

Critical Sizes of Light-Water Moderated  $\text{UO}_2$   
and  $\text{PuO}_2\text{-UO}_2$  Lattices

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日本原子力研究所

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## JAERI レポート

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# Critical Sizes of Light-Water Moderated UO<sub>2</sub> and PuO<sub>2</sub>-UO<sub>2</sub> Lattices\*

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Experimental critical sizes are presented for a total of about 250 lattices with 2.6 w/o UO<sub>2</sub> and 3.0 w/o PuO<sub>2</sub>-natural UO<sub>2</sub> fuel rods. The moderator was H<sub>2</sub>O and water-to-fuel volume ratios in the lattice cells ranged from 1.50 to 3.00 in the UO<sub>2</sub> lattices and from 2.42 to 5.55 in the PuO<sub>2</sub>-UO<sub>2</sub> lattices. The critical sizes were determined with the number of the fuel rods and a water level which were required to make the lattice critical in the shape of a rectangular parallelepiped over the temperature range from room temperature to 80°C. Reactivity variations of the PuO<sub>2</sub>-UO<sub>2</sub> lattices due to decaying of <sup>241</sup>Pu to <sup>241</sup>Am were traced during 3 years. Some critical sizes of the UO<sub>2</sub> and PuO<sub>2</sub>-UO<sub>2</sub> lattices with a water gap and of the UO<sub>2</sub> lattices with liquid poison in the moderator are also reported.

Some physics parameters, such as the temperature coefficient of reactivity, the water-level worth, the reflector saving, the ratio between a migration area and an infinite multiplication factor and the critical buckling, are shown in relation to the critical sizes of the unperturbed lattices without the water gap and liquid poison.

**Keywords:** Uranium Dioxide, Plutonium Dioxide, Mixed Oxide, Critical Size, Light-Water Lattice, Critical Experiment, Temperature Coefficient of Reactivity, Water-Level Worth, Critical Buckling, Reflector Saving, Reactivity.

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\* The experiments on the PuO<sub>2</sub>-UO<sub>2</sub> lattices have been performed in the framework of the joint research program for the Pu utilization in thermal reactor of the Japan Atomic Energy Research Institute and the Power Reactor and Nuclear Fuel Development Corporation.

## 軽水減速 $\text{UO}_2$ および $\text{PuO}_2\text{-}\text{UO}_2$ 燃料炉心の臨界量\*

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2.6 w/o  $\text{UO}_2$  および 3.0 w/o  $\text{PuO}_2$ -天然  $\text{UO}_2$  燃料を用いた約 250 炉心について、その臨界形状の実験値を示した。減速材は軽水であって、単位格子内の水対燃料体積比は、 $\text{UO}_2$  炉心については 1.50 から 3.00,  $\text{PuO}_2\text{-}\text{UO}_2$  炉心については 2.42 から 5.55 の範囲である。臨界形状は、室温から 80°C の温度範囲について直方体炉心の臨界に必要な燃料本数と水位とを用いて決定された。 $\text{PuO}_2\text{-}\text{UO}_2$  燃料炉心において、 $^{241}\text{Pu}$  が  $^{241}\text{Am}$  に転換することによる炉心の反応度変化を 3 年間にわたって追跡した。水ギャップ付の  $\text{UO}_2$  および  $\text{PuO}_2\text{-}\text{UO}_2$  燃料炉心および減速材中に液体ポイズンを含む  $\text{UO}_2$  燃料炉心の臨界形状も示してある。

反応度温度係数、水位等価反応度、反射体節約、中性子移動距離と無限増倍係数の比、および臨界パックリングなどの炉物理パラメータを、水ギャップや液体ポイズンの無い一樣炉心の臨界形状に関連して示した。

\*  $\text{PuO}_2\text{-}\text{UO}_2$  燃料炉心に関する実験は日本原子力研究所と動力炉・核燃料開発事業団との間における Pu の熱中性子炉利用に関する共同研究の一環として行った。

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## 1. Introduction

One of the most basic reactor physics parameters is a critical size of a lattice. This size of the lattice which has a simple structure, plays an important role in evaluation and improvement of nuclear design methods. Therefore, many critical sizes of  $H_2O$  moderated lattices with  $UO_2^{1,2)}$  or  $PuO_2-UO_2^3)$  fuel rods have been measured at various laboratories. From an engineering point of view, the experimental data on the critical sizes are further required as the fundamental physics characteristics of the lattice varied with lattice parameters, such as the enrichment of U and Pu, the isotope composition of Pu, the dimension of a fuel rod, and the water-to-fuel volume ratio in the lattice cell.

Since the Tank-type Critical Assembly (TCA) at the Japan Atomic Energy Research Institute (JAERI) attained the first criticality on August 23, 1962<sup>4)</sup>, it has been operated to serve for reactor physics studies of  $H_2O$  moderated lattices with low-enriched  $UO_2$  or  $PuO_2-UO_2$  fuel rods. During this period, several thousands of critical experiments have been carried out and some criticality data will be referred to in Reference 5 on PWR-type  $UO_2$  lattices and in Reference 6 on two region lattices consisted of  $UO_2$  and  $PuO_2-UO_2$  fuel rods.

From critical sizes measured in the series of the critical experiments, about 250 data were selected under the following criteria :

- 1) Each lattice consists of fuel rods with the same composition.
- 2) Fuel is  $UO_2$  or  $PuO_2-UO_2$ .
- 3) A horizontal section of a lattice is rectangular.
- 4) Materials which affect the reactivity of a lattice, such as a control rod or a neutron detector, are not present inside and nearby the lattice.

This report is intended to serve the selected critical sizes as basic physics data for other extended experiments and as benchmark data for evaluation of nuclear design methods. The simple configuration of the rectangular parallelepiped lattice will make the criticality calculation easier, as such configuration has many geometrical symmetries.

The fuel rods are 2.6 w/o enriched  $UO_2$  and 3.0 w/o enriched  $PuO_2$ -natural  $UO_2$ . The water-to-fuel volume ratios in a lattice cell range from 1.50 to 3.00 for the  $UO_2$  lattices (H/U atom ratio; from 4.3 to 8.7) and from 2.42 to 5.55 for the  $PuO_2-UO_2$  lattices (H/Pu atom ratio; from 400 to 920). The temperature of the lattices was varied from room temperature to 80°C. Some critical sizes of perturbed lattices with a water gap and with liquid poison are also contained in this report.

In relation to the critical sizes of unperturbed lattices without a water gap and without liquid poison, other reactor physics parameters, such as the temperature coefficient of reactivity, the water-level worth, the reflector saving, the ratio between a migration area and an infinite multiplication factor, and the critical buckling are described. The reactivity in dollar units was converted into  $\delta k/k$  units by using calculated effective delayed-neutron fractions, which were verified by correlating the theoretical values of the ratio between an effective delayed-neutron fraction and a prompt-neutron lifetime with experimental values.

## 2. Experimental Facility

### 2.1 Tank-type Critical Assembly (TCA)

The critical assembly TCA essentially consists of fuel rods, grid plates, and a core tank (1.83m in diam. and 2.08m in height). The general view and the mechanical construction are shown in **Figs. 1 and 2**.

The experimental lattices were built in the core tank. The moderator was light water. The reactor was operated by raising a water level from the bottom of the core tank by a feed water pump. No control rod was used for reactor operation. Six neutron detectors were located at the position of 15cm from the periphery of the lattice. The maximum limitation of the operating power was 200 Watts.

### 2.2 Fuel rods

The general descriptions for the  $\text{UO}_2$  and  $\text{PuO}_2\text{-}\text{UO}_2$  fuel rods are presented here. Details of their specifications are shown in **TABLE 1** and **Fig. 3**.

#### 1) $\text{UO}_2$ rod

The enrichment of  $^{235}\text{U}$  is 2.6 w/o. The 1.25cm diam. pellets were clad into an aluminum tube. The effective length of the fuel rod is 144.2cm. A few swaged rods were used in some cases. The nuclear properties of the swaged rod were equivalent to those of the pelletized rod.

#### 2) $\text{PuO}_2\text{-}\text{UO}_2$ rod

The enrichment of plutonium oxide in the  $\text{PuO}_2\text{-}\text{UO}_2$  fuel is 3.0 w/o and uranium is natural. The initial content of  $^{240}\text{Pu}$  in plutonium was 22 w/o. The plutonium composition varied with time due to decaying of  $^{241}\text{Pu}$  to  $^{241}\text{Am}$ . Atomic number densities of  $^{241}\text{Pu}$  and  $^{241}\text{Am}$  in the fuel rod at every year elapsed after assaying are shown in Appendix A1. A diameter of most  $\text{PuO}_2$  particles is less than  $40\ \mu\text{m}$ . Pre-sintered pellets of 1.07 cm diam. were clad into a Zircaloy-2 tube. The effective length of the fuel rod is 70.6cm.

### 2.3 Lattice construction

A lattice was constructed in the core tank by holding the fuel rods vertically with a set of grid plates. They were set at the upper and lower positions in the core tank. In the case of the  $\text{PuO}_2\text{-}\text{UO}_2$  lattices, an additional grid plate was set at the middle position between the upper and lower grid plates. The height of the additional grid plate corresponds to 9cm above the active zone of the  $\text{PuO}_2\text{-}\text{UO}_2$  fuel rod. The arrangement of the lattice is shown in **Photos. 1 and 2**, and the vertical cross-sectional view in **Fig. 4**.

The geometry of the horizontal cross-sectional view of the lattices was rectangular and the lattice cell is square. The water-to-fuel volume ratio of the lattice cell was changed by replacing the grid plates with another set which had a different lattice pitch. The accuracy of the lattice pitch is less than 0.02cm which includes a clearance between the fuel rod and the grid plate.

In some lattices, a water gap was formed by removing the fuel rods from the lattice and arrayed in a line (cf. Appendix A3, Patterns 101~115) or in parallels crossing rectangularly (cf.

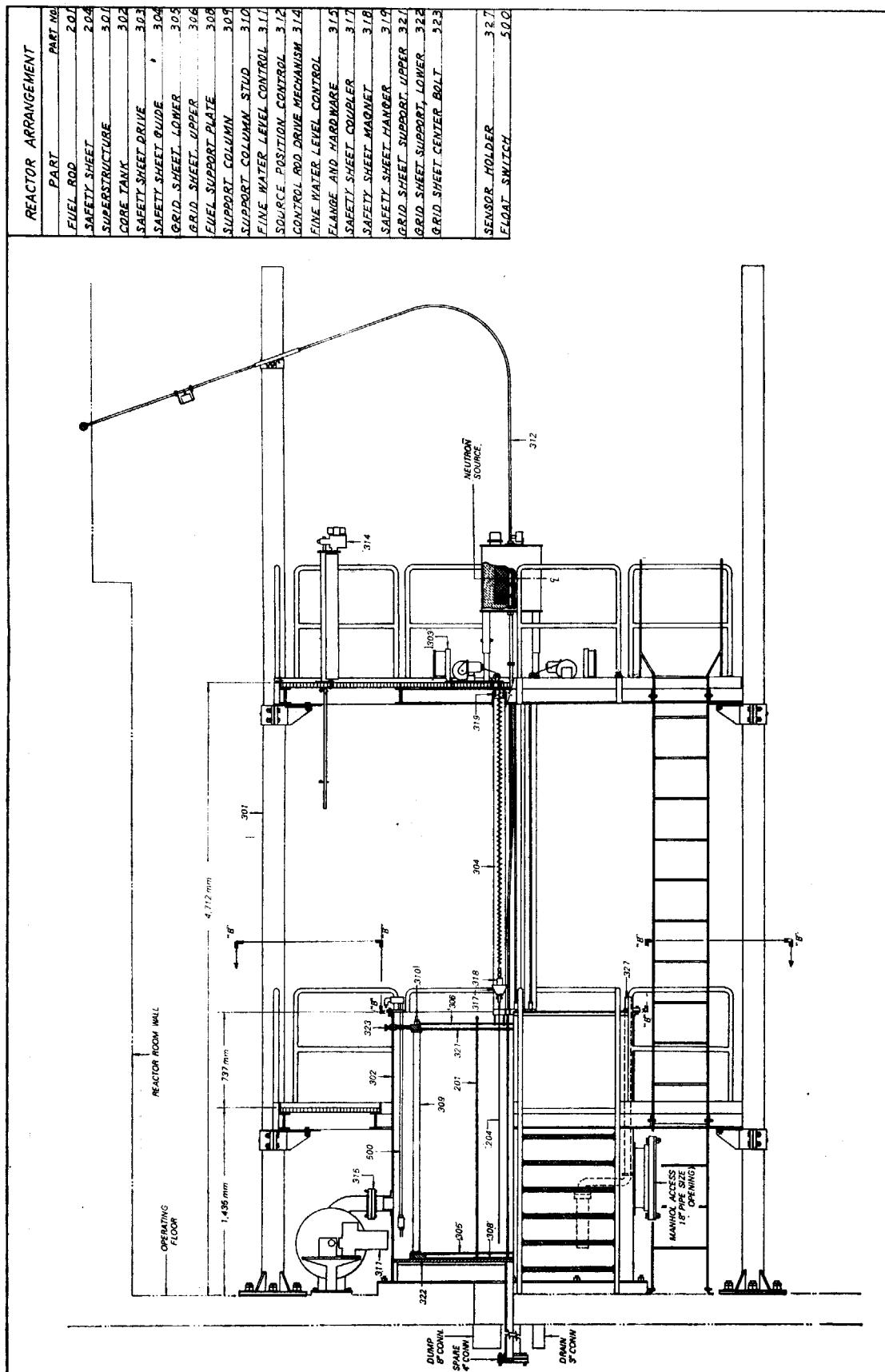


Fig. 1 Vertical cross-sectional view of TCA.

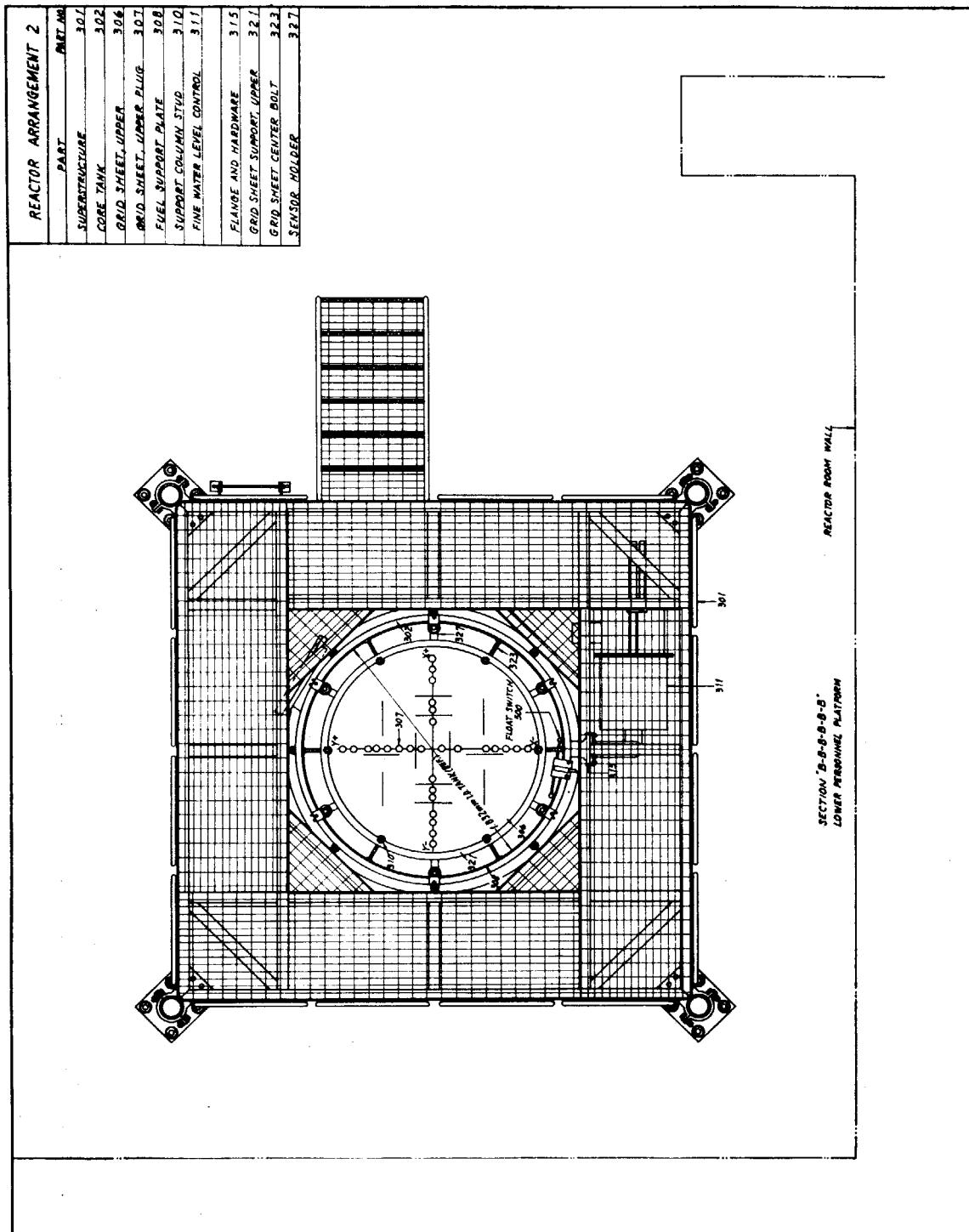


Fig. 2 Horizontal cross-sectional view of TCA.

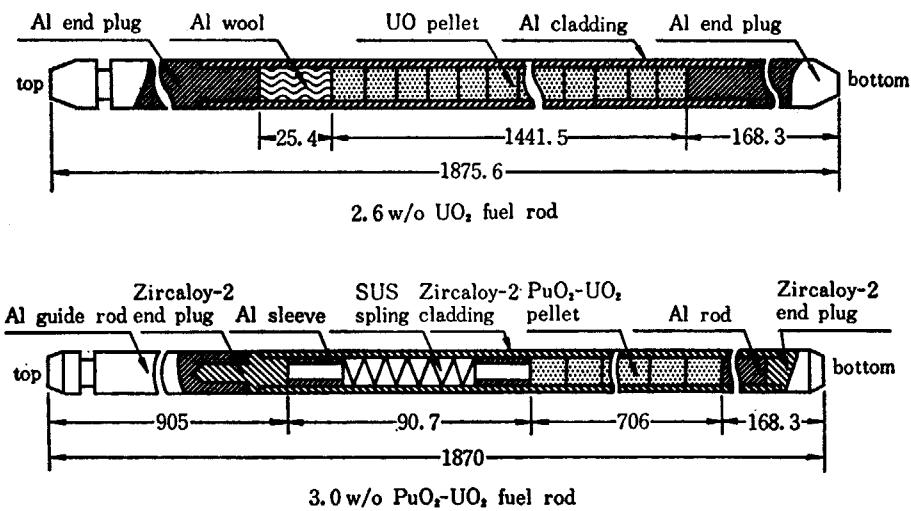
Fig. 3 2.6 w/o  $\text{UO}_2$  and 3.0 w/o  $\text{PuO}_2\text{-natural}$   $\text{UO}_2$  fuel rods.

TABLE I Fuel specifications

	$\text{UO}_2$	$\text{PuO}_2\text{-}\text{UO}_2$
<i>Fuel</i>		
Enrichment, w/o	2.596, $^{235}\text{U}$	$3.01 \pm 0.05$ , $\frac{\text{PuO}_2}{(\text{PuO}_2 + \text{UO}_2)}$
Isotope ratio, w/o		
Uranium		Natural
$^{235}\text{U}$	2.596	
$^{238}\text{U}$	97.404	
Plutonium		
$^{238}\text{Pu}$	—	0.494 (1971-8-19)*
$^{239}\text{Pu}$	—	68.18 (1971-8-19)
$^{240}\text{Pu}$	—	22.02 (1971-8-19)
$^{241}\text{Pu}$	—	7.26 (1971-8-19)
$^{242}\text{Pu}$	—	2.04 (1971-8-19)
Americium		
$^{241}\text{Am}$	—	530 ppm (1971-8-16) in $\text{PuO}_2$
Impurity content	—	$0.90 \pm 0.09$ ppm equivalent boron concentration in $\text{PuO}_2\text{-}\text{UO}_2$
O/M	2.04	2.07
Pellet		
Fabrication method	Sintered	Mechanically blended and pre-sintered
Diameter, mm	12.50	10.65
Density, g/cm <sup>3</sup>	10.40	$6.056 \pm 0.076$
Stack length, mm	$1441.5 \pm 3$	$706 \pm 3$
<i>Cladding</i>		
Material	Al	Zircaloy-2
Inner diameter, mm	12.65	$10.83 \pm 0.06$
Thickness, mm	0.76	$0.70 \pm 0.07$

\* Date of assaying.

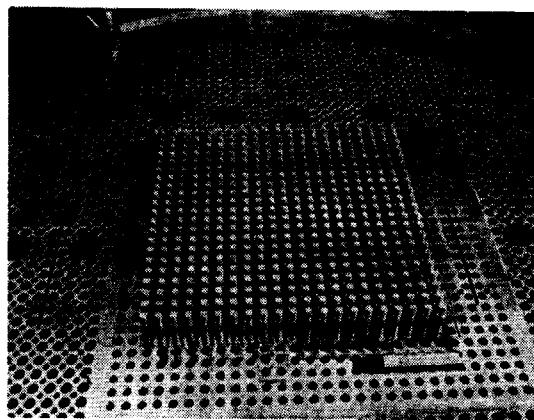


Photo. 1 Top view of 4.24 Pu lattice.

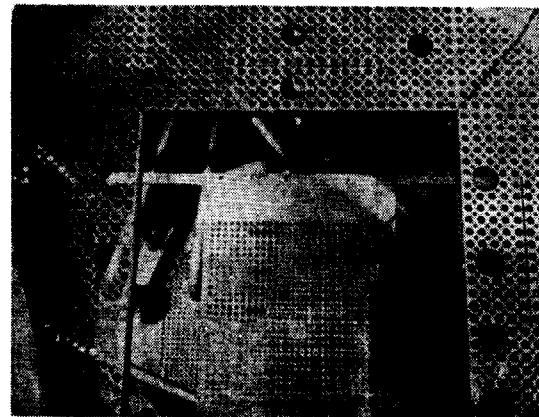


Photo. 2 Arrangement of grid plates at upper, middle, and lower positions.

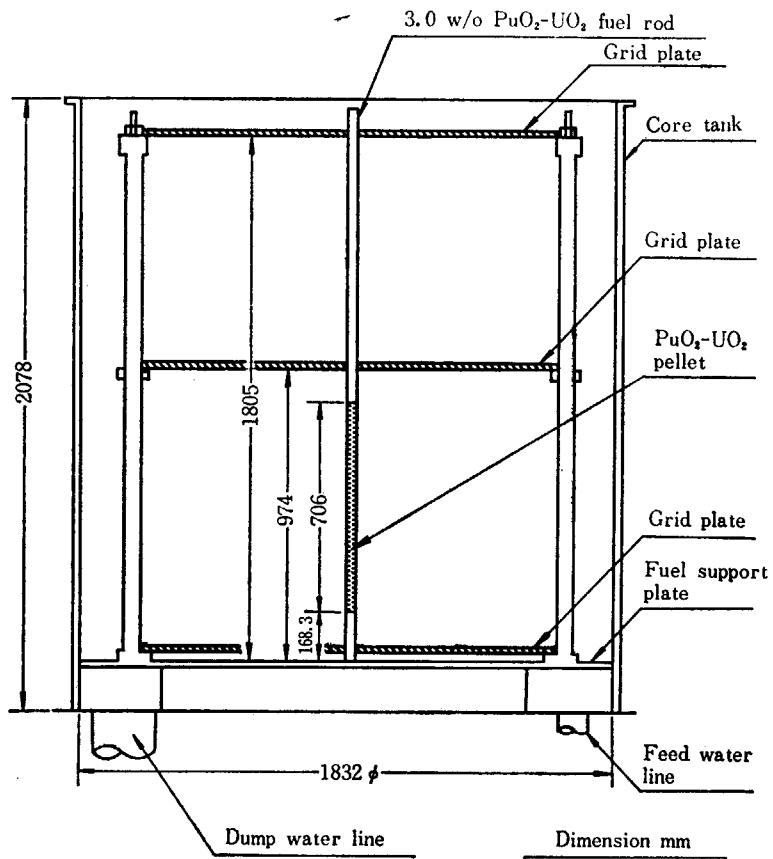


Fig. 4 Vertical cross-sectional view of core tank.

TABLE 2 Name of lattice

Lattice name	H/U or H/Pu	Lattice pitch (cm)
1.50U	4.33	1.849
1.83U	5.28	1.956
2.48U	7.16	2.150
3.00U	8.65	2.293
2.42PU	402	1.825
2.98PU	494	1.956
4.24PU	703	2.225
5.55PU	921	2.474

Patterns 116~119). Therefore, the width of the water gap was an integer multiple of the lattice pitch.

The thickness of a horizontal reflector is more than 40cm. A lower reflector under the lattice consists of water, the lower grid plate, the lower end-plug of the fuel rod, and the fuel support plate. The thickness of the lower reflector is 30cm. The height of the lower end of the lattice is uniform within 0.005cm.

The lattice with liquid poison contains  $H_3BO_3$  in the moderator as well as in the reflector. Boron is natural.

The lattices were named for their water-to-fuel volume ratios and types of the fuel rod. For example, a lattice name 1.50U corresponds to the  $UO_2$  lattice of which water-to-fuel volume ratio is 1.50, and a lattice name 2.42PU to the  $PuO_2-UO_2$  lattice of which water-to-fuel volume ratio is 2.42. A list of the lattice names is shown in TABLE 2 with their H/fuel atom ratios and lattice pitches. Atomic number densities of materials in the lattice are tabulated in Appendix A1.

### 3. Experimental Methods

#### 3.1 General description

Operation for attaining the criticality of the lattice was carried out by adjusting the water level. The critical size was obtained as the number of fuel rods loaded in the lattice and the water level at a critical state. Hereafter, the water level is expressed as the distance above the lower end of the fuel active zone. The temperature of the moderator was measured at the critical state.

The temperature of the lattice was varied in the range from room temperature to 80°C by heating the moderator with electric heaters placed in a water storage tank. To raise uniformly the temperature of the lattice, the heated water was fed into the core tank at first to preheat the pipings, the fuel rods, and the core tank. Then, the water was dumped into the water storage tank, and finally the measurement of the critical size was started.

In addition to the critical size, the temperature coefficient of reactivity, the water-level worth, and the vertical and horizontal reflector savings of each lattice were measured. The temperature coefficient of reactivity and the water-level worth were required to convert the temperature difference between the lattices into the difference in the water level. The reflector savings were used in the calculations of the water-level worth and the critical buckling.

#### 3.2 Water level of lattice

The water level of the lattice was usually measured with a servo-manometer which had a minimum scale of 0.02cm. When the temperature of the lattice was raised above room temperature, the manometer indicated the level lower than the real one in the core tank. This difference was due to the fact that the density of water in the manometer became larger than that in the core tank, as the manometer was placed outside the core tank and the temperature of water in the manometer was lowered by cooling. To overcome this disadvantage, a water surface in the core tank was detected with a needle-shaped electrode which could move up and down along a calibrated scale. The resolution of this water guage was 0.05cm.

### 3.3 Moderator temperature

The temperature of the moderator was usually measured with a resistance thermometer in the experiments before the run number 5337, and a quartz thermometer after 5338. The accuracy was 0.5°C for the former and was 0.02°C for the latter.

When the temperature of the moderator was raised above room temperature, six thermocouples of almel-chromel were additionally used in the experiments before the run number 5337, and another quartz thermometer and three thermisters after the number 5338.

Those thermometers were placed in the horizontal reflector and the variation of the temperature of the moderator was monitored during the experiment.

### 3.4 Reactivity

#### 3.4.1 Criticality

The critical state of the lattice was determined by observing the steady state of neutron flux, which was monitored with two compensated ion chambers. A waiting time of more than 5 minutes was needed before the determination of the critical state to avoid a premature observation of the transient terms.

In the case of the PuO<sub>2</sub>-UO<sub>2</sub> lattices, the critical state was maintained at the reactor power above 5 Watts to decrease the error due to the neutron source from <sup>240</sup>Pu spontaneous fissions and ( $\alpha$ , n) reactions of oxygen.

#### 3.4.2 Temperature coefficient of reactivity

The critical sizes in the range of the temperature from room temperature to about 80°C were measured by changing the temperature of the lattice under a fixed number of the fuel rods loaded in the unperturbed lattices. The critical water level varied with temperature. The difference in the critical water level was converted into the reactivity difference by the use of the water-level worth. The critical water levels of all lattices used in this series of measurements was below 70cm, and an additional measurement was made for the 1.83U lattice having a higher water level of about 110cm.

A quadratic function with respect to temperature was fitted by a least squares method to the reactivity differences based on the value at 20°C. By using parameters *A* and *B* which were obtained by the fitting, the difference of the reactivity of the lattice between at the temperature *T* and a reference point *T*<sub>0</sub> was calculated by

$$\rho = A \cdot (T - T_0) + B \cdot (T^2 - T_0^2). \quad (1)$$

The temperature coefficient of reactivity was deduced by differentiating Eq. (1) with respect to *T* as

$$\frac{d\rho}{dT} = A + 2 \cdot B \cdot T. \quad (2)$$

#### 3.4.3 Water-level worth

In order to convert the difference of the water level into the reactivity, the differential water-level worth was measured by a period method on the unperturbed lattices at room temperature. The water level was changed from the critical level a little higher or lower and the reactor period was observed. After all transient terms in neutron flux behavior had died away, a steady-state

reactor period was measured. Then, the reactor period was converted into the reactivity in the dollar unit with a period-reactivity relation of each lattice.

This measurement was repeated at several critical water levels of the same lattice by adjusting the loaded number of the fuel rods. Thus, the differential water-level worth at each water level was obtained over the wide range of the water level.

The differential water-level worths  $d\rho/dH$  were fitted by a least squares method to a function

$$\frac{d\rho}{dH} = C \cdot \left( \frac{1}{H+\lambda} \right)^3, \quad (3)$$

where

$\rho$ =reactivity

$H$ =water level

$\lambda$ =sum of upper and lower reflector savings in the vertical direction

$C$ =unknown parameter.

By integrating Eq. (3) with respect to  $H$ , the integral water-level worth between two water levels,  $H_1$  and  $H_2$ , was obtained by

$$\rho = -\frac{C}{2} \cdot \left\{ \left( \frac{1}{H_1+\lambda} \right)^2 - \left( \frac{1}{H_2+\lambda} \right)^2 \right\}. \quad (4)$$

The reactivity in  $\delta k/k$  units was given by multiplying the value in the dollar units by an effective delayed-neutron fraction  $\beta_{\text{eff}}$  which was calculated on each lattice by using a 4-group perturbation theory<sup>7)</sup>. The theoretical values of  $\beta_{\text{eff}}$  are shown in TABLE 3. For reference, a comparison between the theoretical and experimental values of  $\beta_{\text{eff}}/l$  is made in Appendix A6, where  $l$  is the prompt-neutron lifetime. The results show that the maximum deviation between both values is 7% of the 5.55PU lattices. From this fact, the calculation method can be said reliable.

The water-level worths of the PuO<sub>2</sub>-UO<sub>2</sub> lattices were measured in the experiments from April 12 to June 7 in 1972. In this series of the measurements, the reactor period was obtained over the range of the reactor power above 1 Watt.

TABLE 3 Effective delayed-neutron fractions,  $\beta_{\text{eff}}$

Lattice name	$\beta_{\text{eff}}$
1.50U	0.007484
1.83U	0.007478
2.48U	0.007423
3.00U	0.007372
2.42P U	0.003635
2.98P U	0.003597
4.24P U	0.003526
5.55P U	0.003453

### 3.5 Reflector saving

The vertical and horizontal reflector savings were obtained from power distributions which were measured by  $\gamma$ -ray scanning of fission products accumulated in the fuel rods through the lattice in a vertical and horizontal lines. The  $\gamma$ -rays above 0.6 MeV were counted with a 3"φ×3" or 2"φ×2" NaI(Tl) scintillation detector with a view of the 1cm length of a fuel rod for the measurement of a vertical power distribution and the 2cm length for a horizontal power distribution. Decaying of the fission products was corrected with the factors which had been obtained by a supplemental experiment.

The  $\gamma$ -ray intensities were fitted by a least squares method to a cosine function as

$$Y = A \cdot \cos(B \cdot X + C), \quad (5)$$

where

$Y$ = $\gamma$ -ray intensity

$X$ =position in the lattice

$A$ ,  $B$ , and  $C$ =unknown parameters.

The reflector saving  $\lambda$  was obtained from the following relation:

$$\lambda = \frac{\pi}{B} - W, \quad (6)$$

where  $W$  is the water level for the vertical reflector saving, or the lattice width for the horizontal reflector saving. Therefore, the vertical reflector saving is expressed as the sum of its upper and lower values and the horizontal reflector saving is as the sum of the values of both sides.

## 4. Results

### 4.1 Measured values of critical sizes

About 250 critical sizes were classified according to the fuel type and the water-to-fuel volume ratio in the lattice cell. They are shown in Appendices A2 and A3. Each column consists of the run number, date, critical water level, temperature, boron content, and lattice configuration.

The boron content was determined chemically by a mannitol method. The accuracy of the content is 1.5%.

There are several sources of the error contained in the determination of the critical size. In the case of the  $\text{PuO}_2\text{-UO}_2$  lattices, there were present in the measurement of the critical state some difficulties due to neutrons from the spontaneous fissions and  $(\alpha, n)$  reactions of oxygen. The intensity of the neutron source from a 3.0w/o  $\text{PuO}_2\text{-UO}_2$  fuel rod was estimated as  $4 \times 10^3$  n/sec, and the error in the determination of the critical state due to the neutron source was suppressed to less than 0.1 cent by operating the reactor above 5 Watts. In the case of the  $\text{UO}_2$  lattices, the effect of the neutron source was entirely negligible.

Other sources of the error were in the readings of the neutron flux, temperature, and water level. The critical state was determined within the error of 0.1 cent by observing the steady state of the neutron flux after enough waiting time<sup>8)</sup>.

During the experiments at the temperature above room temperature, the dispersion of the indications of the thermometers was within  $0.5^\circ\text{C}$ , while the variation of their mean value was  $0.1^\circ\text{C}$  between before and after the measurement of the critical water level.

The water level is expressed as the difference of the readings of the servo-manometer between at a water surface and at the lower end of the fuel active zone. As the accuracy of the servo-manometer is 0.01 cm, the height of the lower end of the fuel active zone has the error of 0.01 cm. Therefore, the error of the water level was calculated as 0.02 cm. It was converted into the reactivity by using the differential water-level worth which depended on the water level. The error of the water level at 40cm is equivalent to 1.3 cents for the  $\text{UO}_2$  lattices and 3.0 cents for the  $\text{PuO}_2\text{-UO}_2$  lattices. Both values correspond to  $0.01\%\delta k/k$ . At the water level above 40cm, the error decreased to less than  $0.01\%\delta k/k$ .

As a consequence, the errors in the temperature and the water level contribute practically to the error in the reactivity at the critical state. Although the error in the reactivity depends on

both the temperature and the water level of the lattice, the amount of  $0.01\%\delta k/k$  is assured to be appropriate for the errors of the critical states.

The reading of the servo-manometer was calibrated at least once a year in an accuracy of 0.01 cm. When the difference in the water level between some lattices is required, it is recommended, whenever available to use the data which were measured in successive experimental runs. In this difference in the water level, the ambiguity of the calibration will be subtracted.

#### 4.2 Critical sizes of unperturbed lattices at 20°C

##### 4.2.1 Temperature coefficients of reactivity and water-level worths

The critical water levels of the unperturbed lattices measured in the temperature range from 10 to 30°C were reduced to the values at 20°C. At first, the temperature difference between the temperature of the lattice and 20°C was converted into the reactivity difference by the use of the temperature coefficient of reactivity. Then, the reactivity difference was changed into the difference of the water level with a conversion factor of the water-level worth. Thus, the temperature difference was calculated in terms of the water level, and the critical water level at any temperature was corrected to the value at 20°C.

The values of the parameters  $A$  and  $B$  in Eq. (2) for the temperature coefficient of reactivity are shown in TABLE 4 and the reactivity differences based on the value at 20°C are listed in Appendix A4. As seen in this Appendix, the temperature coefficient of reactivity depends heavily on both the water-to-fuel volume ratio and the critical configuration of the lattice.

The values of the parameter  $C$  in Eqs. (3) and (4) for the water-level worth are shown in TABLE 5, and the differential and integral water-level worths are listed in Appendix A5. The vertical reflector savings which were used in the calculation of the water-level worths are shown

TABLE 4 Temperature coefficients of reactivity  
The temperature coefficient of reactivity is obtained by

$$\frac{d\rho}{dT} = A + 2 \cdot B \cdot T, \text{ (cent}/^{\circ}\text{C}),$$

where  $T$  is temperature in units of °C.

Lattice name	Water level (cm)	$A$	$B$
1.50U	60	$-0.11 \pm 0.04$	$-0.0136 \pm 0.0004$
1.83U	50	$-0.22 \pm 0.07$	$-0.0138 \pm 0.0007$
	110	$0.23 \pm 0.08$	$-0.0132 \pm 0.0008$
2.48U	60	$0.08 \pm 0.06$	$-0.0137 \pm 0.0006$
3.00U	60	$0.17 \pm 0.04$	$-0.0116 \pm 0.0004$
2.42P U	60	$0.26 \pm 0.10$	$-0.025 \pm 0.001$
2.98P U	60	$0.69 \pm 0.04$	$-0.0228 \pm 0.0004$
4.24P U	60	$2.30 \pm 0.17$	$-0.021 \pm 0.002$
5.55P U	60	$4.21 \pm 0.03$	$-0.0152 \pm 0.0003$

TABLE 5 Proportional coefficients,  $C$ , in the equation of differential reactivity worth of water level

Lattice name	$C$ (cent·cm <sup>2</sup> )
1.50U	$7.57 \pm 0.11 \times 10^6$
1.83U	$7.59 \pm 0.07$
2.48U	$7.64 \pm 0.11$
3.00U	$7.48 \pm 0.06$
2.42P U	$1.57 \pm 0.06 \times 10^7$
2.98P U	$1.58 \pm 0.07$
4.24P U	$1.69 \pm 0.05$
5.55P U	$1.83 \pm 0.03$

TABLE 6 Reflector savings

Lattice name	Vertical (cm)	Horizontal (cm)
1.50U	$12.6 \pm 0.3$	$17.0 \pm 0.8$
1.83U	$12.2 \pm 0.3$	$13.9 \pm 0.8$
2.48U	$11.3 \pm 0.2$	$13.7 \pm 0.5$
3.00U	$11.1 \pm 0.5$	$14.0 \pm 0.8$
2.42P U	$12.5 \pm 0.2$	$14.6 \pm 0.3$
2.98P U	$12.0 \pm 0.2$	$14.1 \pm 0.3$
4.24P U	$11.6 \pm 0.2$	$13.4 \pm 0.2$
5.55P U	$11.3 \pm 0.2$	$13.1 \pm 0.2$

in TABLE 6. Those reflector savings are the values for the lattices of which water level was around 70cm, but they do not vary with the water level as long as the upper reflector is not present<sup>6)</sup>.

According to a one-group diffusion model, the  $C$  is expressed as

$$C = 2 \cdot \pi^2 \cdot \frac{M^2}{k_\infty} \cdot \frac{1}{\beta_{\text{eff}}}, \quad (7)$$

where

$M^2$ =migration area

$k_\infty$ =infinite multiplication factor

$\beta_{\text{eff}}$ =effective delayed-neutron fraction.

The ratio  $M^2/k_\infty$  was obtained by transforming Eq. (7) into

$$\frac{M^2}{k_\infty} = \frac{C \cdot \beta_{\text{eff}}}{2 \cdot \pi^2}, \quad (8)$$

where  $\beta_{\text{eff}}$  was the theoretical value described in Section 3.4.3. The results are shown in TABLE 7 with the errors which were estimated with those of  $C$ .

TABLE 7 Ratios between migration area,  $M^2$ , and infinite multiplication factor,  $k_\infty$

Lattice name	$M^2/k_\infty$ (cm <sup>2</sup> )
1.50U	$28.7 \pm 0.4$
1.83U	$28.8 \pm 0.3$
2.48U	$28.7 \pm 0.4$
3.00U	$27.9 \pm 0.2$
2.42P U	$28.9 \pm 1.1$
2.98P U	$28.8 \pm 1.3$
4.24P U	$30.2 \pm 0.9$
5.55P U	$32.0 \pm 0.5$

#### 4.2.2 Critical water levels

The critical sizes of the UO<sub>2</sub> and PuO<sub>2</sub>-UO<sub>2</sub> lattices at 20°C are listed in TABLES 8-1 and 8-2,

TABLE 8-1 Critical water levels of UO<sub>2</sub> lattices at 20°C

Lattice name	Pattern	Critical water level (cm)	Error, $\pm \delta k_{\text{eff}}$	Lattice name	Pattern	Critical water level (cm)	Error, $\pm \delta k_{\text{eff}}$
1.50U	18	99.45	$3 \times 10^{-4}$	1.83U	18	60.38	$3 \times 10^{-4}$
	20	73.73	7		19	55.53	1
	22	60.81	5		20	51.65	2
	24	53.23	5		21	48.62	1
	26	47.81	3		22	46.01	1
	28	43.94	1		23	43.91	1
	29	40.89	1		24	42.12	1
1.83U	1	131.94	$1 \times 10^{-4}$	2.48U	11	78.67	$2 \times 10^{-4}$
	2	69.01	1		13	59.96	1
	3	85.36	1		15	50.52	1
	4	135.70	1		18	44.55	1
	6	139.72	1		20	40.44	1
	7	113.95	1		25	40.50	1
	8	94.58	1		3.00U	5	$90.75 \pm 1 \times 10^{-4}$
	9	83.45	1		11	64.42	1
	10	75.74	1		13	52.87	1
	12	120.73	1		15	46.06	1
	13	114.59	3		17	41.79	1
	14	81.17	1		18	41.54	1
	15	75.32	6				
	16	66.90	1				

respectively.

For the  $\text{UO}_2$  lattices, the mean value of the critical water levels of the same lattice configuration was adopted as a recommended value except the case that only one measurement was available. The error of the recommended value was calculated from the scattering of the critical water levels. On the other hand, an error which is propagated from those of the water level and of the temperature coefficient of reactivity, was also calculated for each critical water level.

TABLE 8-2 Critical water levels of  $\text{PuO}_2\text{-UO}_2$  lattices at 20°C

Lattice name	Pattern	Critical water level (cm)	Date	Lattice name	Pattern	Critical water level (cm)	Date
2.42 P U	24	69.41	72- 6- 5	4.24 P U	19	65.39	72- 4-13
	25	64.00	72- 6- 7		19	67.79	73- 2- 8
	25	65.28	72-11- 8		19	68.67	73- 5-29
	25	69.57	74- 5-14		19	70.04	73-11-29
	26	59.55	72- 6- 7		20	60.32	72- 4-13
	26	61.95	73- 5-14		20	61.65	72-11-10
	26	61.88	73- 5-14		20	63.01	73- 5-29
	26	61.86	73- 5-14		20	63.01	73- 5-29
	26	64.06	74- 5-14		20	62.95	73- 5-29
	26	66.46	75- 5-16		20	64.05	73-11-29
	27	56.26	72- 6- 7		20	65.63	74- 6- 5
	27	60.06	74- 5-14		20	68.18	75- 5-28
	27	62.06	75- 5-16		20	68.14	75- 6- 6
	28	53.30	72- 6- 7		21	56.60	72- 4-14
	28	55.02	73- 5-14		21	61.07	74- 6- 5
	28	56.68	74- 5-14		21	63.13	75- 5-28
	28	58.36	75- 5-16		22	53.41	72- 4-14
					22	55.48	73- 5-29
2.98 P U	21	67.10	72- 5-18		22	56.21	73-11-29
	22	61.50	72- 5-18		22	57.28	74- 6- 5
	22	63.35	72-12- 6		22	59.05	75- 5-28
	22	63.63	73- 2- 7		23	50.95	72- 4-14
	22	64.00	73- 3-15		23	53.39	73-11-29
	22	64.12	73- 4- 5		23	54.33	74- 6- 5
	22	64.10	73- 4- 6		23	55.87	75- 5-28
	22	64.39	73- 5-22		24	51.74	74- 6- 6
	22	64.41	73- 5-23		24	53.09	75- 5-28
	22	64.41	73- 5-23		26	47.72	74- 6- 6
	22	65.54	73- 6- 6		26	48.85	75- 5-28
	22	66.87	74- 5-28		27	47.17	75- 5-28
	22	69.40	75- 5-21		28	44.67	74- 6- 6
	23	57.38	72- 5-18		28	45.62	75- 5-28
	23	59.88	73- 5-22	5.55 P U	21	66.05	72- 4-26
	23	60.85	73- 6- 6		21	69.16	73- 6- 6
	23	61.92	74- 5-28		22	62.05	72- 4-28
	23	63.88	75- 5-21		22	64.51	73- 6- 6
	24	56.88	73- 6- 6		22	64.54	73- 6- 7
	24	57.83	74- 5-28		23	58.73	72- 4-26
	24	59.49	75- 5-21		23	61.10	73- 6- 6
	25	54.72	74- 5-28		24	58.08	73- 6- 6
	25	56.11	75- 5-21		25	55.69	73- 6- 6
	26	51.94	74- 5-28		26	53.50	73- 6- 6
	26	53.16	75- 5-21				
	27	49.82	74- 5-28				
	27	50.79	75- 5-21				
	28	47.78	74- 5-28				
	28	48.68	75- 5-21				

The propagated error was assigned to the critical water level which was obtained from one measurement. When the error calculated from the scattering of the data was smaller than the propagated error, it was assigned to the critical water level.

The critical water level of the PuO<sub>2</sub>-UO<sub>2</sub> lattice varied with time even though the lattice configuration remained the same. Therefore, those data measured in the different experimental runs were individually shown in TABLE 8-2. Their errors were assigned as 0.01% $\delta k/k$  which was calculated from the errors of the water level and the temperature coefficient of reactivity.

#### 4. 2. 3 Critical bucklings

The critical bucklings of the unperturbed lattices were calculated from the critical dimensions at 20°C. The critical buckling  $B_c^2$  was defined by

$$B_c^2 = \left(\frac{\pi}{a}\right)^2 + \left(\frac{\pi}{b}\right)^2 + \left(\frac{\pi}{c}\right)^2, \quad (9)$$

where  $a$ ,  $b$ , and  $c$  are the critical dimensions of the rectangular parallelepiped lattice, and include the reflector savings. The reflector savings in a vertical and a horizontal directions are shown in TABLE 6.

As the critical sizes of the PuO<sub>2</sub>-UO<sub>2</sub> lattices varied with time, the critical buckling of each water-to-fuel volume ratio was normalized to the value at the specified date, April 1, 1972. The normalization was made by interpolating the critical bucklings of every lattice configuration under the same water-to-fuel volume ratio with a linear function obtained by a least squares method. The normalized values were independent of the lattice configuration in the range of the water level from 40 to 70 cm. Therefore, the coefficients of the linear function were averaged with the weight of the data which were used in the least squares calculation. The results of the coefficients are shown in TABLE 9. The decreasing rate of the critical bucklings has almost the same value of  $0.3 \times 10^{-6} \text{ cm}^{-2}/\text{day}$  for all the water-to-fuel volume ratio of the PuO<sub>2</sub>-UO<sub>2</sub> lattice.

The critical bucklings of the UO<sub>2</sub> and PuO<sub>2</sub>-UO<sub>2</sub> lattices are shown in TABLE 10 and Fig. 5. The values of the UO<sub>2</sub> lattices correspond to those of a cubic geometry. The error of the critical buckling was calculated from the errors of the reflector savings and the critical water level.

TABLE 9 Critical bucklings as a function of time  
The critical buckling  $B_c^2$  is obtained by  
 $B_c^2 = A + B \cdot T$ ,  
where  $T$  is the elapsed time in units of days after April 1, 1972.

Lattice name	$A (\times 10^{-2} \text{ cm}^{-2})$	$B (\times 10^{-6} \text{ cm}^{-2}/\text{day})$
2. 42 P U	$0.8078 \pm 0.0001$	$-0.2956 \pm 0.0044$
2. 98 P U	$0.8278 \pm 0.0012$	$-0.2701 \pm 0.014$
4. 24 P U	$0.7791 \pm 0.0004$	$-0.3077 \pm 0.0042$
5. 55 P U	$0.6511 \pm 0.0003$	$-0.3032 \pm 0.0076$

TABLE 10 Critical bucklings,  $B_c^2$

Lattice name	$B_c^2 (\times 10^{-2} \text{ cm}^{-2})$	Note
1. 50U	$0.833 \pm 0.010$	pattern=28
1. 83U	$0.943 \pm 0.013$	=24
2. 48U	$0.983 \pm 0.008$	=20
3. 00U	$0.952 \pm 0.014$	=18
2. 42P U	$0.808 \pm 0.004$	
2. 98P U	$0.828 \pm 0.004$	
4. 24P U	$0.779 \pm 0.003$	on 1972-4-1
5. 55P U	$0.651 \pm 0.002$	

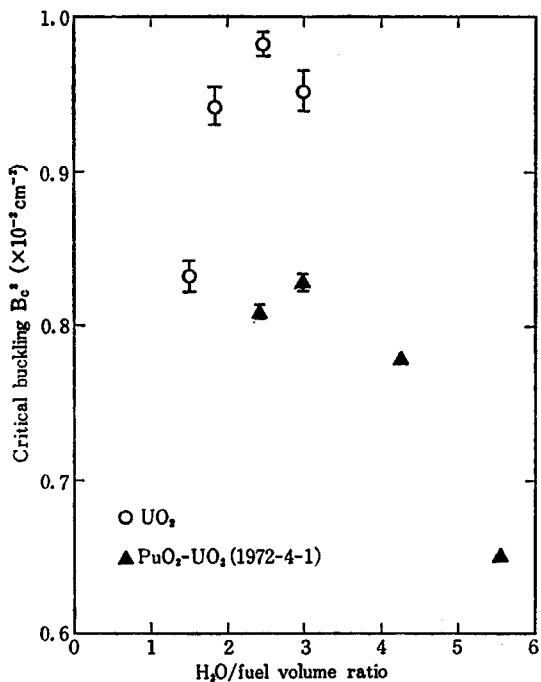


Fig. 5 Critical buckling of unperturbed lattices at 20°C.

## 5. Summary

The critical sizes of the H<sub>2</sub>O-moderated lattices with the 2.6 w/o UO<sub>2</sub> and 3.0 w/o PuO<sub>2</sub>-natural UO<sub>2</sub> fuel rods were measured in the range of the water-to-fuel volume ratio in the lattice cell from 1.50 to 3.00 for UO<sub>2</sub> lattices and from 2.42 to 5.55 for the PuO<sub>2</sub>-UO<sub>2</sub> lattices. The geometry of those lattices was a rectangular parallelepiped. The temperature of the lattice was varied from room temperature to 80°C. Some critical sizes of the perturbed lattices with a water gap and liquid poison are also presented. The critical sizes were determined with the precision of less than  $1 \times 10^{-4} \delta k/k$ .

In relation to the critical sizes of the unperturbed lattices in a simple geometry, following physics parameters were obtained :

- 1) temperature coefficient of reactivity
- 2) water-level worth
- 3) reflector saving
- 4) ratio between a migration area and an infinite multiplication factor
- 5) ratio between an effective delayed-neutron fraction and a prompt-neutron life time.

The critical water levels of the unperturbed lattices were normalized to the values at 20°C. From these normalized critical sizes, the critical bucklings were calculated for every water-to-fuel volume ratio of the lattice.

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## A1. Atomic Number Densities of Materials in Lattice

The atomic number density of each material in the lattice is shown regionwise in TABLE A1.1. As  $^{241}\text{Pu}$  decays rapidly into  $^{241}\text{Am}$  with a half-life of 14.5 years<sup>1)</sup>, they are listed in TABLE A1.2 as a function of time on the basis of the composition assayed on August 16, 1971. Other nuclides were treated as stable.

The atomic number densities of  $^{241}\text{Pu}$  and  $^{241}\text{Am}$  were calculated by

$$N^{\text{Pu}} = N_0^{\text{Pu}} \cdot e^{-\lambda^{\text{Pu}} \cdot t}$$

$$N^{\text{Am}} = N_0^{\text{Am}} + N_0^{\text{Pu}} \cdot (1 - e^{-\lambda^{\text{Pu}} \cdot t}),$$

where

$N^{\text{Pu}}$ ,  $N^{\text{Am}}$  = atomic number densities of  $^{241}\text{Pu}$  and  $^{241}\text{Am}$ , respectively, (atoms/cm<sup>3</sup>)

$N_0^{\text{Pu}}$ ,  $N_0^{\text{Am}}$  = intial values of  $^{241}\text{Pu}$  and  $^{241}\text{Am}$ , respectively, (atoms/cm<sup>3</sup>)

$\lambda^{\text{Pu}}$  = decay constant of  $^{241}\text{Pu}$ ,  $1.31 \times 10^{-4}$  (1/day),

$t$  = elapsed time after the date of assaying, (day).

TABLE A1.1 Atomic number densities

Region	Material	Atomic number density at 20°C ( $\times 10^{24}$ atoms/cm <sup>3</sup> )	
		2.6 w/o UO <sub>2</sub>	3.0 w/o PuO <sub>2</sub> -UO <sub>2</sub>
Fuel	$^{234}\text{U}$	—	$7.436 \times 10^{-7}$
	$^{235}\text{U}$	$6.086 \times 10^{-4}$	$9.393 \times 10^{-5}$
	$^{238}\text{U}$	$2.255 \times 10^{-2}$	$1.295 \times 10^{-2}$
	$^{238}\text{Pu}$	—	$2.000 \times 10^{-6}$
	$^{239}\text{Pu}$	—	$2.749 \times 10^{-4}$
	$^{240}\text{Pu}$	—	$8.843 \times 10^{-5}$
	$^{241}\text{Pu}$	—	$2.903 \times 10^{-5}$
	$^{242}\text{Pu}$	—	$8.124 \times 10^{-6}$
	$^{241}\text{Am}$	—	$2.121 \times 10^{-7}$
Cladding (with air gap)	O	$4.725 \times 10^{-2}$	$2.784 \times 10^{-2}$
	Aluminum Zircaloy-2	$5.587 \times 10^{-2}$ —	— $3.840 \times 10^{-2}$
Moderator	H <sub>2</sub> O	$3.338 \times 10^{-2}$	
	B		
	72 ppm	$4.024 \times 10^{-5}$	
	147 "	$8.155 \times 10^{-5}$	
	345 "	$1.919 \times 10^{-6}$	
	554 "	$3.082 \times 10^{-6}$	

\*) Date of assaying; on 1971-8-16.

TABLE A1.2 Atomic number densities of  $^{241}\text{Pu}$  and  $^{241}\text{Am}$  as a function of time

Date	Elapsed time (days)	Atomic number density ( $\times 10^{24}$ atoms/cm <sup>3</sup> )	
		$^{241}\text{Pu}$	$^{241}\text{Am}$
1971-8-19	0	$2.903 \times 10^{-6}$	$2.121 \times 10^{-7}$
1972-4-1	226	2.819	$1.059 \times 10^{-6}$
1973-4-1	591	2.687	2.374
1974-4-1	956	2.562	3.629
1975-4-1	1321	2.442	4.824
1976-4-1	1686	2.328	5.964
1977-4-1	2051	2.219	7.051

### Reference

- 1) Vaninbroukx R.: EUR 5194e, "The Half-Life of Some Long-Lived Actinides" (1974)

## A2. Table of Critical Sizes

The critical sizes of the UO<sub>2</sub> and PuO<sub>2</sub>-UO<sub>2</sub> lattices are listed here. The explanation of the data set is given below.

**Example :**

(1)	(2)	(3)	(4)	(5)	(6)	(7)
1.50U	4108	1970.09.22	99.20	22.7		18
1.50U	4304	1971.03.12	98.35	14.1		18
1.50U	4305	1971.03.12	72.86	14.2		20

- (1) *Core name*; A figure gives the water-to-fuel volume ratio in the lattice cell and an alphabet does the type of the fuel rod.
- (2) *Run number*; Sequential number of the experimental run.
- (3) *Date of measurement* (year-month-day)
- (4) *Critical water level* (cm); Height from the lower end of the fuel active zone.
- (5) *Temperature of lattice* (°C)
- (6) *Boron concentration in moderator* (ppm); A blank means 0.0 ppm.
- (7) *Pattern of lattice configuration*; The number refers to the pattern illustrated in Appendix A3.

1.50U	4108	1970.09.22	99.20	22.7		18
1.50U	4304	1971.03.12	98.35	14.1		18
1.50U	4385	1971.04.30	99.98	15.1		18
1.50U	4305	1971.03.12	72.86	14.2		20
1.50U	4384	1971.04.30	74.11	16.0		20
1.50U	4306	1971.03.12	60.70	14.1		22
1.50U	4383	1971.04.28	61.18	16.2		22
1.50U	5439	1973.06.13	60.29	21.0		22
1.50U	5440	1973.06.13	60.70	30.1		22
1.50U	5441	1973.06.13	61.28	41.1		22
1.50U	5442	1973.06.14	61.89	49.2		22
1.50U	5443	1973.06.14	62.98	61.2		22
1.50U	5445	1973.06.14	63.95	70.0		22
1.50U	5446	1973.06.14	65.04	78.5		22
1.50U	4307	1971.03.12	52.91	14.1		24
1.50U	4382	1971.04.28	53.33	16.2		24
1.50U	4308	1971.03.12	47.63	14.3		26
1.50U	4381	1971.04.28	47.84	16.4		26
1.50U	4309	1971.03.12	43.74	14.2		28
1.50U	4380	1971.04.27	43.92	16.3		28
1.50U	5629	1974.06.12	44.01	19.0		28
1.50U	4310	1971.03.12	40.83	14.1		29
1.50U	4379	1971.04.27	40.84	16.0		29
1.50U	4061	1970.07.23	94.16	24.0	554.0	30
1.50U	5630	1974.06.13	42.42	19.0		104
1.50U	5631	1974.06.13	48.80	19.0		108
1.50U	5632	1974.06.13	64.05	19.0		111
1.50U	5633	1974.06.13	100.47	19.1		112
1.50U	5634	1974.06.14	41.79	19.1		119

1.83U	313	1963.06.07	131.85	18.0	1	
1.83U	314	1963.06.07	131.6	18.0	1	
1.83U	968	1964.08.03	69.45	27.2	2	
1.83U	1107	1964.09.03	85.62	25.8	3	
1.83U	963	1964.08.03	136.44	24.8	4	
1.83U	589	1963.12.19	139.0	11.3	6	
1.83U	590	1963.12.19	105.77	9.0	7	
1.83U	1192	1964.09.24	114.16	22.4	7	
1.83U	1191	1964.09.24	94.71	22.4	8	
1.83U	1190	1964.09.24	83.54	22.3	9	
1.83U	1189	1964.09.24	75.91	22.3	10	
1.83U	4427	1971.05.28	120.67	19.3	12	
1.83U	582	1963.12.13	113.7	11.8	13	
1.83U	4253	1971.03.02	116.33	16.3	13	
1.83U	4390	1971.05.06	114.85	16.3	13	
1.83U	5469	1973.07.11	113.01	24.7	13	
1.83U	5470	1973.07.11	114.34	34.7	13	
1.83U	5471	1973.07.11	117.01	45.3	13	
1.83U	5472	1973.07.12	119.33	54.0	13	
1.83U	5473	1973.07.12	122.15	60.3	13	
1.83U	5474	1973.07.12	126.50	69.3	13	
1.83U	5475	1973.07.12	131.07	76.7	13	
1.83U	4103	1970.09.16	81.28	23.0	14	
1.83U	4254	1971.03.02	75.68	13.9	15	
1.83U	4392	1971.05.07	75.38	16.8	15	
1.83U	5790	1975.07.04	74.38	20.9	15	
1.83U	4100	1970.09.09	85.78	22.9	72.3	16
1.83U	4393	1971.05.07	66.76	17.0	16	
1.83U	4093	1970.09.03	96.85	23.9	146.6	18
1.83U	4255	1971.03.02	60.32	13.9	18	
1.83U	4394	1971.05.07	60.12	17.0	18	
1.83U	4397	1971.05.11	55.45	17.3	19	
1.83U	4256	1971.03.02	51.69	13.9	20	
1.83U	4398	1971.05.11	51.57	17.6	20	
1.83U	5461	1973.07.04	51.56	22.3	20	
1.83U	5462	1973.07.04	51.78	30.6	20	
1.83U	5463	1973.07.04	52.24	40.5	20	
1.83U	5464	1973.07.04	52.75	50.4	20	
1.83U	5465	1973.07.05	53.33	59.7	20	
1.83U	5466	1973.07.05	54.12	70.1	20	
1.83U	5467	1973.07.05	55.04	80.4	20	
1.83U	4399	1971.05.12	48.58	18.0	21	
1.83U	4257	1971.03.02	45.96	13.9	22	
1.83U	4400	1971.05.12	46.05	18.1	22	
1.83U	5330	1973.02.21	45.81	11.	22	
1.83U	5351	1973.03.29	45.81	13.8	22	
1.83U	4401	1971.05.13	43.88	18.1	23	
1.83U	4087	1970.08.31	84.99	23.0	345.0	24
1.83U	4258	1971.03.02	42.06	13.9	24	
1.83U	4402	1971.05.13	42.06	18.1	24	
1.83U	4403	1971.05.13	40.47	18.1	25	
1.83U	4076	1970.08.24	85.79	24.8	554.0	29

2,48U	4347	1971.04.08	78.69	16.0	11
2,48U	4372	1971.04.22	78.36	16.5	11
2,48U	4345	1971.04.08	59.98	15.5	13
2,48U	4373	1971.04.22	59.82	16.7	13
2,48U	5447	1973.06.20	59.96	21.7	13
2,48U	5448	1973.06.20	60.25	32.1	13
2,48U	5449	1973.06.20	60.60	40.0	13
2,48U	5450	1973.06.21	61.16	49.9	13
2,48U	5451	1973.06.21	61.89	59.9	13
2,48U	5452	1973.06.21	62.65	68.3	13
2,48U	5453	1973.06.21	63.69	78.9	13
2,48U	4344	1971.04.08	50.49	15.5	15
2,48U	4374	1971.04.23	50.46	17.0	15
2,48U	4336	1971.04.07	44.51	15.5	18
2,48U	4378	1971.04.23	44.52	17.3	18
2,48U	4335	1971.04.07	40.41	15.5	20
2,48U	4075	1970.08.03	86.89	25.9	554.0
					29

3,00U	4362	1971.04.14	90.65	15.6	5
3,00U	4363	1971.04.16	90.56	16.0	5
3,00U	4361	1971.04.14	64.39	15.6	11
3,00U	4365	1971.04.19	64.43	16.0	11
3,00U	5454	1973.06.27	64.38	23.0	11
3,00U	5455	1973.06.27	64.63	32.7	11
3,00U	5456	1973.06.27	65.04	42.3	11
3,00U	5457	1973.06.27	65.52	50.7	11
3,00U	5458	1973.06.28	66.21	61.3	11
3,00U	5459	1973.06.28	67.17	71.9	11
3,00U	5460	1973.06.28	67.86	78.8	11
3,00U	4360	1971.04.14	52.88	15.5	13
3,00U	4366	1971.04.19	52.82	16.3	13
3,00U	4367	1971.04.19	52.82	16.3	13
3,00U	4358	1971.04.14	46.06	15.3	15
3,00U	4368	1971.04.21	46.01	16.5	15
3,00U	5651	1974.07.04	41.79	19.3	17
3,00U	4349	1971.04.13	41.53	15.0	18
3,00U	4369	1971.04.21	41.51	16.5	18
3,00U	5652	1974.07.04	46.97	19.3	101
3,00U	5657	1974.07.11	46.84	19.8	101
3,00U	5653	1974.07.04	65.81	19.4	105
3,00U	5654	1974.07.04	130.77	19.4	109

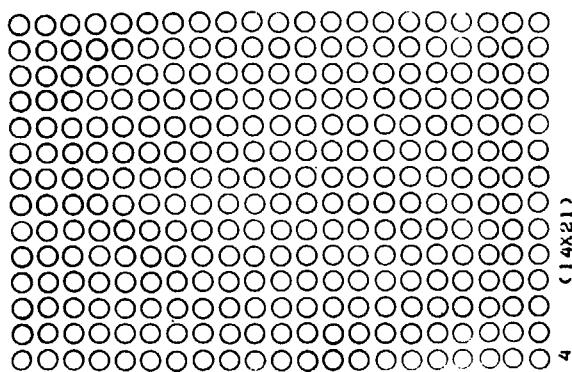
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2,42PU	5584	1974,05,14	69,45	14.6	25
2,42PU	5109	1972,06,07	59,53	19.1	26
2,42PU	5390	1973,05,14	61,93	18.7	26
2,42PU	5392	1973,05,14	61,86	18.7	26
2,42PU	5393	1973,05,14	61,92	22.9	26
2,42PU	5394	1973,05,14	62,12	30.4	26
2,42PU	5395	1973,05,15	62,58	41.5	26
2,42PU	5396	1973,05,15	63,04	49.2	26
2,42PU	5397	1973,05,15	63,75	59.3	26
2,42PU	5398	1973,05,15	64,61	69.3	26
2,42PU	5399	1973,05,15	65,27	76.3	26
2,42PU	5585	1974,05,14	63,97	14.8	26
2,42PU	5751	1975,05,16	66,38	16.2	26
2,42PU	5110	1972,06,07	56,25	19.2	27
2,42PU	5586	1974,05,14	59,98	14.9	27
2,42PU	5750	1975,05,16	61,99	16.1	27
2,42PU	5111	1972,06,07	53,29	19.6	28
2,42PU	5391	1973,05,14	55,00	18.7	28
2,42PU	5587	1974,05,14	56,61	15.0	28
2,42PU	5749	1975,05,16	58,30	16.1	28
2,42PU	5588	1974,05,15	57,26	15.2	104
2,42PU	5592	1974,05,15	58,98	15.6	119

2.98PU	5093	1972.05.18	67.09	17.5	21
2.98PU	5094	1972.05.18	61.49	17.6	22
2.98PU	5265	1972.12.06	63.34	14.7	22
2.98PU	5322	1973.02.07	63.62	12.9	22
2.98PU	5348	1973.03.15	63.99	11.9	22
2.98PU	5362	1973.04.05	64.10	15.4	22
2.98PU	5363	1973.04.06	64.08	15.6	22
2.98PU	5401	1973.05.22	64.39	19.9	22
2.98PU	5406	1973.05.23	64.42	21.1	22
2.98PU	5407	1973.05.23	64.42	21.2	22
2.98PU	5408	1973.05.23	64.58	31.6	22
2.98PU	5409	1973.05.23	64.83	40.8	22
2.98PU	5410	1973.05.23	65.18	50.1	22
2.98PU	5411	1973.05.23	65.72	59.9	22
2.98PU	5412	1973.05.23	66.25	67.7	22
2.98PU	5413	1973.05.24	67.11	78.5	22
2.98PU	5528	1973.06.06	65.53	17.2	22
2.98PU	5603	1974.05.28	66.86	17.1	22
2.98PU	5759	1975.05.21	69.38	16.5	22
2.98PU	5095	1972.05.18	57.37	17.8	23
2.98PU	5403	1973.05.22	59.88	20.0	23
2.98PU	5529	1973.06.06	60.84	17.3	23
2.98PU	5604	1974.05.28	61.91	17.2	23
2.98PU	5758	1975.05.21	63.87	16.4	23
2.98PU	5530	1973.06.06	56.87	17.4	24
2.98PU	5605	1974.05.28	57.82	17.2	24
2.98PU	5757	1975.05.21	59.48	16.4	24
2.98PU	5606	1974.05.28	54.71	17.3	25
2.98PU	5756	1975.05.21	56.10	16.3	25
2.98PU	5607	1974.05.28	51.93	17.4	26
2.98PU	5755	1975.05.21	53.15	16.3	26
2.98PU	5608	1974.05.28	49.81	17.5	27
2.98PU	5754	1975.05.21	50.78	16.3	27
2.98PU	5609	1974.05.28	47.77	17.6	28
2.98PU	5753	1975.05.21	48.67	16.2	28
2.98PU	5267	1972.12.06	63.55	16.0	103
2.98PU	5277	1972.12.12	63.43	16.0	103
2.98PU	5272	1972.12.06	65.32	18.5	107
2.98PU	5270	1972.12.06	57.81	17.8	113
2.98PU	5269	1972.12.06	59.45	17.8	114
2.98PU	5268	1972.12.06	60.90	16.0	115
2.98PU	5276	1972.12.07	61.39	16.3	116
2.98PU	5275	1972.12.07	56.11	16.0	117
2.98PU	5273	1972.12.07	64.89	16.2	118
2.98PU	5405	1973.05.22	66.58	20.1	118

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4,24PU	5329	1973.02.08	68.12	13.2	19
4,24PU	5415	1973.05.29	68.69	19.6	19
4,24PU	5540	1973.11.29	70.14	17.9	19
4,24PU	5060	1972.04.13	60.56	13.2	20
4,24PU	5244	1972.11.10	61.71	18.2	20
4,24PU	5416	1973.05.29	63.02	19.8	20
4,24PU	5418	1973.05.29	63.01	19.9	20
4,24PU	5419	1973.05.29	62.67	29.0	20
4,24PU	5420	1973.05.29	62.44	40.4	20
4,24PU	5421	1973.05.30	62.37	50.0	20
4,24PU	5422	1973.05.30	62.42	59.5	20
4,24PU	5423	1973.05.30	62.45	68.7	20
4,24PU	5424	1973.05.30	62.62	78.3	20
4,24PU	5541	1973.11.29	64.13	18.0	20
4,24PU	5615	1974.06.05	65.65	19.4	20
4,24PU	5769	1975.05.28	68.30	17.3	20
4,24PU	5773	1975.06.06	68.24	17.7	20
4,24PU	5062	1972.04.14	56.81	13.1	21
4,24PU	5616	1974.06.05	61.09	19.4	21
4,24PU	5768	1975.05.28	63.23	17.3	21
4,24PU	5063	1972.04.14	53.59	13.0	22
4,24PU	5417	1973.05.29	55.49	19.8	22
4,24PU	5539	1973.11.29	56.27	17.9	22
4,24PU	5617	1974.06.05	57.29	19.5	22
4,24PU	5767	1975.05.28	59.14	17.2	22
4,24PU	5064	1972.04.14	51.11	13.0	23
4,24PU	5538	1973.11.29	53.44	17.8	23
4,24PU	5618	1974.06.05	54.34	19.5	23
4,24PU	5766	1975.05.28	55.95	17.2	23
4,24PU	5619	1974.06.06	51.75	19.4	24
4,24PU	5765	1975.05.28	53.16	17.2	24
4,24PU	5621	1974.06.06	47.73	19.5	26
4,24PU	5764	1975.05.28	48.91	17.1	26
4,24PU	5763	1975.05.28	47.22	17.1	27
4,24PU	5622	1974.06.06	44.68	19.5	28
4,24PU	5762	1975.05.28	45.67	17.0	28
4,24PU	5626	1974.06.06	50.37	19.6	104
4,24PU	5624	1974.06.06	66.06	19.5	108
4,24PU	5627	1974.06.06	58.76	19.6	119
5,55PU	5077	1972.04.26	66.40	16.2	21
5,55PU	5426	1973.06.06	69.09	20.7	21
5,55PU	5080	1972.04.28	62.21	18.0	22
5,55PU	5427	1973.06.06	64.44	20.8	22
5,55PU	5432	1973.06.07	64.45	21.1	22
5,55PU	5433	1973.06.07	63.64	31.2	22
5,55PU	5434	1973.06.07	62.92	41.4	22
5,55PU	5435	1973.06.07	62.37	50.3	22
5,55PU	5436	1973.06.08	61.99	57.2	22
5,55PU	5437	1973.06.08	61.48	67.6	22
5,55PU	5438	1973.06.08	61.12	75.9	22
5,55PU	5078	1972.04.26	58.98	16.4	23
5,55PU	5428	1973.06.06	61.04	20.8	23
5,55PU	5429	1973.06.06	58.02	20.9	24
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5,55PU	5431	1973.06.06	53.45	21.0	26

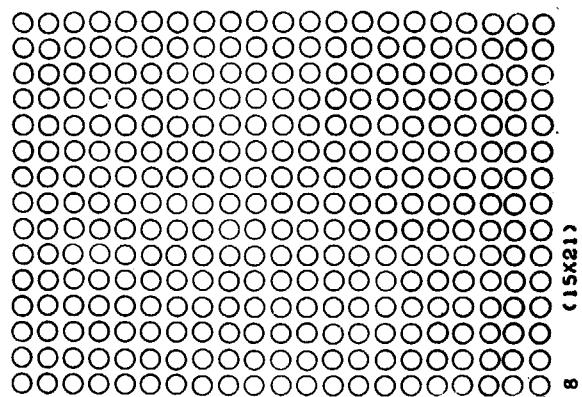
### A3. Patterns of Lattice Configurations

Horizontal cross-sectional views of the lattices are illustrated in the order of the number of the pattern. The numbers from 1 to 30 correspond to the uniform lattices and the numbers from 101 to 119 to the lattices with a water gap.



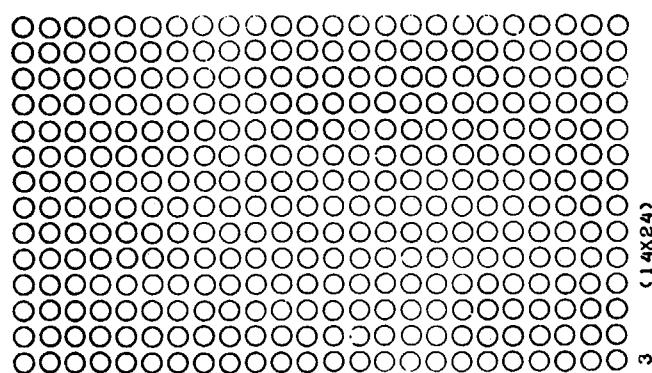
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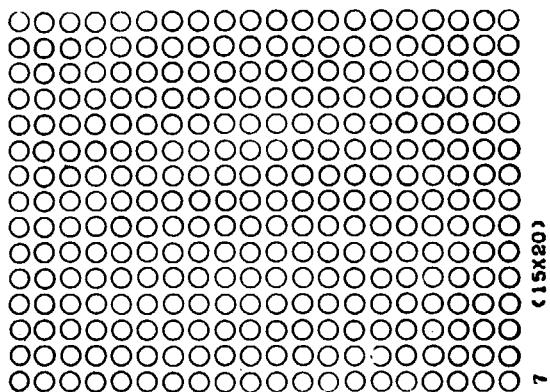
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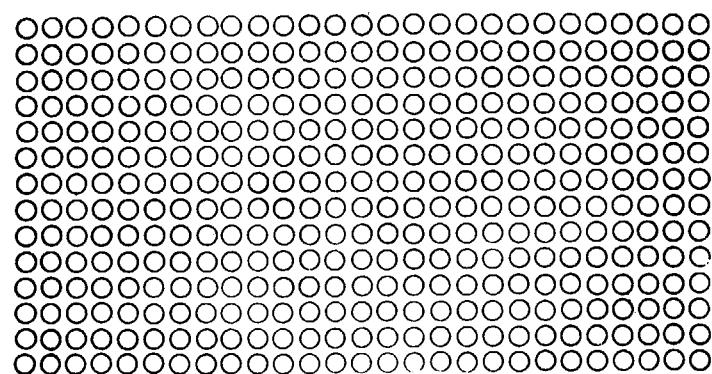
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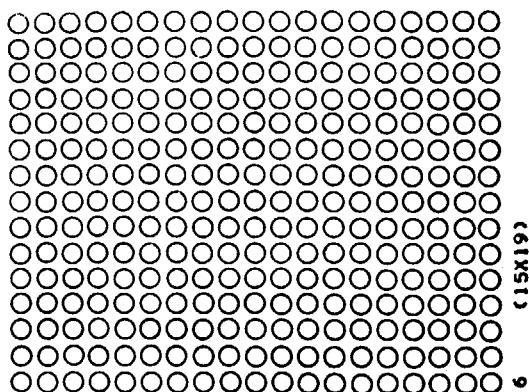
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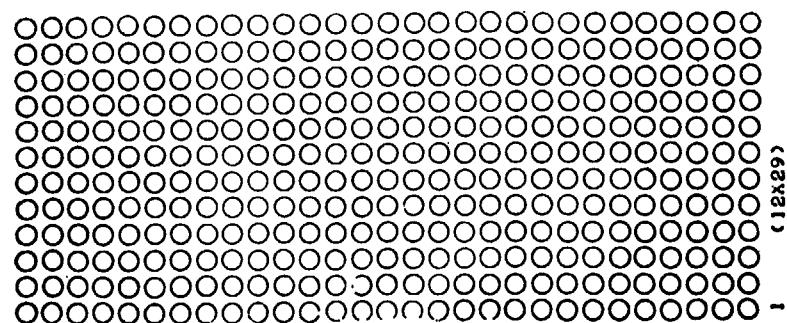
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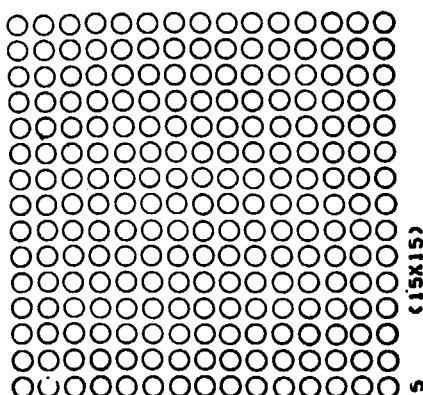
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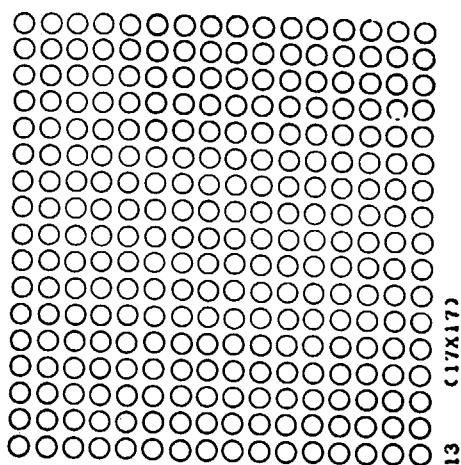
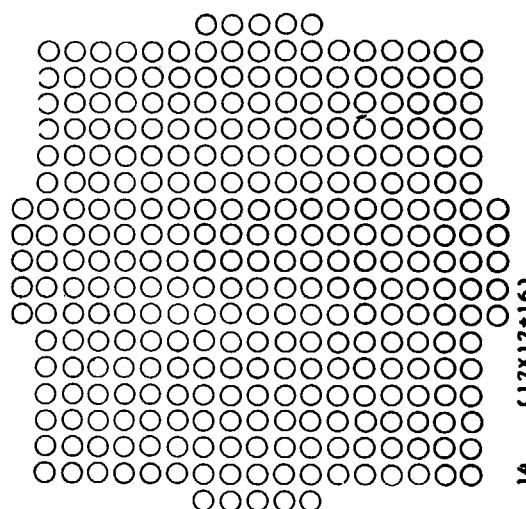
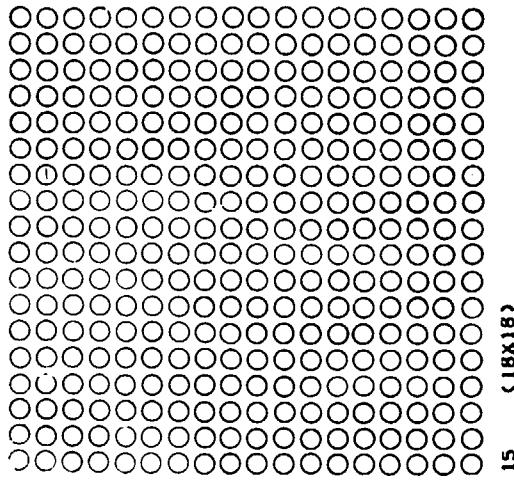
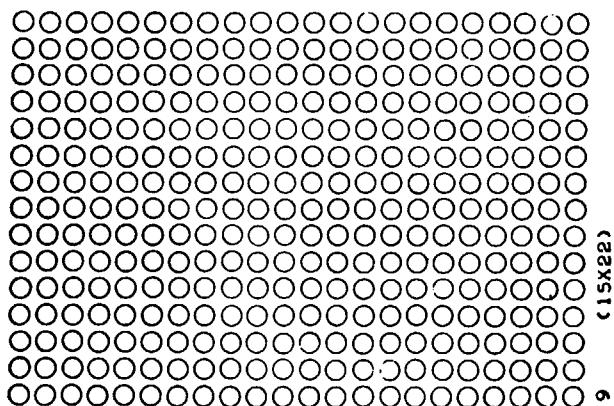
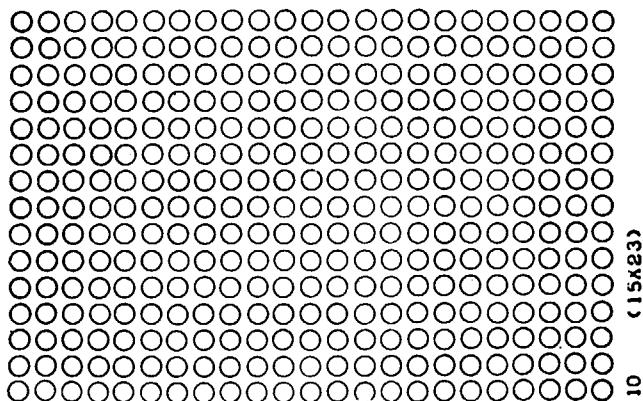
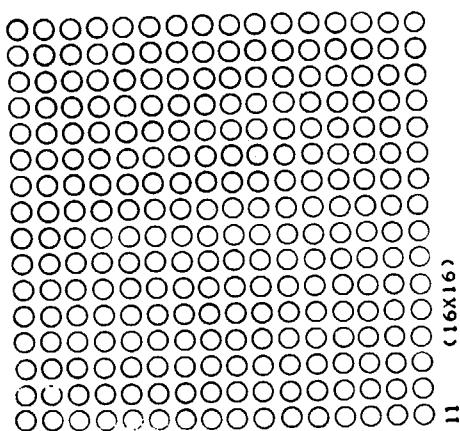
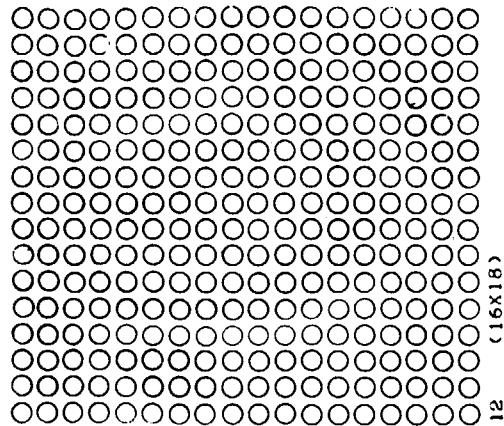
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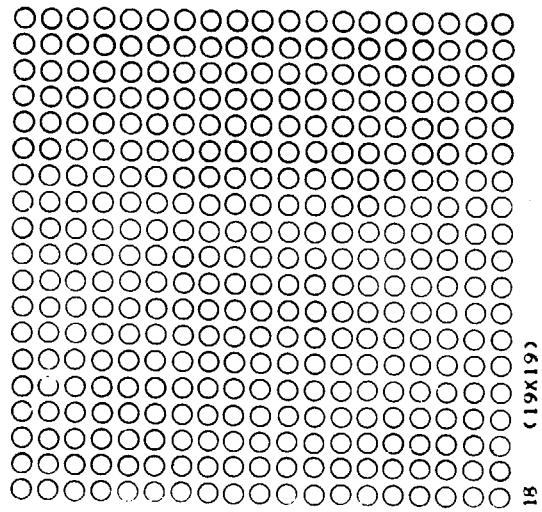
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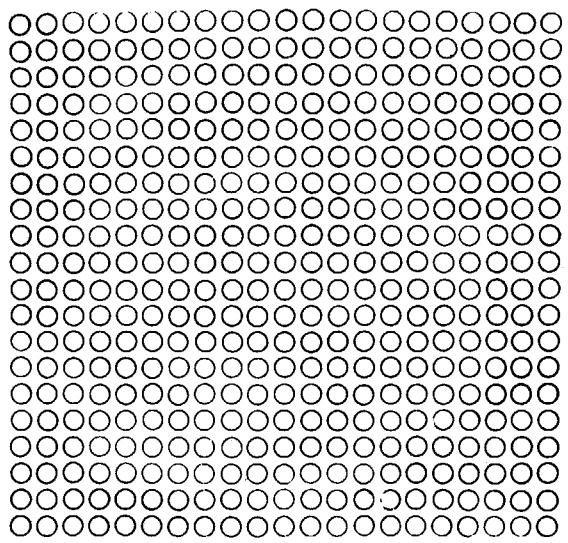
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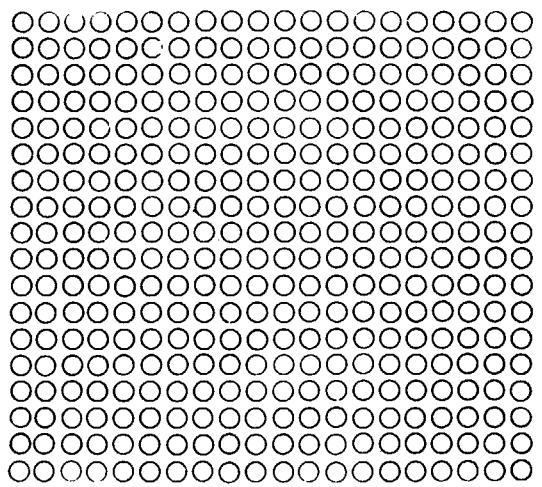




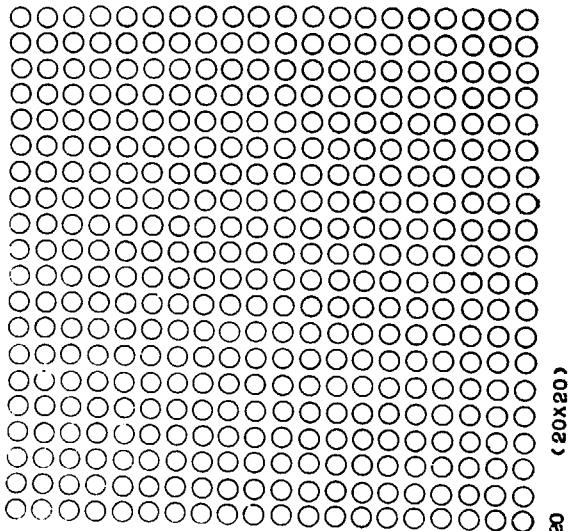
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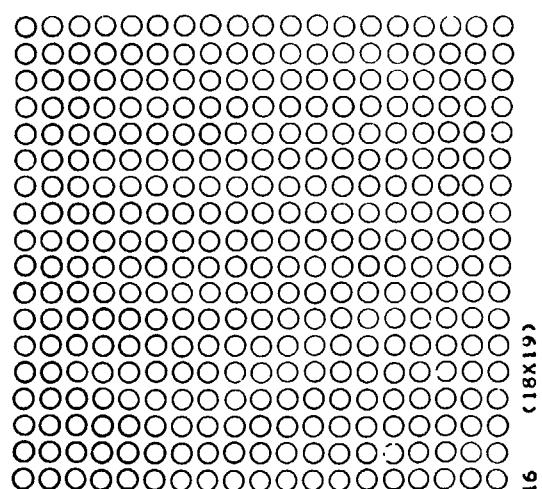
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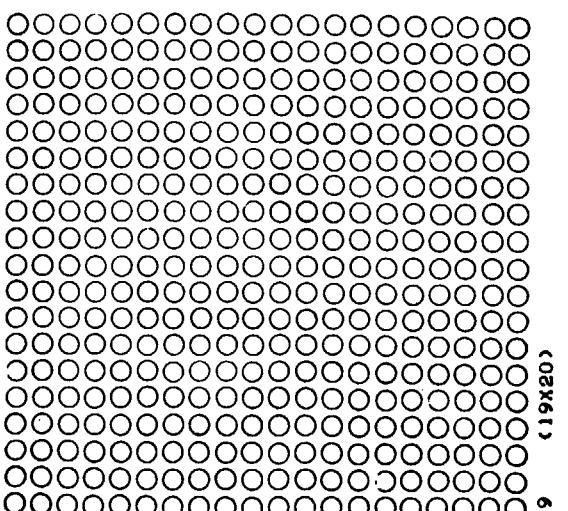
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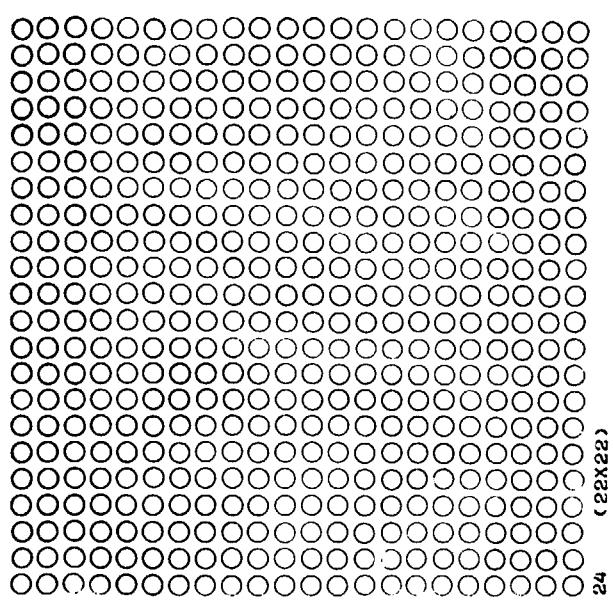
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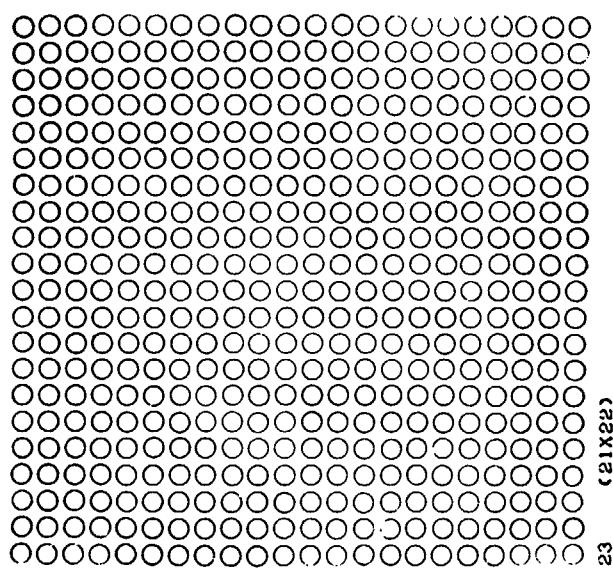
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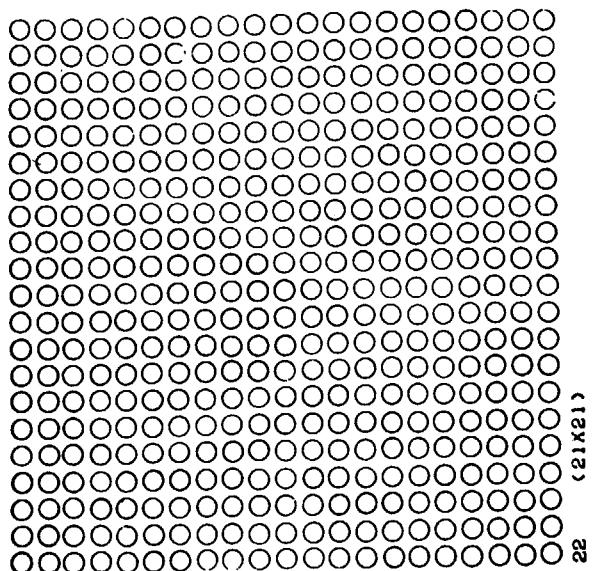
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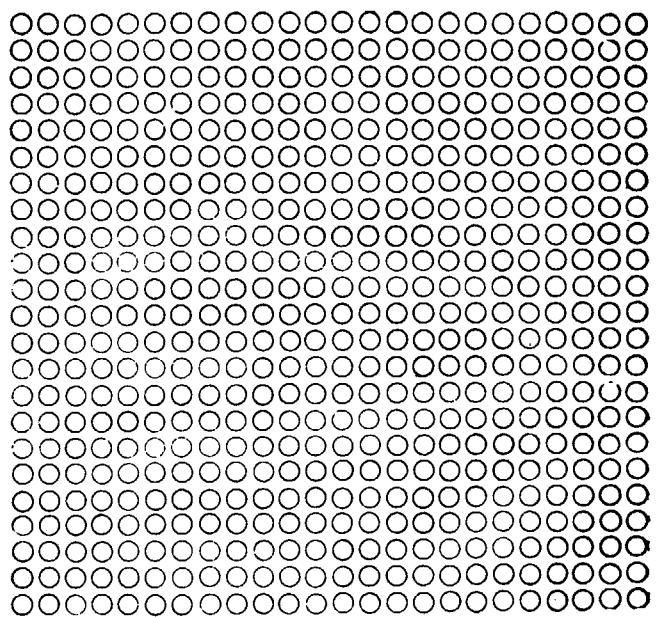
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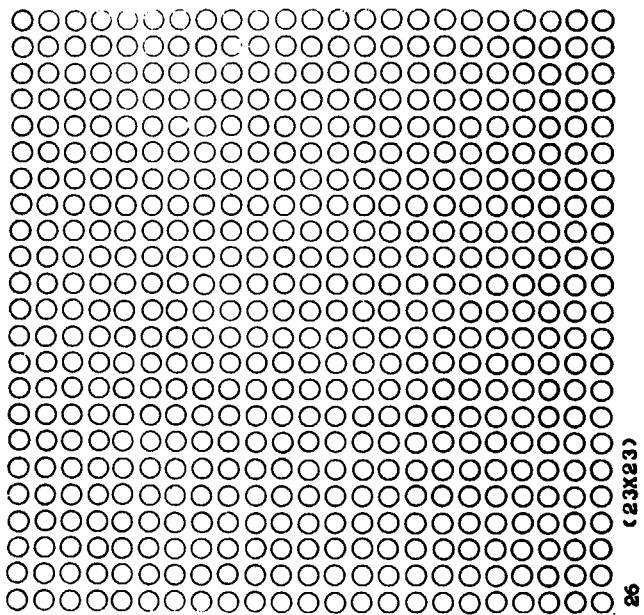
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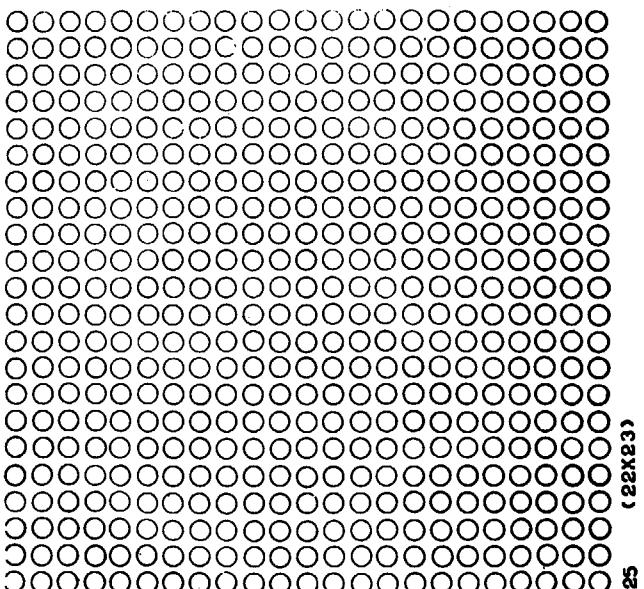
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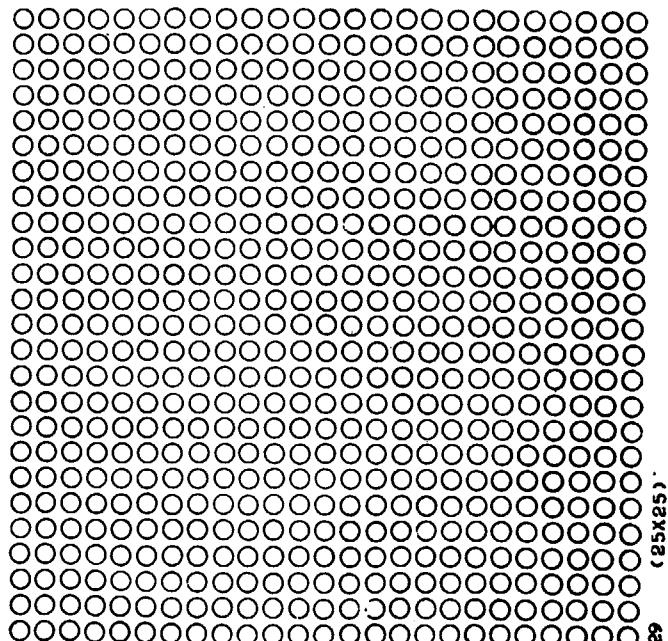
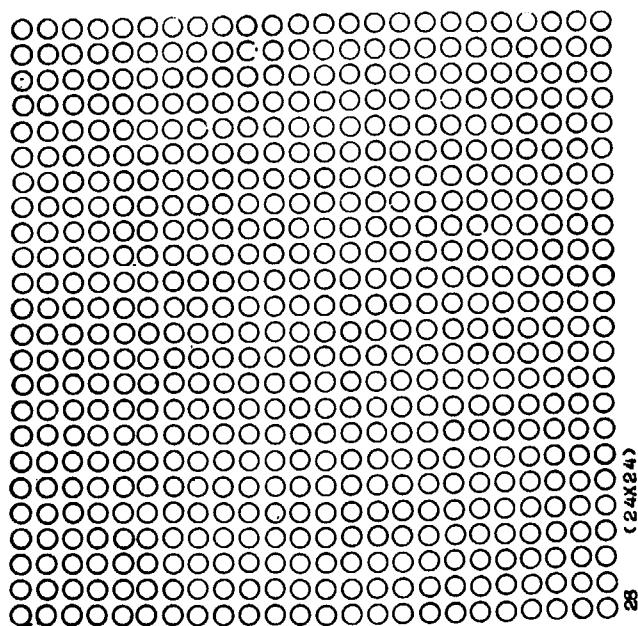
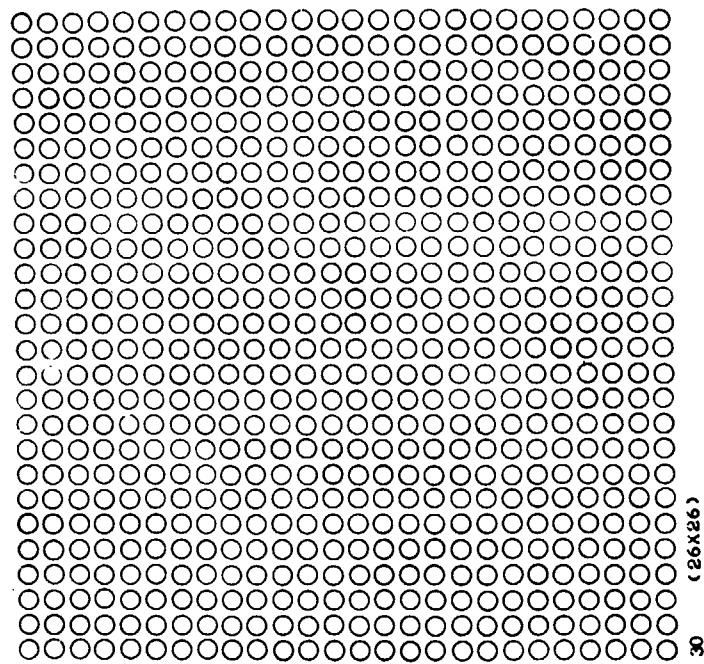
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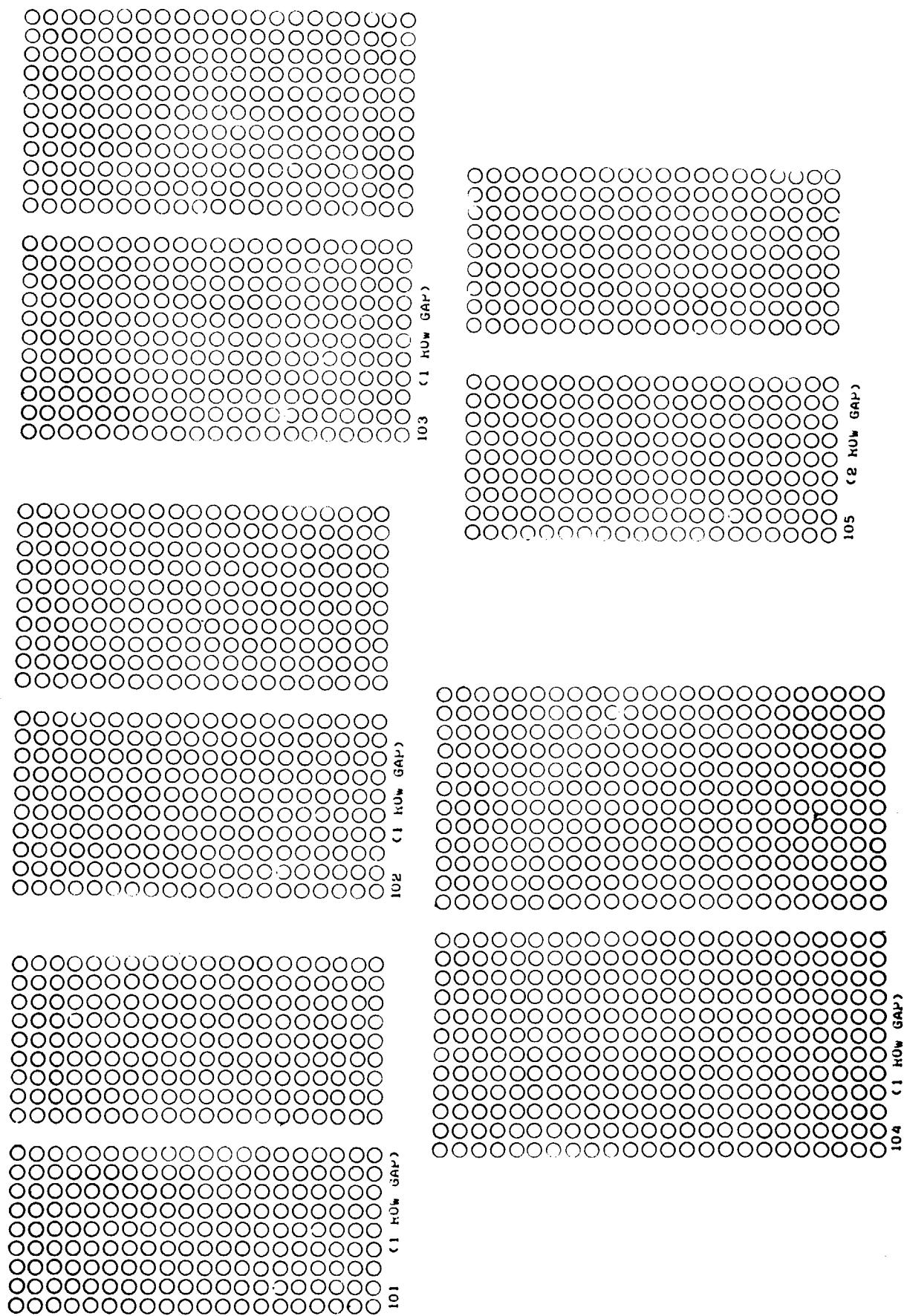


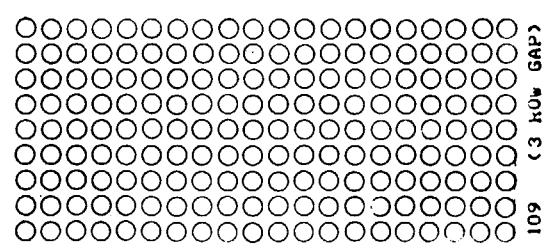
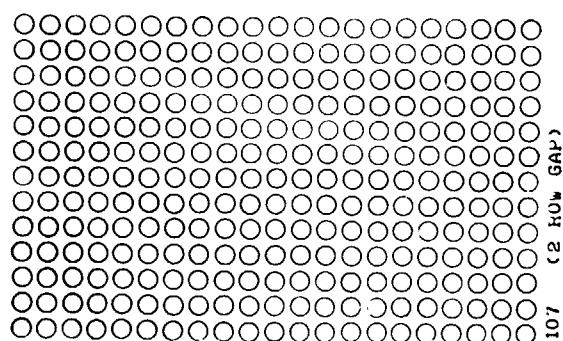
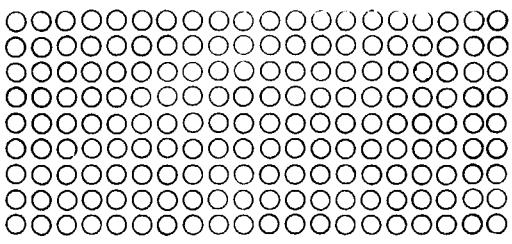
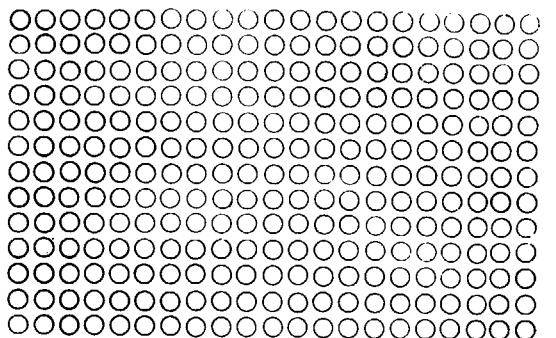
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25 (22x23)





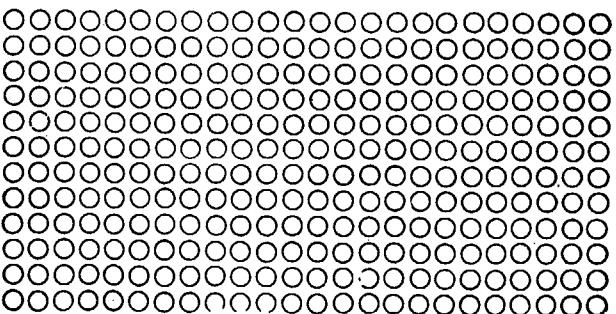
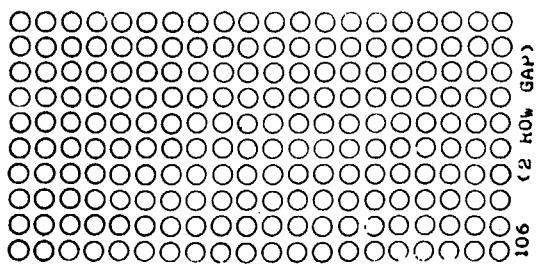
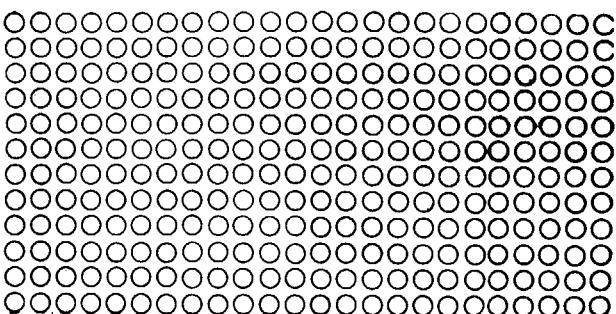
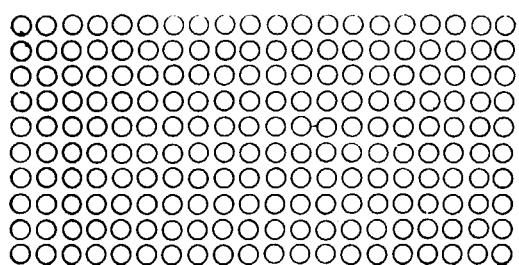


108

109

(2 H0w GAP)

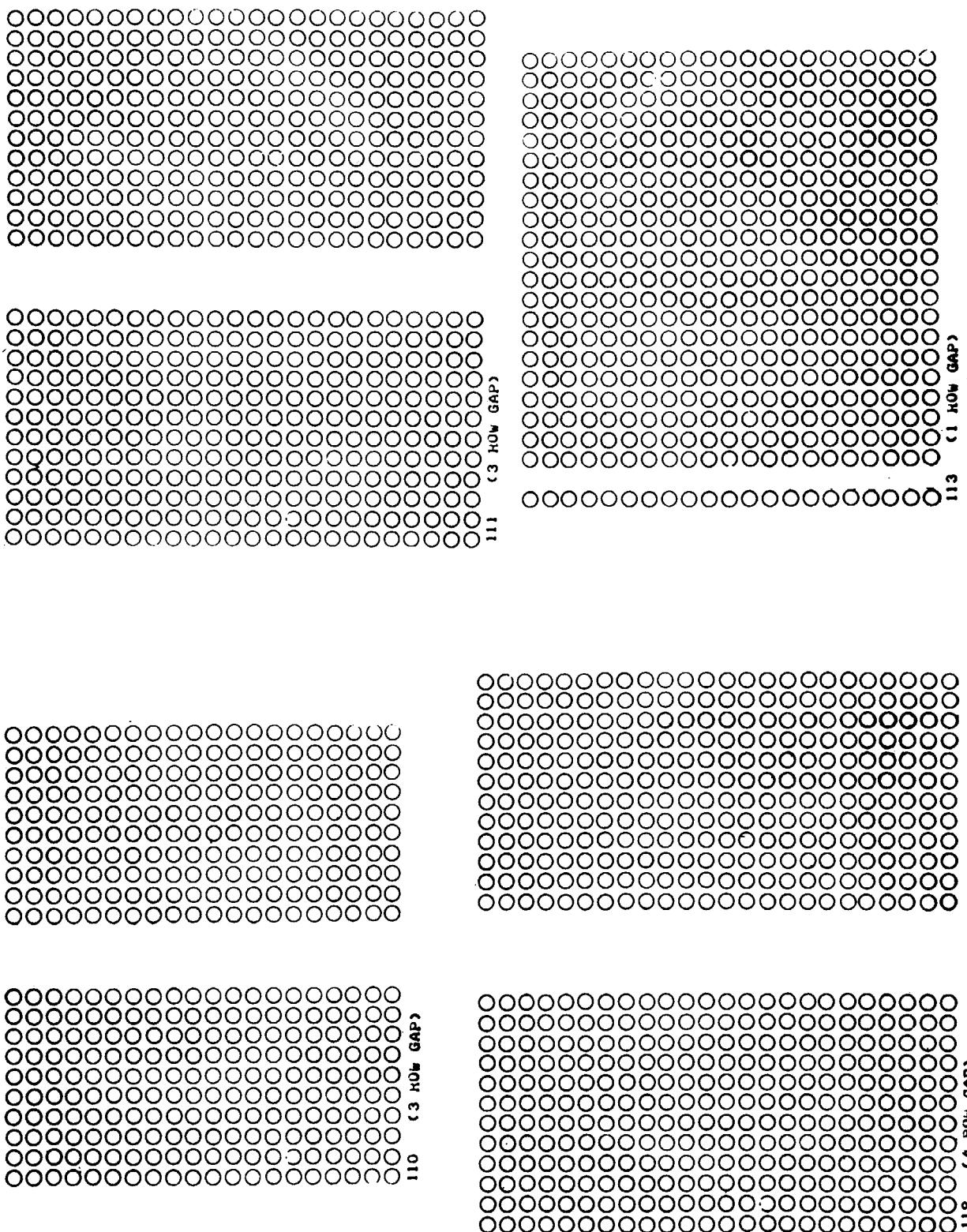
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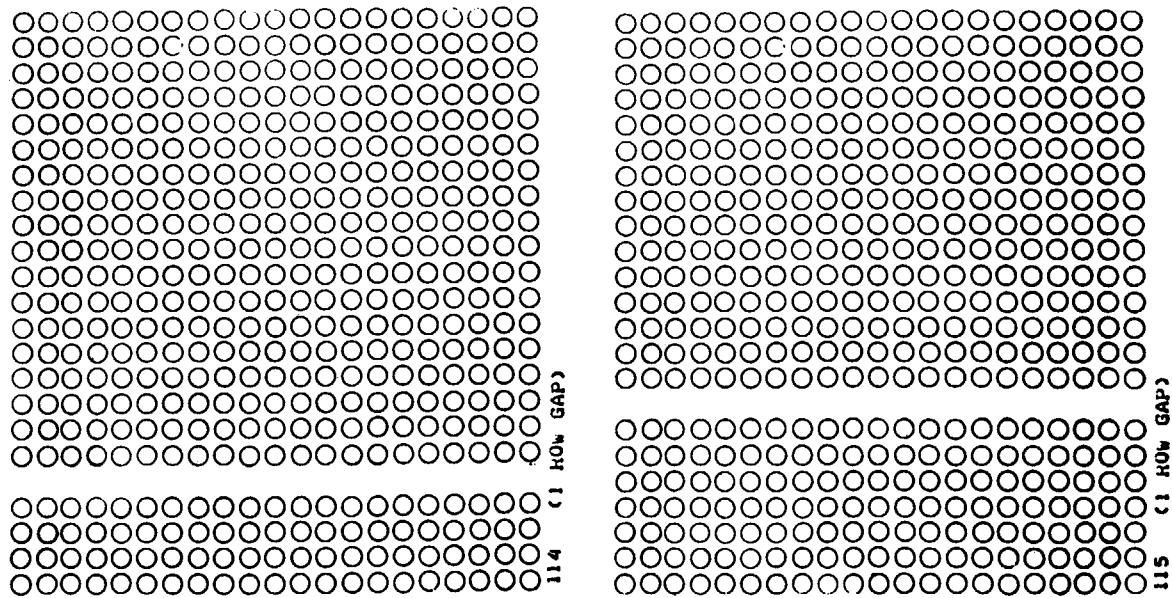
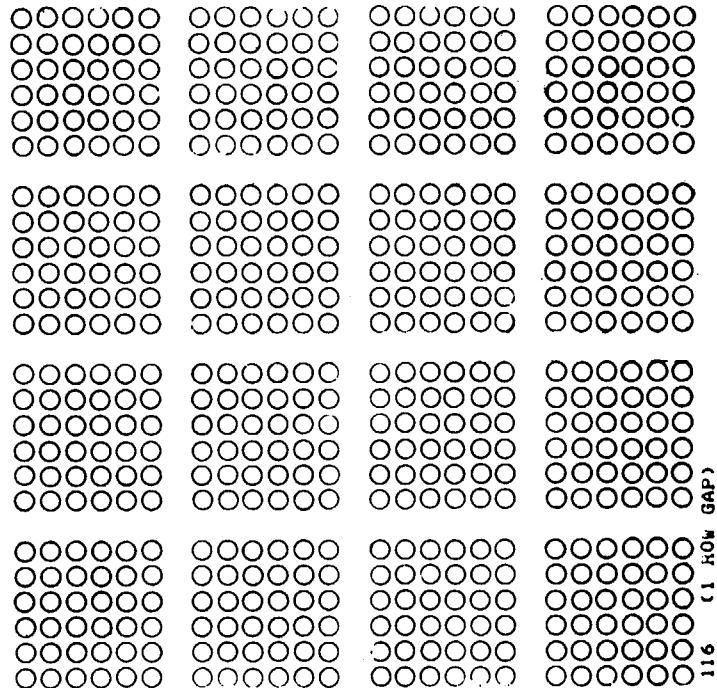


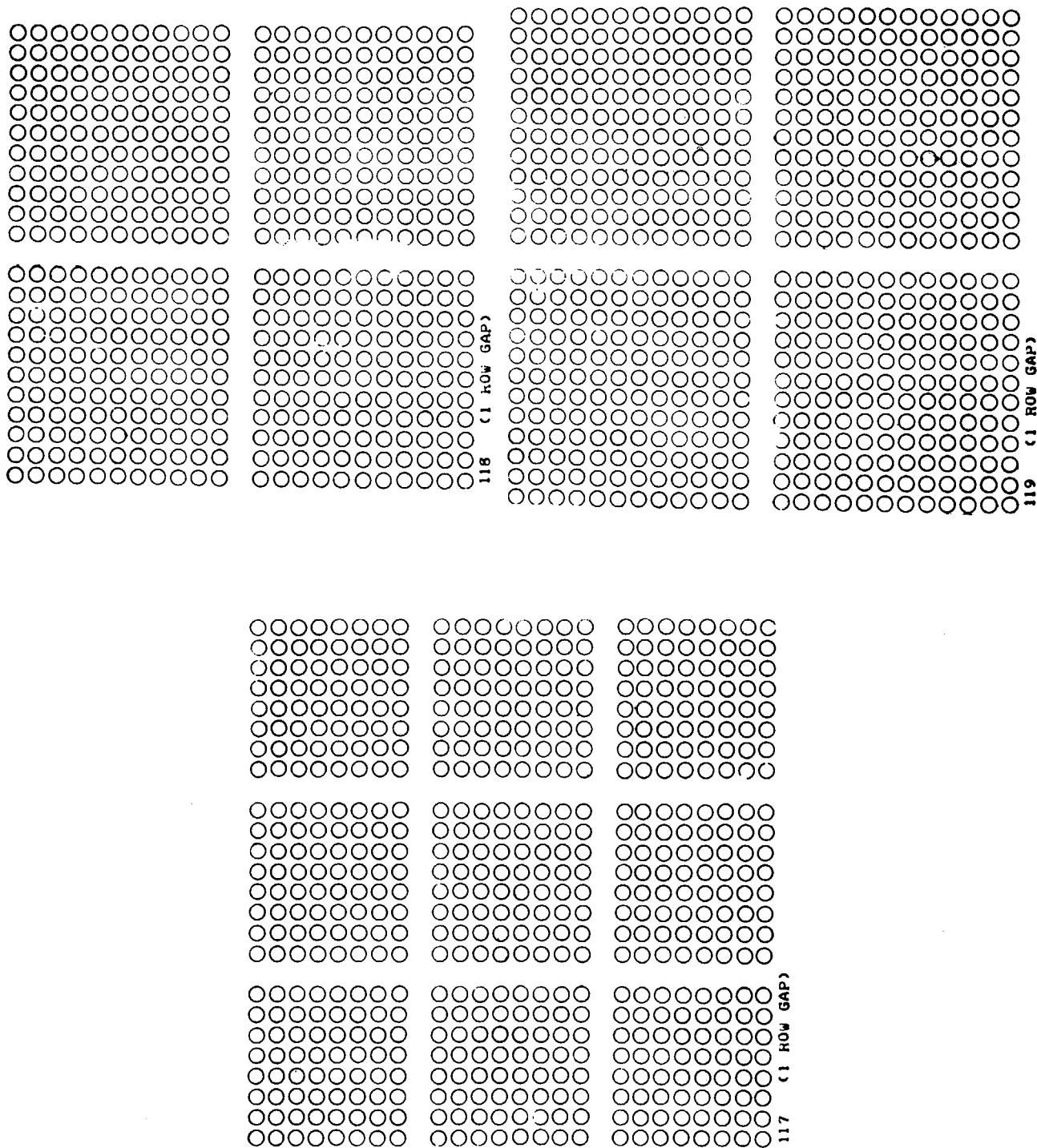
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109

(2 H0w GAP)







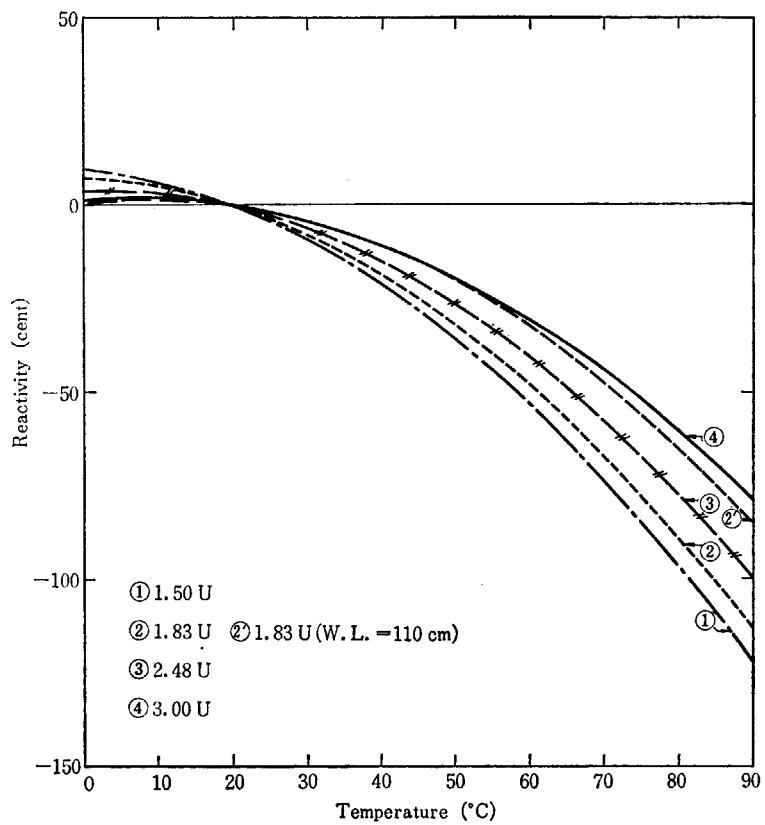
#### A4. Reactivity Variations of Unperturbed Lattices with Temperature

The variations of the reactivity with temperature are shown for the unperturbed lattices in the range of the temperature from 0 to 90°C at the water level around 60 cm. The reactivity was calculated as the deviated amount from the value at 20°C. The results are shown in TABLE A4.1 and FIGS. A4.1 and A4.2. The variation at the high water level of 110 cm is also listed for the 1.83 U lattices.

The measurements on the  $\text{PuO}_2\text{-}\text{UO}_2$  lattices were carried out from May 14 to June 8 in 1973.

TABLE A4.1 Reactivity variations with temperature (unit: cent)

Temperature (°C)	1.50 U	1.83 U	2.48 U	3.00 U	1.83 U	2.42 PU	2.98 PU	4.24 PU	5.55 PU
0	7.6 ± 1.0	9.9 ± 1.7	3.8 ± 1.5	1.3 ± 1.0	0.6 ± 2.0	4.9 ± 2.2	-4.7 ± 0.8	-37.6 ± 3.9	-78.1 ± 0.6
10	5.2 0.7	6.3 1.2	3.3 1.0	1.8 0.7	1.6 1.4	5.0 1.4	-0.1 0.5	-16.7 2.5	-37.5 0.4
20	0.0 0.5	0.0 0.8	0.0 0.6	0.0 0.5	0.0 0.9	0.0 0.9	0.0 0.4	0.0 1.5	0.0 0.3
30	-7.9 0.4	-9.1 0.7	-6.0 0.5	-4.2 0.3	-4.3 0.7	-10.0 0.7	-4.5 0.3	12.5 1.2	34.5 0.3
40	-18.5 0.5	-20.9 0.7	-14.7 0.5	-10.6 0.3	-11.2 0.7	-25.1 0.7	-13.6 0.4	20.9 1.5	65.9 0.3
50	-31.9 0.5	-35.4 0.7	-26.2 0.5	-19.5 0.4	-20.7 0.7	-45.3 0.7	-27.2 0.4	25.0 1.8	94.3 0.3
60	-48.0 0.4	-52.7 0.7	-40.4 0.5	-30.6 0.4	-32.8 0.7	-70.5 0.6	-45.4 0.4	25.0 2.2	119.7 0.4
70	-66.8 0.4	-72.8 0.7	-57.3 0.5	-44.1 0.5	-47.6 0.7	-100.8 0.7	-68.2 0.4	20.8 2.6	142.0 0.4
80	-88.4 0.4	-95.6 0.8	-77.0 0.7	-59.8 0.5	-65.1 0.9	-136.2 1.1	-95.5 0.5	12.4 2.8	161.3 0.5
90	-112.6 0.5	-121.1 0.7	-99.4 1.1	-78.0 0.4	-85.2 1.4	-176.6 1.8	-127.4 0.7	-0.2 2.5	177.5 0.7
Water level (cm)	60	50	60	60	110	60	60	60	60

Fig. A4.1 Reactivity variations with temperature in unperturbed  $\text{UO}_2$  lattices.

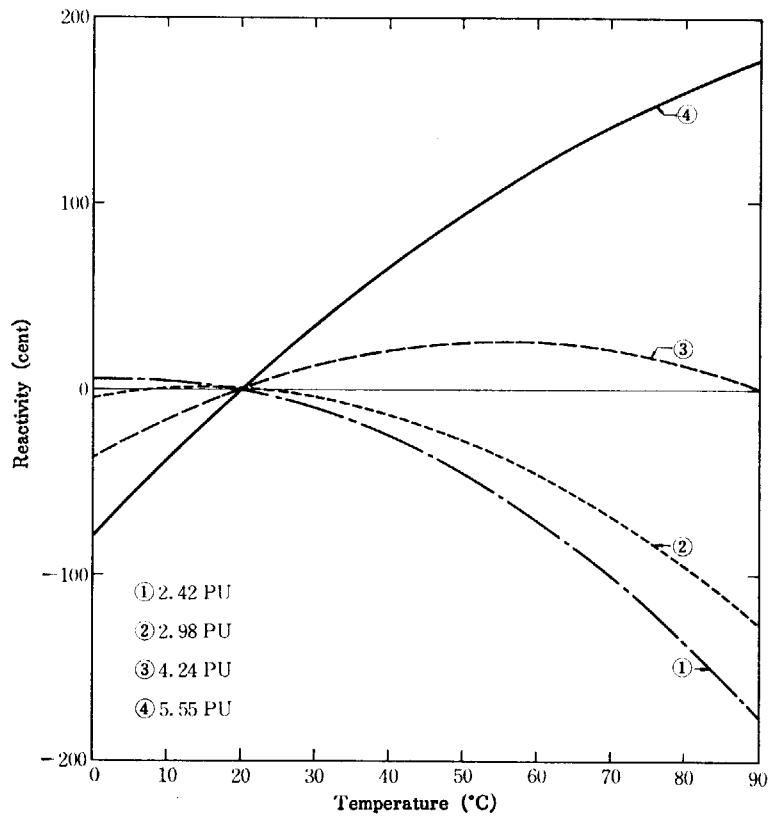


Fig. A4.2 Reactivity variations with temperature in unperturbed PuO<sub>2</sub>-UO<sub>2</sub> lattices.

## A5. Water-level Worths

The integral and differential water-level worths are shown here at some specified water levels. The reference water level of the integral water-level worth is 40.0 cm.

The measurements on the PuO<sub>2</sub>-UO<sub>2</sub> lattices were carried out from April 12 to June 7 in 1972.

TABLE A5.1 Integral and differential water-level worths of UO<sub>2</sub> lattices

Water level (cm)	1.50U		1.83U		2.48U		3.00U	
	Integral	Differential	Integral	Differential	Integral	Differential	Integral	Differential
40.0	0	5.19 ± 0.11	0	5.34 ± 0.09	0	5.67 ± 0.10	0	5.61 ± 0.16
45.0	227 ± 5	3.95 ± 0.08	233 ± 4	4.06 ± 0.07	247 ± 4	4.29 ± 0.07	244 ± 7	4.24 ± 0.11
50.0	401 8	3.08 0.06	412 7	3.16 0.05	436 8	3.32 0.06	431 12	3.28 0.08
55.0	539 11	2.45 0.05	553 9	2.50 0.04	584 10	2.63 0.04	577 15	2.59 0.06
60.0	649 13	1.97 0.04	665 11	2.02 0.03	701 12	2.11 0.03	693 18	2.08 0.04
65.0	738 14	1.62 0.03	757 12	1.65 0.02	797 13	1.72 0.03	787 20	1.70 0.03
70.0	812 15	1.34 0.02	832 13	1.37 0.02	875 15	1.42 0.02	864 21	1.40 0.03
80.0	925 17	0.952 0.016	947 15	0.969 0.012	995 17	1.005 0.016	982 23	0.990 0.017
90.0	1007 19	0.700 0.015	1030 16	0.711 0.009	1081 18	0.736 0.011	1067 25	0.724 0.012
100.0	1067 20	0.530 0.009	1092 16	0.538 0.006	1145 19	0.555 0.008	1130 26	0.546 0.008
110.0	1114 20	0.410 0.007	1139 17	0.416 0.005	1194 20	0.428 0.006	1178 26	0.421 0.006
120.0	1151 21	0.324 0.005	1176 17	0.329 0.004	1232 20	0.338 0.005	1216 27	0.332 0.005
130.0	1180 21	0.261 0.004	1206 18	0.264 0.003	1262 21	0.271 0.004	1245 27	0.266 0.003
140.0	1203 22	0.213 0.003	1230 18	0.215 0.002	1287 21	0.221 0.003	1269 28	0.217 0.003

unit : Integral (cent)  
Differential (cent/mm)

TABLE A5.2 Integral and differential water-level worths of PuO<sub>2</sub>-UO<sub>2</sub> lattices

Water level (cm)	2.42 PU		2.98 PU		4.24 PU		5.55 PU	
	Integral	Differential	Integral	Differential	Integral	Differential	Integral	Differential
40.0	0	$10.84 \pm 0.40$	0	$11.26 \pm 0.54$	0	$12.29 \pm 0.38$	0	$13.56 \pm 0.30$
45.0	$474 \pm 17$	$8.25 \pm 0.30$	$491 \pm 24$	$8.55 \pm 0.41$	$536 \pm 16$	$9.31 \pm 0.28$	$590 \pm 13$	$10.26 \pm 0.22$
50.0	838 30	6.42 0.23	869 42	6.65 0.32	946 29	7.22 0.22	1042 22	7.95 0.17
55.0	1125 41	5.10 0.18	1165 56	5.27 0.25	1268 38	5.72 0.17	1396 30	6.28 0.13
60.0	1354 49	4.11 0.15	1401 67	4.24 0.20	1524 46	4.60 0.14	1678 36	5.05 0.10
65.0	1540 56	3.37 0.12	1539 76	3.47 0.16	1732 52	3.76 0.11	1906 40	4.12 0.08
70.0	1694 62	2.79 0.10	1751 84	2.87 0.14	1903 57	3.11 0.09	2094 44	3.41 0.07

unit; Integral (cent)  
Differential (cent/mm)

## A6. Ratios between Effective Delayed-Neutron Fraction and Prompt-Neutron Lifetime

The ratio between an effective delayed-neutron fraction  $\beta_{\text{eff}}$  and a prompt-neutron lifetime  $\tau$  was experimentally obtained by a pulsed neutron method<sup>1)</sup>. The results are shown in TABLE A6. 1 accompanied with the lattice pattern. For the PuO<sub>2</sub>-UO<sub>2</sub> lattice, the date of measurement is also listed in the table. The details of the measurement and data processing are given in Reference 2.

In order to confirm the calculation method based on a 4-group perturbation theory, the theoretical value of  $\beta_{\text{eff}}/\tau$  was compared with the experimental one. The theoretical values are also shown in the same table. The data on the delayed neutron, such as a decay constant, fission yield, and energy spectrum, were taken from Reference 3, and the decay constants of every delayed-neutron group were assumed to be the same as those of <sup>235</sup>U for all nuclides. The composition of Pu was that on May 16, 1972.

The maximum difference between the theoretical and experimental  $\beta_{\text{eff}}/\tau$  was 7% for the 5.55 Pu lattice.

TABLE A6.1 Ratios between effective delayed-neutron fraction,  $\beta_{\text{eff}}$ , and prompt-neutron lifetime,  $\tau$ 

Lattice name	Pattern	Experimental		Theoretical
		Date	$\beta_{\text{eff}}/\tau$ (sec <sup>-1</sup> )	$\beta_{\text{eff}}/\tau$ (sec <sup>-1</sup> )
1.50 U	18		$219 \pm 1$	218
1.83 U	13		$201 \pm 3$	201
2.48 U	11		$175 \pm 3$	168
3.00 U	5		$161 \pm 5$	152
2.42 PU	24	1972- 6-13	$98 \pm 2$	97
2.98 PU	22	1972- 5-19	$91 \pm 2$	86
4.24 PU	20	1972- 4-19	$72 \pm 4$	69
5.55 PU	22	1972-10-26	$61 \pm 1$	57

\* Pu composition; on 1972-5-16

## References

- 1) Simmons B. E. and King J. S.: "A Pulsed Neutron Technique for Reactivity Determination", *Nucl. Sci. Eng.*, 3, 595 (1958)

- 2) Tsuruta H. and Kitamoto K.: JAERI-M 4696, "Experiments and Calculation of  $\beta_{\text{eff}}/l$  for the light-Water Moderated Two-Region Core of UO<sub>2</sub> and PuO<sub>2</sub>-UO<sub>2</sub> lattices" (1972) [in Japanese]
- 3) Keepin G. R. : "Physics of Nuclear Kinetics", Addison-Wesley Publishing Co., Inc., Reading, Massachusetts (1965)