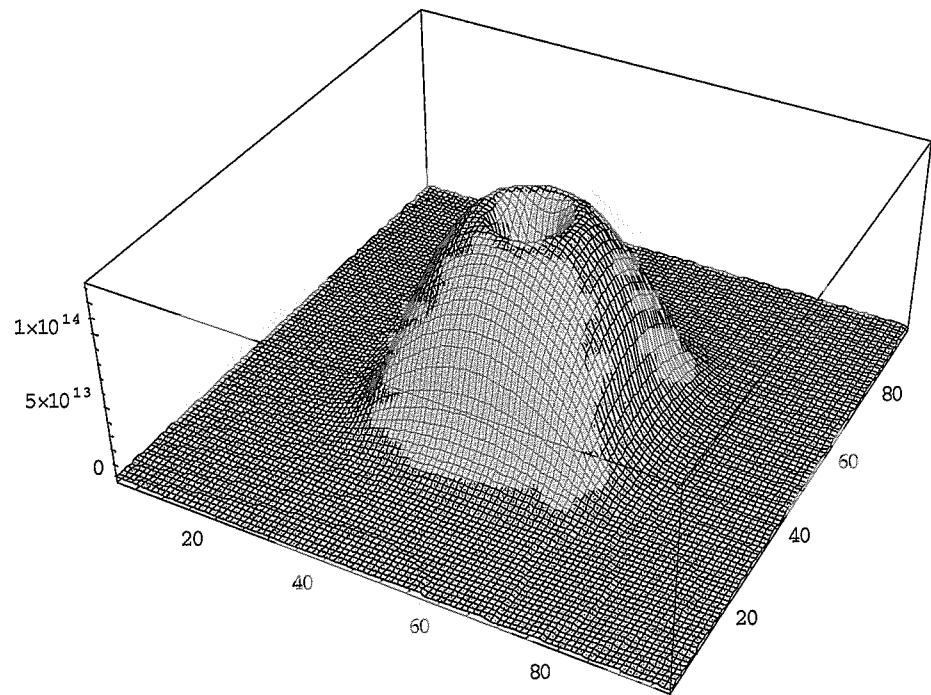
17-energy-group model (second group)



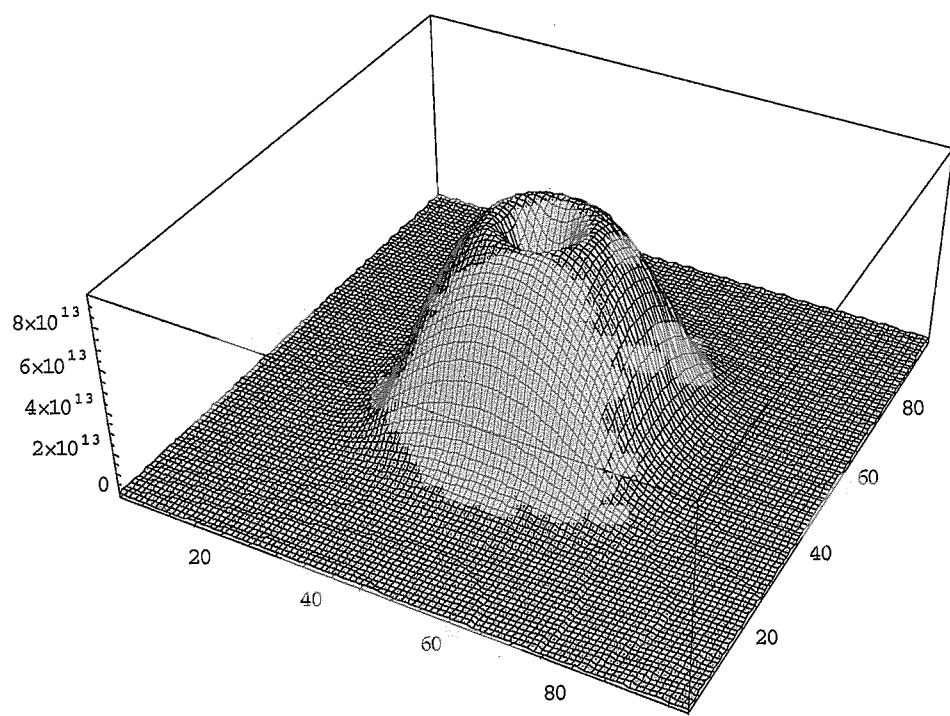
17-energy-group model (third group)



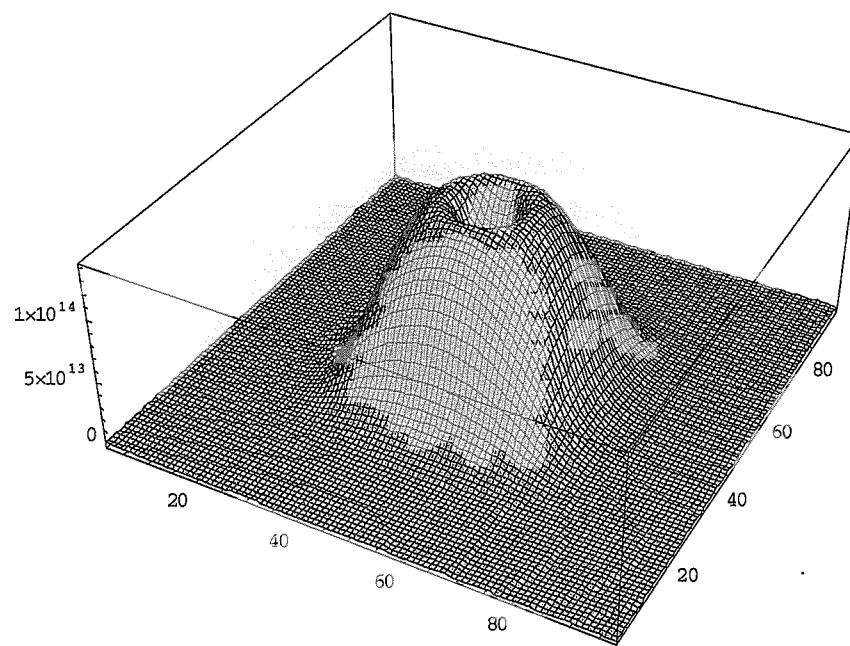
17-energy-group model (4th group)



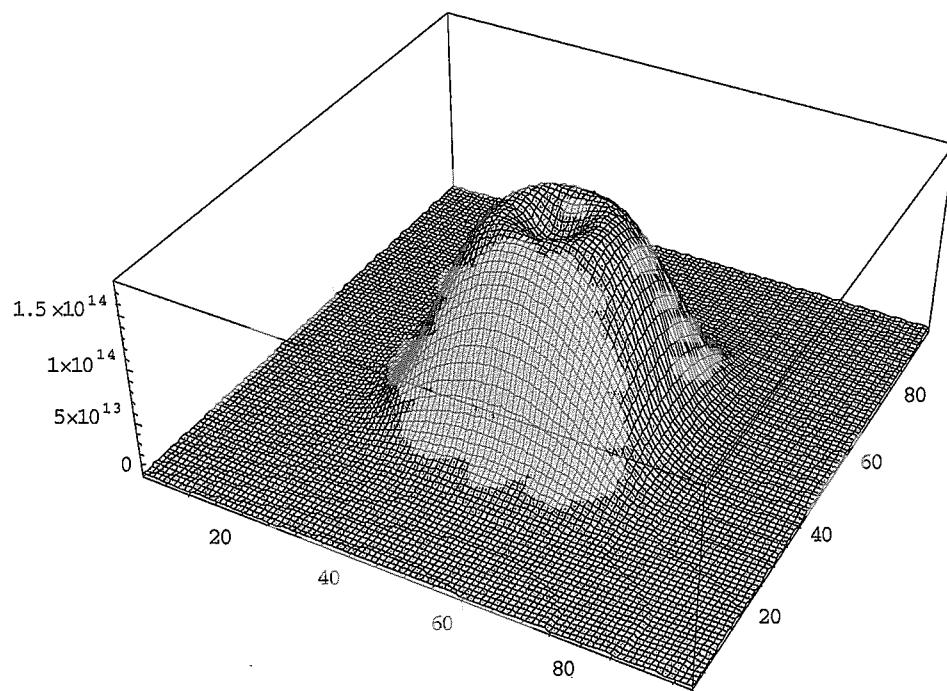
17-energy-group model (5th group)



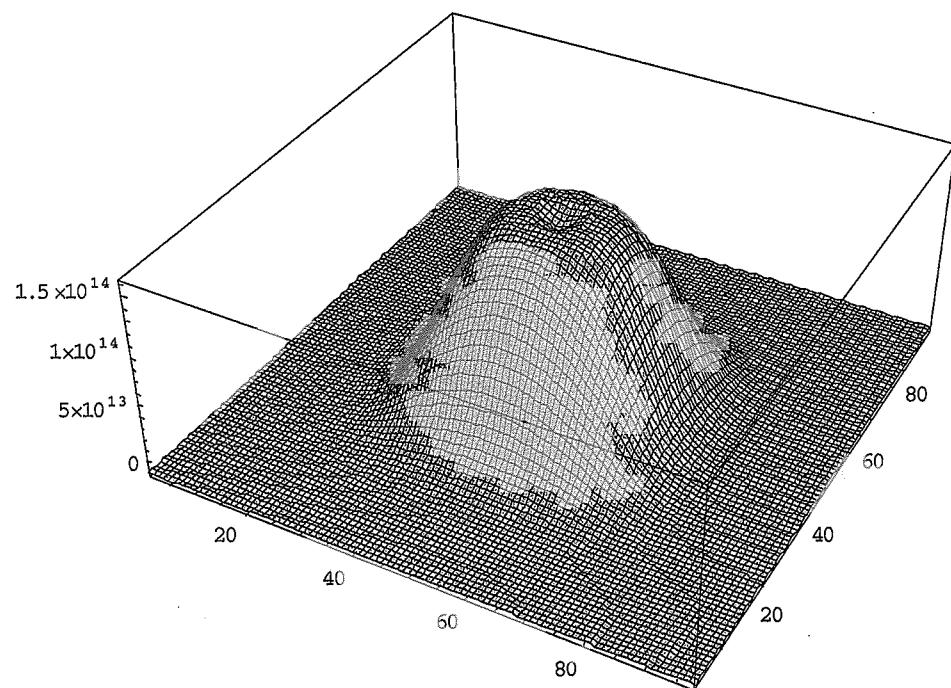
17-energy-group model (6th group)



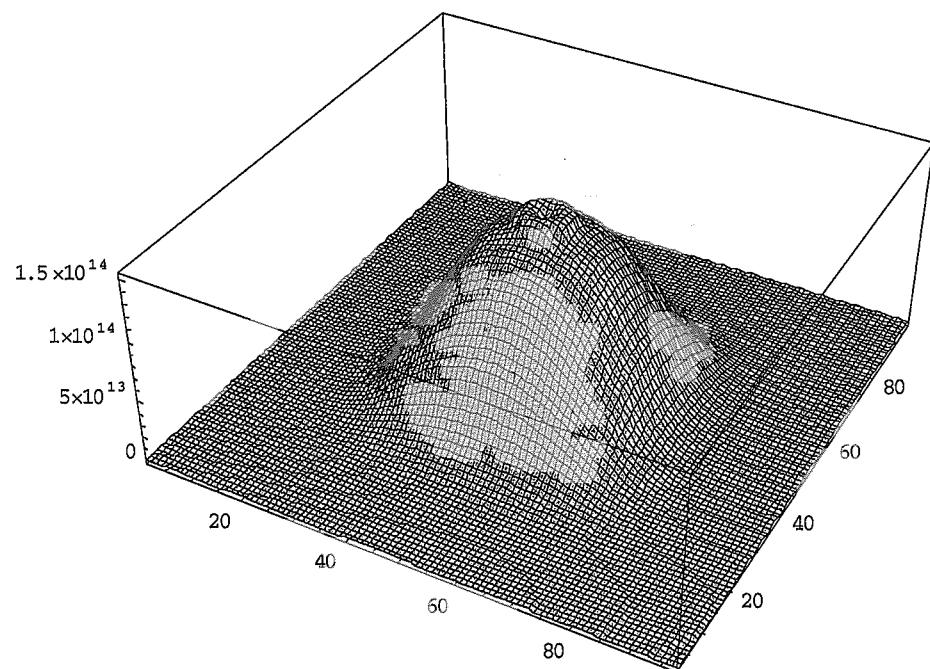
17-energy-group model (7th group)



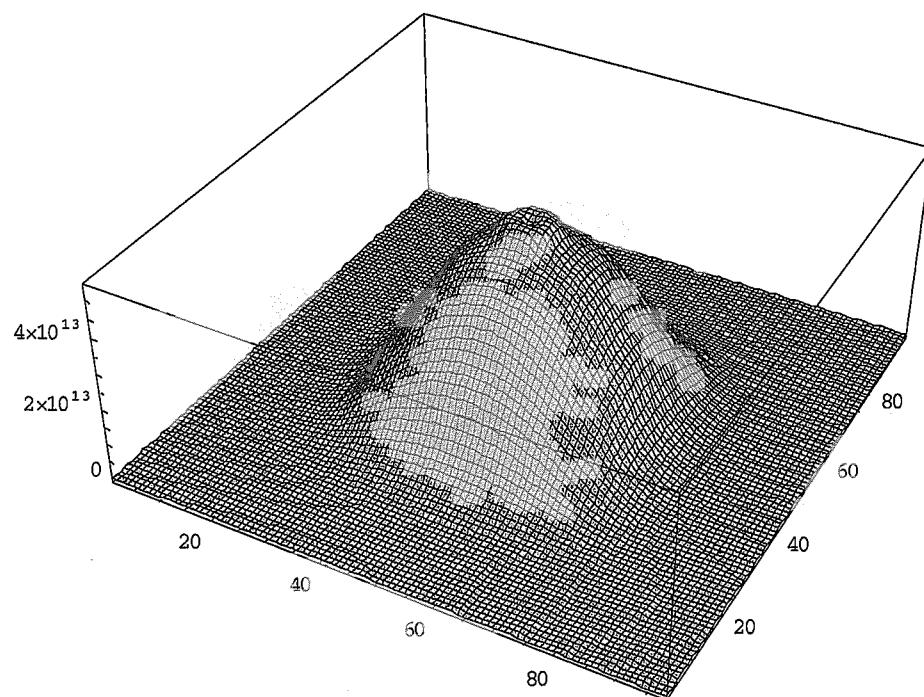
17-energy-group model (8th group)



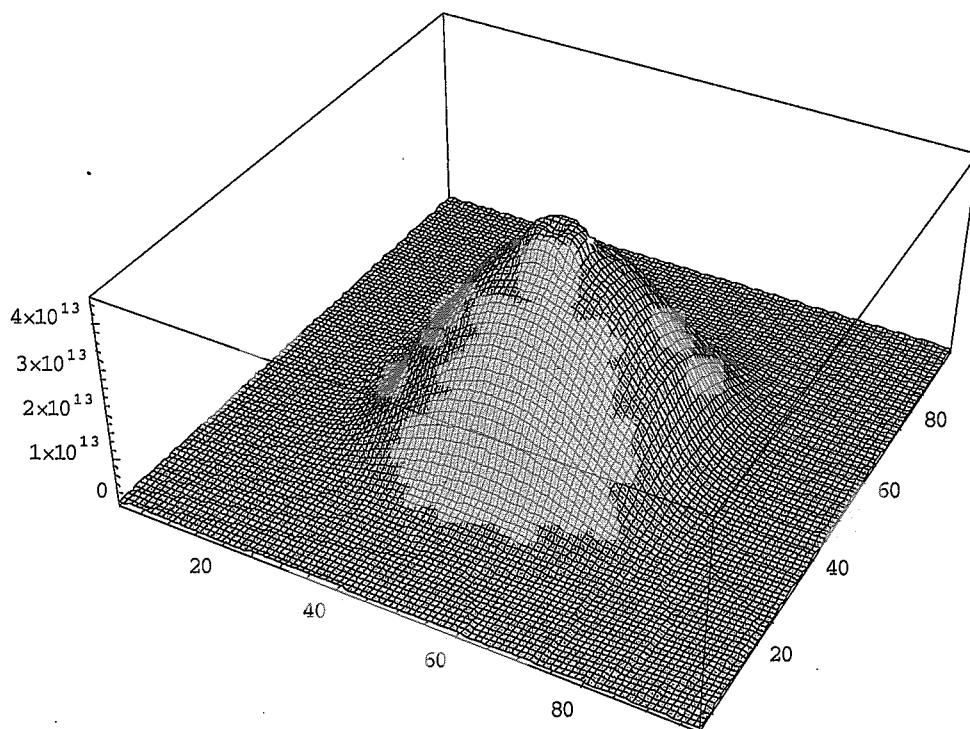
17-energy-group model (9th group)



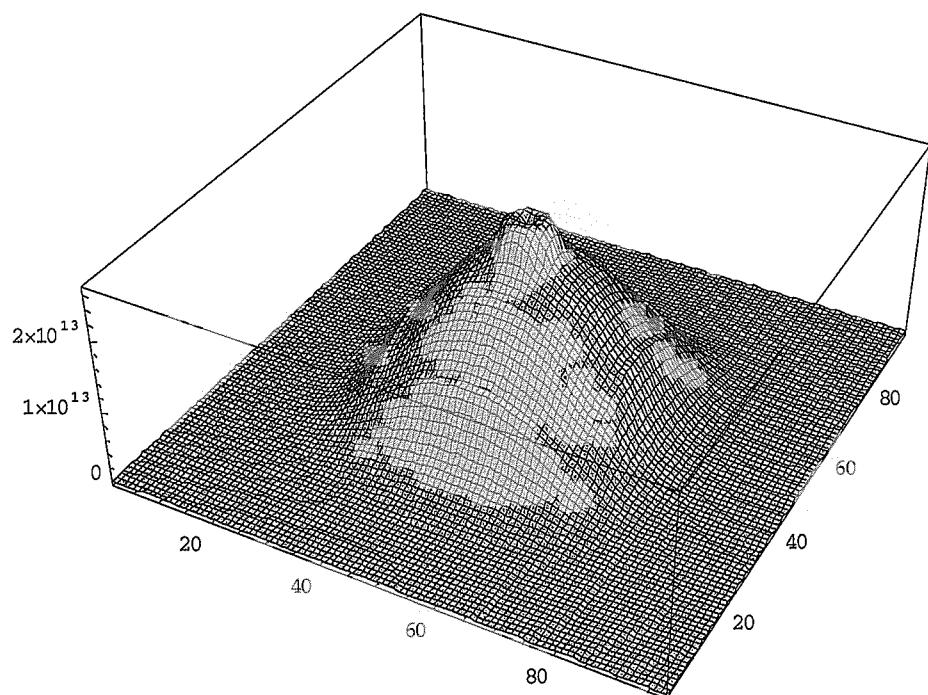
17-energy-group model (10th group)



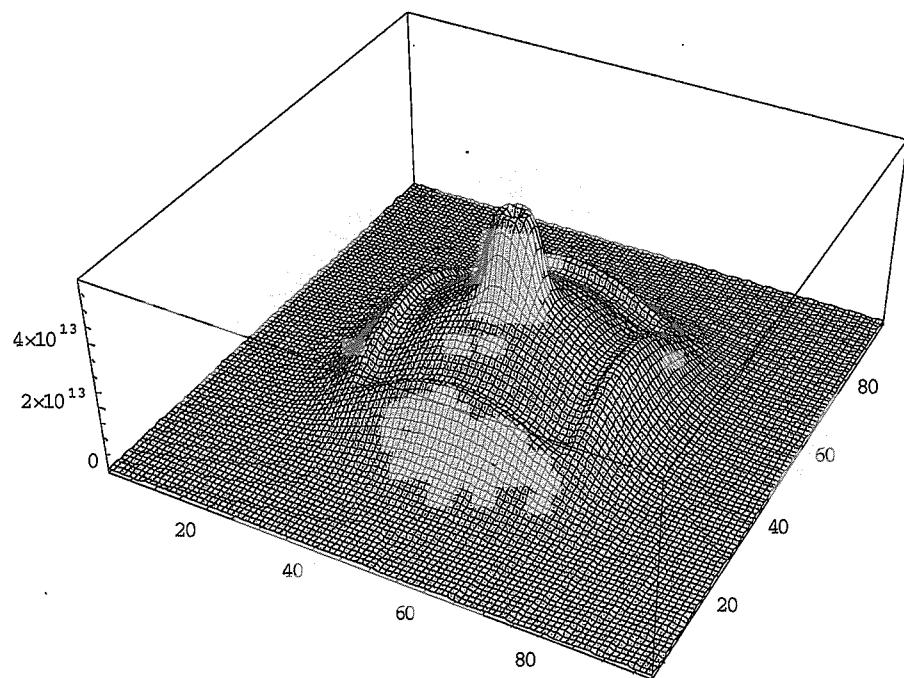
17-energy-group model (11th group)



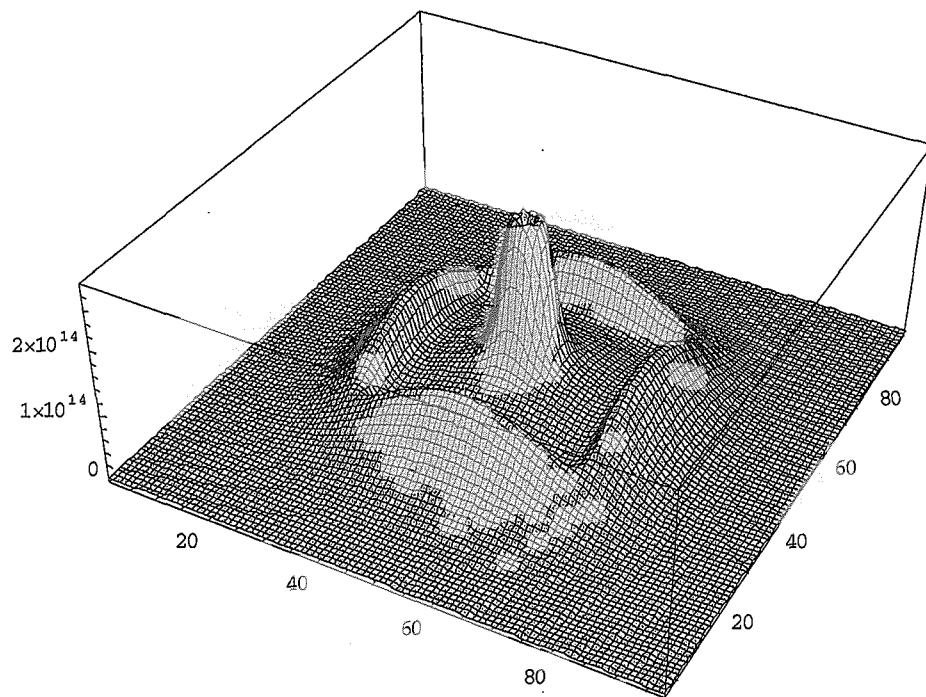
17-energy-group model (12th group)



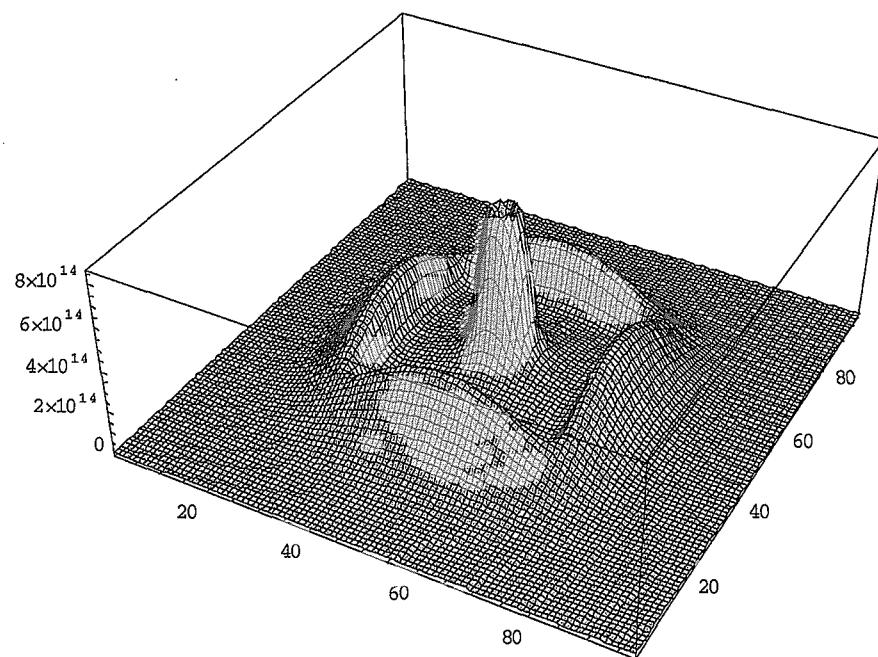
17-energy-group model (13th group)



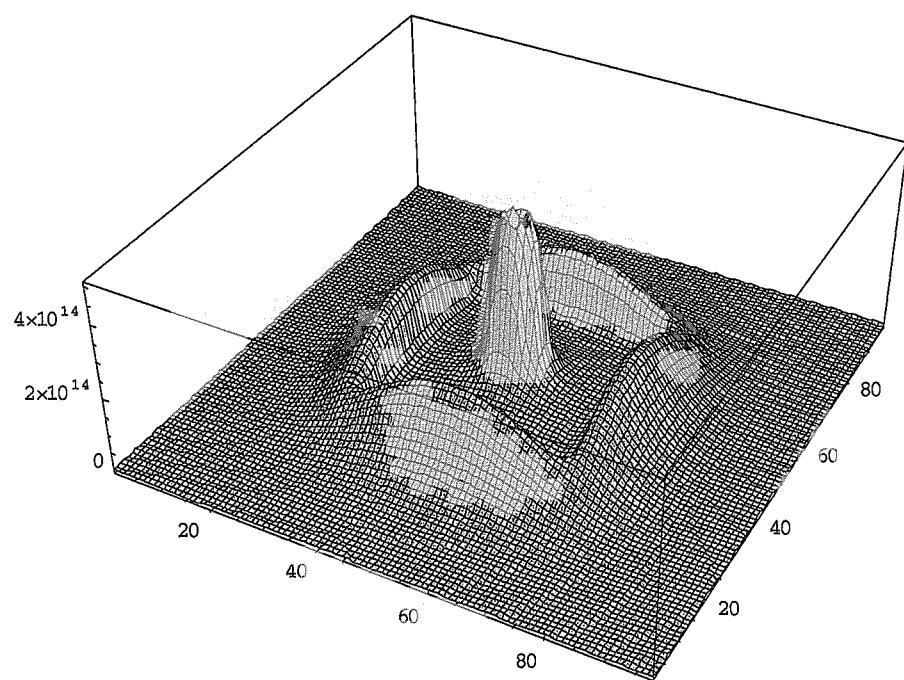
17-energy-group model (14th group)



17-energy-group model (15th group)



17-energy-group model (16th group)



17-energy-group model (17th group)

国際単位系(SI)と換算表

表1 SI基本単位および補助単位

量	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表3 固有の名称をもつSI組立単位

量	名称	記号	他のSI単位による表現
周波数	ヘルツ	Hz	s^{-1}
力	ニュートン	N	$m \cdot kg/s^2$
圧力、応力	パスカル	Pa	N/m^2
エネルギー、仕事、熱量	ジュール	J	$N \cdot m$
工率、放射束	ワット	W	J/s
電気量、電荷	クーロン	C	$A \cdot s$
電位、電圧、起電力	ボルト	V	W/A
静電容量	ファラード	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束密度	ウェーバ	Wb	$V \cdot s$
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	$^{\circ}C$	
光照度	ルーメン	lm	$cd \cdot sr$
放射能	ルクス	lx	lm/m^2
吸収線量	ベクレル	Bq	s^{-1}
吸収線量当量	グレイ	Gy	J/kg
	シーベルト	Sv	J/kg

表2 SIと併用される単位

名称	記号
分、時、日	min, h, d
度、分、秒	°, ', "
リットル	L, L
トントン	t
電子ボルト	eV
原子質量単位	u

$$1 \text{ eV} = 1.60218 \times 10^{-19} \text{ J}$$

$$1 \text{ u} = 1.66054 \times 10^{-27} \text{ kg}$$

表5 SI接頭語

倍数	接頭語	記号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^9	ギガ	G
10^6	メガ	M
10^3	キロ	k
10^2	ヘクト	h
10^1	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	アト	a

(注)

- 表1～5は「国際単位系」第5版、国際度量衡局1985年刊行による。ただし、1eVおよび1uの値はCODATAの1986年推奨値によった。
- 表4には海里、ノット、アール、ヘクタールも含まれているが日常の単位なのでここでは省略した。
- barは、JISでは流体の圧力を表わす場合に限り表2のカテゴリーに分類されている。
- EC間際理事会指令ではbar、barnおよび「血圧の単位」mmHgを表2のカテゴリーに入れている。

換算表

力	N($=10^5$ dyn)	kgf	lbf
1	0.101972	0.224809	
9.80665	1	2.20462	
4.44822	0.453592	1	

粘度 $1 \text{ Pa} \cdot \text{s} (\text{N} \cdot \text{s}/\text{m}^2) = 10 \text{ P} (\text{ポアズ}) (\text{g}/(\text{cm} \cdot \text{s}))$

動粘度 $1 \text{ m}^2/\text{s} = 10^4 \text{ St} (\text{ストークス}) (\text{cm}^2/\text{s})$

圧力	MPa($=10$ bar)	kgf/cm ²	atm	mmHg(Torr)	lbf/in ² (psi)
力	1	10.1972	9.86923	7.50062×10^3	145.038
0.0980665	0.0980665	1	0.967841	735.559	14.2233
0.101325	0.101325	1.03323	1	760	14.6959
1.33322×10^{-4}	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
6.89476×10^{-3}	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

エネルギー・仕事・熱量	J($=10^7$ erg)	kgf·m	kW·h	cal(計量法)	Btu	ft · lbf	eV	1 cal = 4.18605 J(計量法)	
								= 4.184 J(熱化学)	= 4.1855 J(15 °C)
1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}			
9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}			
3.6×10^6	3.67098×10^5	1	8.59999×10^5	3412.13	2.65522×10^6	2.24694×10^{25}			
4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}			
1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}			
1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}			
1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1			

放射能	Bq	Ci	吸収線量	Gy	rad	照射線量	C/kg	R	線量当量	Sv	rem
	1	2.70270×10^{-11}		1	100		1	3876		1	100
	3.7×10^{10}	1	0.01	1			2.58×10^{-4}	1	0.01	1	

Effects of Volume Fraction and Non-uniform Arrangement of Water Moderator on Reactivity

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