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Neutron Behavior in Cluster-Type Fuel Lattices, (I)

Experimental Method and Results*

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Lattice parameters δ^{28}, δ^{25}, ρ^{28} and C^* were measured on cluster-type fuel lattices of the ATR (Advanced Thermal Reactor) by using a two region critical facility (D_2O-cluster test and H_2O-rod driver regions). Their dependence on lattice pitch, coolant-void ratio and fuel composition (whether UO_2 or PuO_2-UO_2) have been made clear by this experiment.

A foil handling technique has been developed for determining the lattice parameters of the PuO_2-UO_2 fuel pins, and the resulting measurement errors are almost as small as those obtained on the UO_2 fuel pins.

The effects of the Cd-filter and of the presence of UO_2 buttons in the measurement of ρ^{28} and δ^{25} were studied experimentally and correction factors have been determined.

A method of observing the spatial distribution of the γ-ray source in an activated foil has been developed, and the relation between the spatial distribution and the coincidence counting efficiency of the foil has been examined.

KEYWORDS: ***cluster-type fuel lattice, foil handling technique, cadmium filter, counting efficiency, voids, reactor lattice parameter, ATRC reactor, uranium dioxide, plutonium dioxide, mixtures, fuel pins, heavy water, coolant, light water, neutron behavior, neutron transport theory***

I. INTRODUCTION

In a D_2O-moderated, H_2O-cooled reactor such as the Advanced Thermal Reactor (ATR) in Japan, the reactor core is highly heterogeneous in structure: cluster-type fuel elements are contained in pressure tubes together with coolant, which are separated from the moderator, the moderator being different in substance from the coolant.

In this system, reactor constants such as the void coefficient, important for reactor safety, are largely affected by slight changes in such factors as the number of fuel pins in a cluster, the fuel composition, the volume ratio between fuel and coolant, and between coolant and moderator. It is therefore not easy to obtain the reactor constants with the required accuracy by extrapolating other data[1][2] or by using other "survey codes"[3] whose accuracy is established only in reference to lattices other than those of the ATR. A new code for calculation is called for, and the validity of the model adopted must be verified in as direct as possible reference to data obtained for the ATR itself.

In Part (I) are described the experimental studies performed for this purpose: lattice parameters with different energy dependence have been measured, including their spatial dependence. They are: the fast fission ratio δ^{28}, the epithermal fission ratio δ^{25}, the resonance capture ratio ρ^{28} and the relative conversion ratio C^*. Other parameters, *i.e.* the thermal neutron disadvantage factor and spectral indices, measured in the course of the same experiments, are reported in another paper[4] by Shimamura *et al.*

The experimental conditions for the unit lattice are as follows:

(1) Fuel: 28-pin cluster with either UO_2 or PuO_2-UO_2

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(2) Lattice pitch: 22.5 cm or 25.0 cm
(3) Coolant void ratio: 0, 30 or 100%

Experiments on Pu fuel have so far been restricted in respect of measured quantities due to the difficulty in handling, despite the high importance of such data to fuel burn up calculations. In the present experiments, a new foil handling technique[5] developed by the present author was applied to the Pu fuel.

In Part (II), to follow the present report, there will be presented a new calculational treatment based on multigroup transport equations; there, the validity of the treatment will also be discussed by analyses of the corresponding experimental results obtained in Part (I), together with some previously obtained on light water lattices[6].

II. Experimental Facility

The two-region critical facility used in the experiments consists of a test region, composed of D_2O moderator and pressure tubes of 28-pin clusters with H_2O coolant, and a surrounding driver region containing H_2O moderator and lowly enriched uranium. The fuel pins in the driver region are made up of 20 mm diameter UO_2 pellets in Al cladding tube of 24 mm outside diameter. The arrangement is in a triangular lattice of 35 mm pitch. The length of the fuel portion in the pins is 100 cm in both the driver and the test region. The two ends of each pin are terminated by polyethylene filling.

Figure 1 shows the lattice arrangement and dimensions of the two-region critical facility. Measurements of the lattice parameters were mainly performed on the central unit cell (lattice) shown by the broken line in Fig. 1. While admittedly, the dimensions of the test region are not so large compared with the values of τ and L^2, a theoretical verification (see also Part (II)) of the spacial and spectral equilibrium of the neutron flux in the region showed that there was a little deviation (2~3%) only in the ratio between resonance and thermal neutron fluxes. Experimental evidence related to this matter is given further on in the present report, and it will be seen that the results indicate the deviation to be small enough as to be within experimental error.

Figure 2 shows the quarter cross section of a (central) fuel cluster in the test region. The cluster in a pressure tube consists of three concentric layers of fuel pins. The cladding tube for the PuO_2-UO_2 fuel is of Zircaloy-2 but the shape is the same as for the UO_2 fuel. The fuel pins for measurement in the central cluster (T) are designated respectively T-1, T-2 and T-3-1 and T-3-2 (Figs. 1 and 2). In Fig. 1, N-3-1 in the buffer fuel-cluster (N) indicates the position where the equilibrium of the neutron spectrum in the central unit cell is observed.

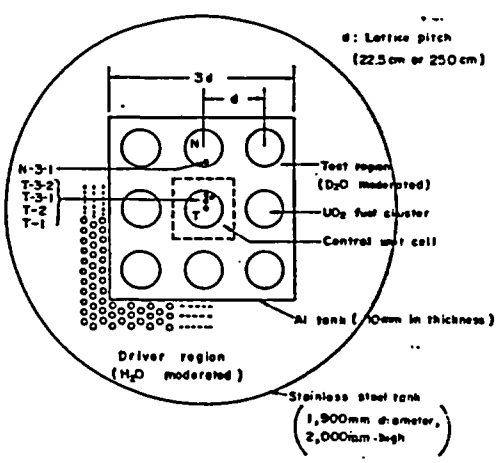

Fig. 1 Lattice arrangement of two region critical facility

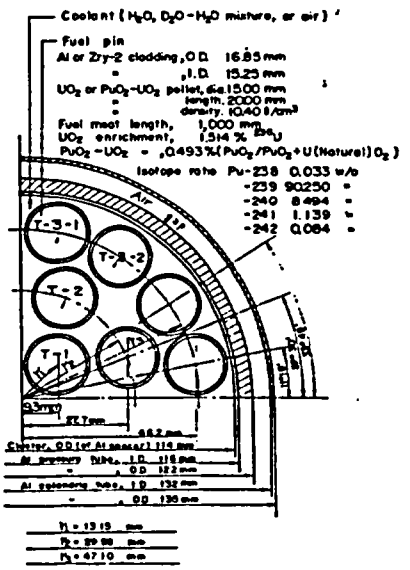

Fig. 2 Quarter cross section of fuel cluster

The heavy water used as moderator in the test region is of 99.82 wt% concentration, which

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In relation to the

$$\delta^{28}=(N_f^{28}/N_f$$

here,

$$R^b\equiv\frac{\gamma(t)^b-}{N_d^{28}/N}$$

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The coolant can be introduced and withdrawn at will from the pressure tubes, depending on the experimental conditions to be applied. For the purpose of varying the void ratio of the light-water coolant in the pressure tubes, three "coolants" with different effective densities were used; light-water, mixed light- and heavy-water (D_2O concentration 28.9%; which was chosen in due consideration of the 30% void ratio of the ATR in normal operation), and air (no coolant). In the present paper, these coolant compositions correspond to void ratios of 0%, 30% (D_2O-H_2O mixture) and 100%, respectively.

The pressure tube lattice pitches of 22.5 cm and 25.0 cm were chosen to confirm the validity of the calculational model on both sides of the 24.0 cm pitch of the ATR.

III. Lattice Parameter Measurements

1. Theory and Method

Foils of natural and depleted uranium, 15.0 mm in diameter and 0.1 mm thick, were prepared as a "pack". Two of these packs were inserted into a fuel pin to be measured. One was bare and the other Cd-covered. After irradiation in the facility, the packs were removed from the pin; and the γ-ray activities of the foils were measrued with NaI scintillator.

The fast fission ratio is defined by

$$\delta^{28}=\frac{^{238}\text{U fission rate in the fuel pin}}{^{235}\text{U fission rate in the fuel pin}}. \quad (1)$$

In relation to the measured quantities,

$$\delta^{28}=(N_f^{28}/N_f^{25})\cdot(N_n^{25}/N_n^{28})\cdot P(t)\cdot R^b, \quad (2)$$

here,

$$R^b\equiv\frac{\gamma(t)^b-N_d^{25}/N_n^{25}}{N_d^{28}/N_n^{28}-\gamma(t)^b}, \quad \gamma(t)^b\equiv F_d^b/F_n^b. \quad (3)$$

Further, $P(t)$ is the ratio of F.P. activity per fission between ^{235}U and ^{238}U, $\gamma(t)$ the ratio of F.P. activity between the depleted and natural uranium foils in a pack. N and F represent the atomic density and the specific F.P. activity, respectively, of the foil or fuel, for natural uranium, depleted uranium or fuel pin, as indicated respectively; by the suffixes n, d and f, while the suffix b indicates the case of "bare" irradiation, and t is the time elapsed from completion of the irradiation up to measurement of the foil activities.

The value of $P(t)$ varies with the shape of foil, irradiation time, the time lapse t from irradiation to measurement, the geometry of the measurement of F.P. activity, and the discrimination energy. The $P(t)$ values used were determined as function of time, based on the data by Futch[7], assuming the same value of δ^{28} in both Futch's and the authors' experimental conditions. Shimamura has more recently measured[8] $P(t)$ under the same conditions as in the present study, using a double-fission chamber, and the resulting values are in agreement within experimental error.

The epithermal fission ratio is defined by

$$\delta^{25}=\frac{1}{(^{235}\text{U fission Cd ratio})-1}. \quad (4)$$

Its relation to measured quantities is then

$$\delta^{25}=\left(\frac{F_n^b}{F_n^c}\cdot\frac{1+R^c}{1+R^b}-1\right)^{-1}. \quad (5)$$

The suffix c indicates the case of Cd-covered pack.

Resonance capture ratio is defined by

$$\rho^{28}=\frac{1}{(^{238}\text{U capture Cd ratio})-1}. \quad (6)$$

The ^{238}U-capture Cd ratio is obtained as the ratio of ^{239}Np activities between bare and Cd-covered depleted uranium. With the ^{239}Np activity of the irradiated foil represented by Np

$$\rho^{28}=(\text{Np}_d^b/\text{Np}_d^c-1)^{-1}. \quad (7)$$

The ^{239}Np activity (106.7 keV γ- and 103.7 keV X-rays) was measured by a γ-X coincidence counting method to eliminate the influence of F.P. activities.

The method just described is based on direct measurement of the ^{238}U-capture Cd ratio in the fuel pin. However, ρ^{28} can also be determined by activation ratio method[9]. In this method, the Cd ratio of a monitor (Cu) foil in the fuel pin is measured. And the ^{238}U-capture Cd ratio in the pin is obtained from the activity of the monitor foil and of the U foil (^{239}Np activity).

Representing the quantities relating to ^{238}U-

capture by the suffix 28 and those to Cu absorption by M,

$$\left(\frac{R_{Cd}{}^{28}-1}{R_{Cd}{}^{28}}\right)_f=\left(\frac{A^M}{A^{28}}\right)_f\cdot\left(\frac{R_{Cd}{}^M-1}{R_{Cd}{}^M}\right)_f\cdot\left(\frac{A^{28}}{A^M}\right)_{ref}\cdot\left(\frac{R_{Cd}{}^{28}-1}{R_{Cd}{}^{28}}\right)_{ref}\cdot\left(\frac{R_{Cd}{}^M}{R_{Cd}{}^M-1}\right)_{ref}\cdot K, \quad (8)$$

$$K\equiv(\bar{\sigma}_{cth}{}^{28}/\bar{\sigma}_{ath}{}^M)_f\cdot(\bar{\sigma}_{ath}{}^M/\bar{\sigma}_{cth}{}^{28})_{ref}. \quad (9)$$

A and R_{Cd} represent respectively the "bare" activity and the Cd ratio for the foil indicated by the respective suffixes; $(\ )_{ref}$ indicates irradiation at a position more thermalized than in the fuel pin, which in the present experiment is within the reflector of the light-water driver region; K is the correction factor for different thermal spectra in fuel pin and light-water driver reflector. Since Cu is used for the monitor foil, $K=1$ may be used.

The relative conversion ratio C^* is the ^{238}U capture (^{239}Np production) to ^{235}U fission ratio in a fuel pin, normalized to that in a thermal column:

$$C^*=\frac{\left(\frac{^{239}\text{Pu production}}{^{235}\text{U fission}}\right)_{\text{fuel}}}{\left(\frac{^{239}\text{Pu production}}{^{235}\text{U fission}}\right)_{\text{thermal column}}} \quad (10)$$

The relation to measured quantities is then given as

$$C^*=\frac{\left[\frac{\text{Np}_d{}^b}{F_n{}^b}\cdot(1+R^b)\right]_f}{\left[\frac{\text{Np}_d{}^b}{F_n{}^b}\right]_{\text{thermal column}}} \quad (11)$$

The pack of foils irradiated in the thermal column is the same as that for the fuel pin. The thermal column used was a graphite block annexed to a light-water reactor (TRIGA type); the Cd ratio of Au at the irradiation position was over 1,000.

2. Foil Arrangements

(1) UO_2 Fuel

Two foil packs shown in Fig. 3 (B) were used. One was placed in a "bare" Al receptacle, and the other in a Cd-covered one. Both were inserted in the fuel pin, as shown in Fig. 3 (A). For the irradiation of the foils, a special Al cladding tube was prepared. The purpose of this tube is to improve the reproducibility of foil

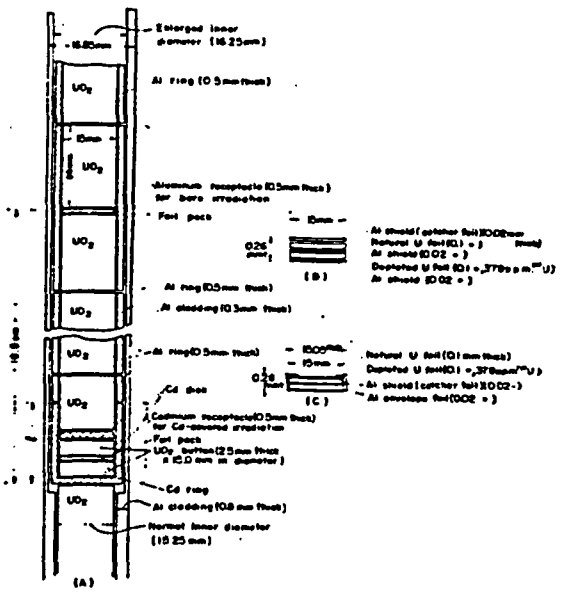

Fig. 3 (A) Foil packs in special cladding tube
(B) Foil pack for UO_2 fuel
(C) Foil cassette for PuO_2–UO_2 fuel

alignment, especially in measuring ρ^{28}, and further to eliminate neutron streaming along the cladding tube. A normal cladding tube is 15.25 mm in inner diameter. In the special cladding tube, it is bored wider to 16.25 mm from top end to mid-length, to accommodate the Cd receptacle (see Fig. 3).

The "bare" receptacle is made of two pellets, the lower pellet being bonded onto the Al ring with araldite. By means of these arrangements for the bare and Cd-covered receptacles, perfect alignment of foil packs and pellets could be obtained, thereby entirely eliminating experimental error due to misalignment.

Plugs of UO_2 "buttons" are placed in the receptacle, as shown in Fig. 3 (A), to prevent the streaming of epithermal neutrons through the Cd discs.

In order to minimize the quantity of Cd in the fuel cluster, the experiments (runs) were performed on a single fuel pin.

(2) PuO_2-UO_2 Fuel

It is very difficult to introduce foil packs into the PuO_2-UO_2 fuel pin and remove them without contamination by Pu. Therefore, the foil cassette shown in Fig. 3 (C) was prepared, using Al catcher foils. Two of these cassettes are then

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placed in a fuel capsule 35 cm long and sealed by welding. The capsule is inserted in position in the fuel pin by way of the extension rods attached to either ends of the capsule. After irradiation, the cassettes are removed from the capsule in a glove box. In this way, irradiated foils can be measured without contamination by Pu. (Details of this experimental technique are described in a separate paper[5].)

3. Counting Methods

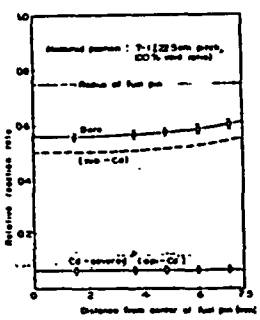
An irradiated U-foil was placed between the upper and lower 2″×2″ in diameter NaI (Tl) scintillators for measurement of F. P. or ^{239}Np activity. The F. P. activity was measured several times during the period of between 90 and 180 min after irradiation. The discrimination level for F. P. γ-ray energies was set at 600 keV in both the upper and lower scintillator systems. The specific F. P. activity was obtained from the counted value by correcting for background, natural activity, systems dead time, measuring period, foil weight, integrated neutron flux of irradiation, and difference in neutron flux between the two foil positions. The ^{239}Np activity of the depleted-U foil was also measured several times by γ-X coincidence counting method for the period of about 20 to 100 hr[10]. The window width of the single-channel pulse-height analyzer was set between 60 and 160 keV. The specific ^{239}Np activity of the foils and their solution (described later in the section on correction factors) were obtained similarly to the case of F. P. activities with corrections for background *etc.* as well as for chance coincidence. The γ-activity of Au foil (for the integrated neutron flux) and of Cu foil (for the activation ratio method) were both measured with a well-type NaI scintillation counter.

The measurements on PuO_2-UO_2 fuel were made in the same apparatus as for UO_2, in an open-port box; the discrimination level used was also the same. Thanks to the foil cassette, no contamination was caused to the head of the coincidence counter or to the well-type counter, throughout the 8 month period of experiments, thus avoiding any rise in background.

4. Correction Factors

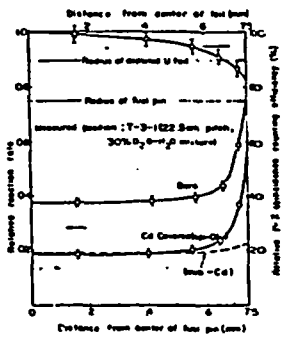
(1) UO_2 Fuel

The distributions of ^{235}U fission rate and ^{238}U capture rate in a fuel pin were first examined to bring the necessary corrections[10][11] for the Cd-filter and Np γ-ray efficiency. For this purpose, the foils were irradiated in the manner depicted in Fig. 3. After irradiation, a foil was divided into 5 concentric sections. Then, further, to have a constant counting efficiency for all the sections, each section was dissolved in 8 cm^3 of nitric acid contained in a plastic vessel. For the measurement of ^{235}U fission rate, a U-Al foil enriched to 90% in ^{235}U was used; hydrochloric acid was used to dissolve the foil. The results obtained are shown in Figs. 4 and 5.



Radial distributions of bare and Cd-covered ^{235}U-fission rates in fuel pin

Fig. 4



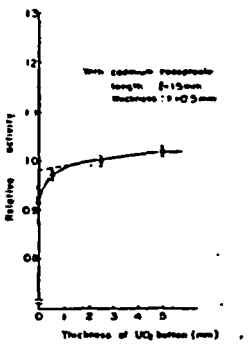
Radial distributions of bare and Cd-covered ^{238}U-capture rates in fuel pin, and radial variation of ^{239}Np γ-X coincidence counting efficiency in depleted-U foil

Fig. 5

In both ^{235}U fission and ^{238}U capture, the sub-Cd rate is lower in the central part than in the outer part of a fuel pin. For the epi-Cd rates, however, it is a flat distribution for ^{235}U fission, whereas for ^{238}U capture the rate of the central part is about 1/3 of that of the outer most part; it may be assumed that such a pattern of distribution is governed by the type of nuclear reaction, and is little dependent on the measuring position or the lattice condition. From these results, it appears that the streaming of epi-thermal neutrons through the Cd discs has a large influence on ^{238}U capture, but little on ^{235}U fission.

As already described, each button was placed between foil pack and Cd disc, to prevent the streaming of epi-thermal neutrons (this is a commonly practiced method[12] in this kind of experiment). In order to examine the effect of the presence of these UO_2 buttons, the Cd-covered

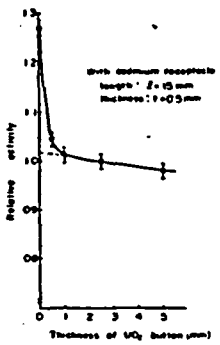
activity was measured with various thicknesses of buttons. In this case the length l of the Cd receptacle (see Fig. 3(A)) was 15 mm. The results for ^{235}U fission and ^{238}U capture are shown in Figs. 6 and 7, respectively.



^{235}U-fission activity as a function of thickness of UO_2 button

The values are normalized in reference to a thickness of 2.5 mm.

Fig. 6



^{238}U-capture activity as a function of thickness of UO_2 button

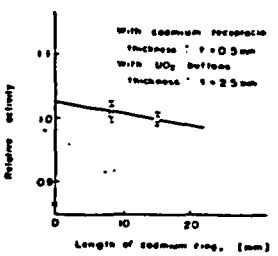
The values are normalized in reference to a thickness of 2.5 mm.

Fig. 7

It is seen from Fig. 7 that the buttons effectively prevent epi-thermal neutron streaming in the case of ^{238}U capture. The activity further decreases slightly with further increase of button thickness. This is possibly because the central portion of the pellet—where thermal fission is inhibited—increases, and hence the epi-thermal neutrons axially reaching the foil decrease. Axial self-shielding in the buttons is thus conceivable. Consequently, the actual (or true) activity is at the extrapolated point shown in the figure.

In Fig. 6, the ^{235}U fission activity is seen to increase with button thickness. In this case, the streaming of epi-thermal neutrons through Cd discs is hardly possible. Therefore, the increase in activity with the button thickness is probably caused by a combination of effects including the slowingdown and absorption of neutrons with energies near the Cd cut-off value in the vicinity of Cd foil and UO_2 button, and the distortion in epi-thermal neutron distribution near the point of measurement due to the decrease in thermal flux.

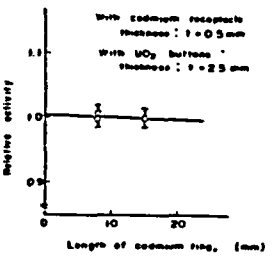
The Cd-covered activity was also measured with various thicknesses of Cd disc and lengths of Cd ring. In respect of disc thickness, the results[13] showed that, as far as the same buttons (2.5 mm thick) were used, the activity was not changed with increasing disc thickness up to about 1 mm in both ^{235}U fission and ^{238}U capture. For the length of Cd ring, the results obtained are as shown in Figs. 8 and 9.



^{235}U-fission activity as a function of length of Cd ring

The values are normalized in reference to a length of 15 mm.

Fig. 8



^{238}U-capture activity as a function of length of Cd ring

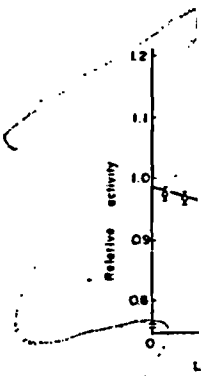
The values are normalized in reference to a length of 15 mm.

Fig. 9

The change in activity of ^{238}U capture is very small. But for ^{235}U fission, the effect is quite appreciable; the activity at $l=0$ is higher by 2.5% than at $l=15$ mm. Considering that the activity did not change with increase of the Cd disc thickness, the result shown in Fig. 8 indicates the large effect of reduction in thermal flux near the foils due to Cd. From Figs. 6 and 8, it is seen that for measurement of the ^{235}U fission epi-Cd activity the UO_2 buttons are not necessary, and it is desirable that the Cd receptacle be small. Experiments, therefore, were made with the UO_2 buttons removed, and with various lengths (l) of the Cd receptacle. The results are shown in Fig. 10.

The measured values are scattered to some extent, but the general trend of the curve is quite evident. It is considered that the value by extrapolation to $l=0$ is the closest one could obtain to the actual epi-Cd activity. This value corresponds to the epi-Cd activity of 0.99 obtained with Cd receptacle length (l) of 15 mm, disc thickness of 0.5 mm and UO_2 button thickness of 2.5 mm (this value is normalized to 1.00 in the figures so far given).

In order to obtain δ^{25} and ρ^{28} in a single irradiation, the use of UO_2 buttons is indispensable. Then, to have good alignment and contact between UO_2 pellets and the Cd cover, a length about 15



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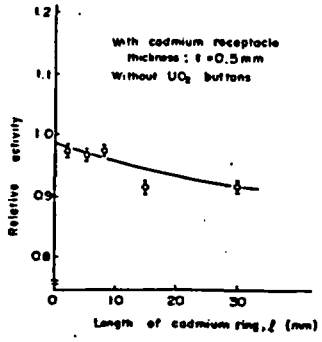

Fig. 10 ^{235}U-fission activity without UO_2 buttons as a function of length of Cd ring
Normalization of the activity is the same as in Figs. 6 and 8.

mm for the Cd receptacle is necessary. Under these circumstances, it can be considered that the true epi-Cd ^{235}U fission activity is obtainable by multiplying the measured value by 0.99.

For the epi-Cd ^{238}U capture activity, the value of 1.020 obtained by extrapolation in Fig. 7 was used as correction factor. The ^{238}U capture cross section is relatively low near the Cd cut-off energy, in contrast to the case of ^{235}U fission cross section. Therefore, there is little influence from the Cd, and no problem should be raised in experiment if UO_2 buttons are used to prevent epi-thermal neutron streaming.

For ^{238}U capture activities, the following corrections are further necessary[10][11] with regard to counting efficiency. The activity distribution in radial directions was shown in Fig. 5 for bare and Cd-covered depleted-U foils. The Np source distribution is different between bare and Cd-covered foils.

In Fig. 5 is also shown the change in counting efficiency in the 2″×2″ in diameter NaI coincidence counter according to distance from center in a depleted-U foil. The results shown are obtained from the ratio in counting efficiency before and after dissolution in nitric acid, for the 5 concentric foil sections. With the efficiency normalized to 100% for the central section, the efficiency of the outermost section is as low as 85%.

For the above reason, the overall counting efficiency differs between bare and Cd-covered foils. To examine this aspect, a foil was dissolved as a whole in 8 cm^3 of nitric acid contained in a plastic vessel 2 cm in diameter and 3 cm high, to obtain "uniform" samples of both bare and Cd-covered foils. The ratio of counting efficiencies was obtained therefrom. The counting efficiency of the Cd-covered foil was found to be 0.987 of that for the bare one. The measured epi-Cd ^{238}U capture activity was corrected by this factor: the correction factor to be multiplied to ρ^{28} is 1.026.

In this correction factor, the difference in the axial (thickness) direction of the self-shielding factor, though small, is also included. The activity distribution in this direction is shown in Fig. 11 for both bare and Cd-covered foils. The difference between the two is small: the self-shielding is about 2% higher for the bare foil. To obtain these measurements, the bare and Cd-covered foils, each 0.11 mm thick, were gradually dissolved in nitric acid, and the resultant solute was taken in 4 portions as the foil thickness diminished, thus obtaining samples representing 4 different zones according to distance from surface. The entire area of the foil was simultaneously dissolved, but the diameter being 150 times the thickness, a good average over the entire surface will have been obtained. By this axial measurement it becomes evident that the previously mentioned value of 0.987 is mostly due to the difference in radial distribution between the bare and Cd-covered activities.

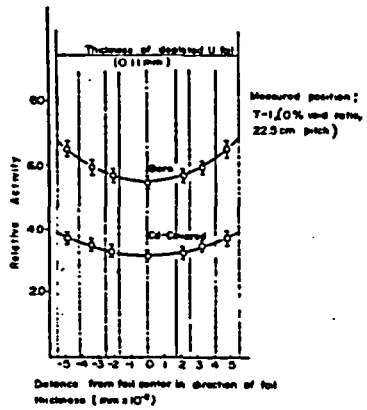

Fig. 11 ^{238}U-capture activity distributions in axial (thickness) direction in bare and Cd-covered foils

(2) PuO_2-UO_2 Fuel

To obtain the ^{235}U and ^{238}U activity Cd ratios for the PuO_2-UO_2 fuel pin, the Cd ring was set

outside the cladding tube, and further, the length was made larger to obtain good alignment. To examine the possible effect of this modification, comparative experiments were made on Cd-covered activities with the set-ups (A) and (B) shown in Fig. 12, using UO_2 fuel; it was assumed that the difference in neutron spectrum between PuO_2-UO_2 and UO_2 fuel lattices should only bring a minor effect on the corrections to be made to account for the modification. The correction factors to be applied to the Cd-covered activity measured with set-up (B), were determined as 1.03 and 1.02 for ^{235}U fission and ^{238}U capture, respectively, to obtain values corresponding to set-up (A). For measurement of δ^{25} and ρ^{28}, the set-up (A) is by far the better. The reasons for this are that: (1) the coolant is not displaced by the Cd receptacle; (2) since there is no gap between Cd disc and ring, the streaming of thermal neutrons can be prevented; (3) when the length (l) of Cd ring is

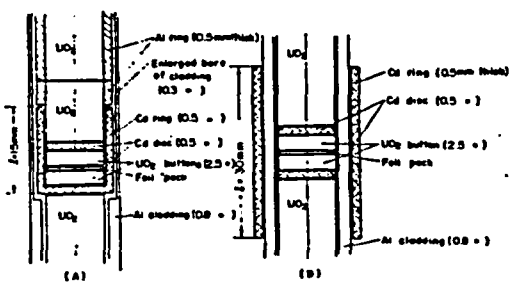

Fig. 12 Cd ring inside (A) and outside (B) cladding tube used for comparative measurements of Cd-covered ^{235}U-fission and ^{238}U-capture activities

large, the Cd-covered activity is reduced for both ^{235}U fission and ^{238}U capture, thereby increasing the correction factor (Figs. 8 and 9).

The results, which were larger than unity, indicate that, of the three causes mentioned, the effect of larger length of the Cd ring is the predominant. This situation is also implied by the smaller correction factor found for ^{238}U capture.

IV. Results and Discussion

1. Accuracies of the Measurements

Statistical error arises first from the random nature of counting and then from the factors of reproducibility, including those for pin and foil position[10] (Cd-covered and bare receptacles in the fuel pin) in the cluster, flantness of the foils and their weight, foil position at the time of counting, and the discrimination level in counter. The statistical error in the counting itself is below 0.2% for each parameter, which is therefore included in the experimental reproducibility. For the reproducibility, a measurement was made several (eight) times under the same experimental conditions to obtain the standard deviation. The reproducibility is defined as the statistical error for a single measurement. The same value of standard deviation may be applied to other experimental conditions, since the measuring method is the same. **Table 1** shows the reproducibility (statistical error) for each parameter. For UO_2 fuel, the measurement was always made twice, and the reproducibility was verified for its being within the standard deviation given in Table 1.

Table 1 Experimental errors in lattice parameter measurements

Error \ Lattice parameter	δ^{28}	δ^{25}	ρ^{28}	C^*
(1) Statistical error (Reproducibility of each measurement) (%)	±2.5	±1.5	±2.5	±2.0
(2) Systematic errors (%)				
1) Counter dead time	±0.2	±0.1	~0	~0
2) ^{235}U contents in depleted-U foil	±0.5	±0.1	—	—
3) Self-attenuation of γ-rays in U foils	~0	~0	±0.1	~0
4) Counting efficiency of bare and Cd-covered foil	~0	~0	±0.5	±0.2
5) Epi-Cd activity correction factors	—	±0.5	±0.5	—
6) F.P. γ-rays	—	—	±0.2	±0.1
7) $P(t)$ function	±0.5	—	—	—
Total experimental error (%)	±3.0	±2.0	±3.5	±2.0

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Discussion

Measurements

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arameter. For UO_2
always made twice,
verified for its being
ın given in Table 1.

	ρ^{28}	C^*
	±2.5	±2.0
	~0	~0
	—	—
	±0.1	~0
	±0.5	±0.2
	±0.5	—
	±0.2	±0.1
	—	—
	±3.5	±2.0

When it was found to exceed the standard deviation a third measurement was made. The number of measurements was limited for PuO_2-UO_2 fuel to one per pin position, and deviations were detected from the continuity observed on the measured values at different pin positions. The values deviating beyond the limits were remeasured. The reproducibility for the PuO_2-UO_2 fuel was confirmed to be nearly the same[5] as for the UO_2 fuel.

The systematic errors considered and their values are shown in Table 1. Some of these values represent errors in the correction factors. The following remarks are headed by the same numbers as those in the table.

(1) The counter dead time was 2.7±0.5 μsec. The error induced at the maximum value of ^{235}U fission activity count rate is shown.

(2) The ^{235}U content in depleted-U foil was obtained by comparison with that of natural U, by irradiation in a thermal column. The error caused in this measurement is given.

(3) Coincidence counts of ^{239}Np activity vary largely with the thickness of depleted-U foil. The γ-ray self-attenuation was determined by experiment[14], but the correction was minimized by choosing bare and Cd-covered foils of thicknesses as close to each other as possible.

(4) The values given here for counting efficiency represent the errors in determining the correction factor.

(5) In measuring the correction factors, the errors caused in δ^{25} and ρ^{28} due to the deviations of the measured values and of the extrapolation are both considered to be ±0.5%.

(6) The error[10] caused by the F.P. γ-rays entering into the coincidence counting of ^{239}Np is at most ±0.2% for ρ^{28}[13] and ±0.1% for C^*, with the 378 ppm depleted-U foil used.

(7) The error in the $P(t)$ function arises in the conversion of Futch's data to those under the present experimental conditions, which has been considered to be ±0.5%.

For PuO_2-UO_2 fuel, another error—that in the correction factor relating to the setting of the Cd ring was added. As seen from Fig. 8, the correction necessary for ^{235}U fission increases with the length of Cd ring. The error caused in the correction factor was considered to be ±1.0%, which led to ±3.0% measuring error in δ^{25}.

As the value of the Cd ratio approaches 1.00, accurate measurement of ρ^{28} by direct Cd ratio method becomes very difficult, as easily understood from the above relation (7). In actuality, however, there is practically no difference between the values of ρ^{28} obtained by the direct Cd ratio method and the activation ratio method (marked by † in Table 2), even for the maximum value of ρ^{28} at T-1 with 25 cm lattice pitch and 30% void ratio. It can be concluded that there is no systematic error of significance inherent in the present measurement of ρ^{28} by direct Cd ratio method.

2. Results of the Measurements

The lattice parameters measured for UO_2 fuel and PuO_2-UO_2 fuel are shown in Tables 2 and 3, respectively. As seen from these tables, the measured results are in good agreement between T-3-1 and T-3-2, which are both in the third bank of fuel pins. The cell-average values given were obtained from the reaction rates in the central unit cell (cluster), through the following formulas:

$$\text{Cell-average } \delta^{28}=\frac{\sum_{\text{cell}}{}^{238}\text{U fission rate}}{\sum_{\text{cell}}{}^{235}\text{U fission rate}}$$

$$\text{Cell-average } \delta^{25}=\frac{\sum_{\text{cell}}\text{epi-Cd}\,{}^{235}\text{U fission rate}}{\sum_{\text{cell}}\text{sub-Cd}\,{}^{235}\text{U fission rate}}$$

$$\text{Cell-average } \rho^{28}=\frac{\sum_{\text{cell}}\text{epi-Cd}\,{}^{238}\text{U capture rate}}{\sum_{\text{cell}}\text{sub-Cd}\,{}^{238}\text{U capture rate}}$$

$$\text{Cell-average } C^*=\frac{\left(\dfrac{\sum_{\text{cell}}{}^{238}\text{U capture rate}}{\sum_{\text{cell}}{}^{235}\text{U fission rate}}\right)^{\text{fuel}}}{\left(\dfrac{{}^{238}\text{U capture rate}}{{}^{235}\text{U fission rate}}\right)^{\text{thermal column}}}$$

Now, if the nuclear cross sections of a fuel pin averaged in the thermal or epi-thermal energy region do not change very sharply with change of neutron spectrum, the variation of the lattice parameter is caused principally by change in the ratio of epi-thermal to thermal neutron flux; which can be understood from the definitions given by Eqs. (1), (4), (6) and (10). As seen in Tables 2 and 3, all the parameters relevant to the outer banks of fuel pins are smaller compared with

Table 2 Lattice parameters measured for UO_2 fuel

Lattice pitch		22.5 cm			25 cm	
Parameter \ Coolant void ratio		0%	30% (D_2O-H_2O mixture)	100%	30% (D_2O-H_2O mixture)	100%
δ^{28}	Position T-1	0.0709±0.0021	0.0801±0.0024	0.0904±0.0027	0.0792±0.0024	0.0830±0.0025
	T-2	0.0649±0.0019	0.0648±0.0020	0.0817±0.0025	0.0628±0.0019	0.0736±0.0022
	T-3-1	0.0459±0.0014	0.0449±0.0013	0.0545±0.0016	0.0412±0.0012	0.0494±0.0015
	T-3-2	0.0443±0.0013	0.0447±0.0013	0.0550±0.0017	0.0421±0.0013	0.0495±0.0015
	Cell average	0.0529±0.0016	0.0531±0.0016	0.0651±0.0020	0.0500±0.0015	0.0587±0.0018
	Position N-3-1	0.0428±0.0013	0.0445±0.0013	0.0548±0.0016	0.0403±0.0016	0.0467±0.0019
δ^{25}	Position T-1	0.107 ±0.002	0.116 ±0.002	0.141 ±0.003	0.108 ±0.002	0.113 ±0.002
	T-2	0.0868±0.0017	0.0927±0.0018	0.131 ±0.003	0.0845±0.0017	0.101 ±0.002
	T-3-1	0.0645±0.0013	0.0697±0.0014	0.109 ±0.002	0.0576±0.0012	0.0798±0.0016
	T-3-2	0.0661±0.0013	0.0691±0.0014	——	0.0572±0.0011	0.0783±0.0017
	Cell average	0.0744±0.0015	0.0794±0.0016	0.118 ±0.002	0.0676±0.0014	0.0874±0.0017
	Position N-3-1	0.0634±0.0013	0.0671±0.0013	0.106 ±0.002	0.0573±0.0011	0.0795±0.0016
ρ^{28}	Position T-1	1.39 ±0.05	1.62 ±0.06	1.67 ±0.06	1.48 ±0.05 1.50 ±0.05†	1.24 ±0.04 1.22 ±0.04†
	T-2	1.17 ±0.04	1.30 ±0.05	1.56 ±0.05	1.18 ±0.04 1.20 ±0.04†	1.12 ±0.04 1.10 ±0.04†
	T-3-1	0.891 ±0.031	0.992 ±0.035 0.970 ±0.034†	1.44 ±0.05	0.876 ±0.031 0.888 ±0.031†	1.06 ±0.04 1.06 ±0.04†
	T-3-2	0.848±0.030	0.996 ±0.035	1.46 ±0.05	0.847 ±0.030 0.845 ±0.029†	1.07 ±0.04 1.07 ±0.04†
	Cell average	0.987 ±0.034	1.13 ±0.04	1.50 ±0.05	0.984 ±0.034	1.10 ±0.04
	Position N-3-1	0.877 ±0.031	0.968 ±0.034	1.40 ±0.05	0.846 ±0.030	1.10 ±0.04
C^*	Position T-1	2.28 ±0.05	2.55 ±0.05	2.76 ±0.05	2.29 ±0.04	2.00 ±0.04
	T-2	2.18 ±0.04	2.27 ±0.04	2.71 ±0.05	2.05 ±0.04	2.00 ±0.04
	T-3-1	1.95 ±0.04	2.01 ±0.04	2.66 ±0.05	1.74 ±0.03	1.93 ±0.04
	T-3-2	1.86 ±0.04	2.00 ±0.04	2.57 ±0.05	1.73 ±0.03	1.88 ±0.04
	Cell average	1.98 ±0.04	2.14 ±0.04	2.64 ±0.05	1.86 ±0.04	1.94 ±0.04
	Position N-3-1	1.84 ±0.03	1.98 ±0.04	2.62 ±0.05	1.74 ±0.03	1.87 ±0.04

† Values obtained by the activation ratio method

those of inner banks, which leads to the conclusion that in the cluster type fuel, the self-shielding effect is overwhelmingly strong on thermal neutrons compared with other neutrons.

In the case of 22.5 cm pitch and UO_2 fuel, a strong dependence on void ratio is seen for all lattice parameters. The values increase with the void ratio. In general, an increase of H_2O coolant in the cluster fuel lattice should give, as far as epi-thermal neutron energy is concerned, the same effect as an increase in the moderator-to-fuel volume ratio in the case of regular lattices, resulting in an increase of the lattice parameter value with increase of void ratio. This effect is clearly seen in the case of 22.5 cm pitch lattice of UO_2 fuel.

On the other hand, with 25.0 cm pitch lattice UO_2 fuel, the dependence on the void ratio is weak as seen in Table 2; only the cell-averaged values increase with the void ratio for all parameters. The current of thermal neutrons, which are mostly produced in the D_2O moderator region, is considered to be directed from the D_2O toward the cluster fuel. Therefore, as far as the thermal neutron energy is concerned, increase of H_2O coolant should enhance the neutron self-shielding

25 cm	
:ture)	100%
.0024	0.0830±0.0025
.0019	0.0736±0.0022
.0012	0.0494±0.0015
.0013	0.0495±0.0015
.0015	0.0587±0.0018
.0016	0.0467±0.0019
.002	0.113 ±0.002
.0017	0.101 ±0.002
.0012	0.0798±0.0016
.0011	0.0783±0.0017
.0014	0.0874±0.0017
.0011	0.0795±0.0016
.05	1.24 ±0.04
.05†	1.22 ±0.04†
.04	1.12 ±0.04
.04†	1.10 ±0.04†
.031	1.06 ±0.04
.031†	1.06 ±0.04†
.030	1.07 ±0.04
.029†	1.07 ±0.04†
.034	1.10 ±0.04
.030	1.10 ±0.04
.04	2.00 ±0.04
.04	2.00 ±0.04
.03	1.93 ±0.04
.03	1.88 ±0.04
.04	1.94 ±0.04
.03	1.87 ±0.04

This effect is clearly
a pitch lattice of UO_2

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Table 3 Lattice parameters measured for PuO_2-UO_2 fuel

Lattice pitch		25 cm		
Parameter	Coolant void ratio	0%	30% (D_2O-H_2O mixture)	100%
δ^{28}	Position T-1	0.192 ±0.006	0.187 ±0.006	0.207 ±0.006
	T-2	0.143 ±0.004	0.144 ±0.004	0.181 ±0.005
	T-3-1	0.0889±0.0027	0.0906±0.0027	0.122 ±0.004
	T-3-2	0.0903±0.0027	0.0901±0.0027	0.121 ±0.004
	Cell average	0.110 ±0.003	0.111 ±0.003	0.145 ±0.004
	Position N-3-1	0.0871±0.0026	0.0882±0.0026	0.128 ±0.004
δ^{25}	Position T-1	0.106 ±0.004	0.115 ±0.004	0.114 ±0.004
	T-2	0.0807±0.0028	0.0897±0.0031	0.105 ±0.004
	T-3-1	0.0517±0.0019	0.0595±0.0021	0.0832±0.0029
	T-3-2	0.0544±0.0019	0.0586±0.0021	0.0808±0.0028
	Cell average	0.0638±0.0022	0.0705±0.0025	0.0908±0.0032
	Position N-3-1	0.0525±0.0018	0.0593±0.0021	0.0926±0.0032
ρ^{28}	Position T-1	1.50 ±0.05	1.70 ±0.06	1.44 ±0.05
	T-2	1.22 ±0.04	1.33 ±0.05	1.35 ±0.05
	T-3-1	0.813 ±0.028	0.908 ±0.031	1.17 ±0.04
	T-3-2	0.824 ±0.029	0.915 ±0.032	1.23 ±0.04
	Cell average	0.968 ±0.034	1.08 ±0.04	1.26 ±0.04
	Position N-3-1	0.779 ±0.027	0.892 ±0.031	—
C^*	Position T-1	2.08 ±0.04	2.44 ±0.05	2.10 ±0.04
	T-2	1.94 ±0.04	2.11 ±0.04	2.04 ±0.04
	T-3-1	1.65 ±0.03	1.76 ±0.03	1.96 ±0.04
	T-3-2	1.64 ±0.03	1.76 ±0.03	1.95 ±0.04
	Cell average	1.75 ±0.03	1.90 ±0.04	1.99 ±0.04
	Position N-3-1	1.66 ±0.03	1.71 ±0.03	2.09 ±0.04

effect in the cluster fuel, which should bring about a decrease of the lattice parameters with increase of void ratio. Hence, it would appear that the observed slight dependence in the 25.0 cm pitch lattice of UO_2 fuel is a consequence of the superposition of the two opposing effects of H_2O coolant: slowing down in the epi-thermal and shielding in the thermal energy region. In the inner fuel pin positions (T-1 and T-2), the values of ρ^{28} and C^* of 25.0 cm pitch lattice of UO_2 fuel decrease with increasing void ratio. This tendency is considered due to the strong difference in neutron shielding effects in the case of 100% void ratio between thermal and resonance (especially of ^{238}U capture) energy regions: in the former the shielding effect decreases by the absence of H_2O coolant, while in the latter the shielding effect increases due to inhibition of neutron production by the coolant.

In both 30% and 100% void ratios, all the values decrease with increasing lattice pitch as seen in Table 2, which leads to the conclusion that increase of lattice pitch simply results in increase of the D_2O moderator to fuel volume ratio, irrespective of the presence of the H_2O coolant.

Upon replacing UO_2 by PuO_2-UO_2 fuel, with 25.0 cm pitch lattice, no marked change is seen in the void-ratio-dependence of the lattice parameters. The absolute values, however, are somewhat larger; for comparison, however, the values of δ^{28} given in Table 3 should be divided by a factor of 2.18 to account for the difference in ^{235}U atomic density in the fuel pins (see Eq. (2)).

The values of ρ^{28} and C^* in the inner fuel pin positions (T-1 and T-2), reveal a tendency similar to the case of UO_2 fuel lattice.

The values given in Tables 2 and 3 have been obtained for a system with $K_{eff}=1$. In order to make comparisons with the calculated results for an infinite system, correction for neutron leakage is necessary. The value of such correction, while dependent somewhat on the structure of the unit cells, is considerable, exceeding by far the measurement error. According to the calculations by METHUSELAH-II, they are as follows; δ^{28}: ~20%, ρ^{28} and δ^{25}: 10% and C^*: ~5%.

The comparison between measured and calculated results is described in detail in Part (II) of the present paper.

3. Characteristics of the Two-region Core

It must now be verified that the lattice parameters measured in the central unit cell are characteristic of the single region D_2O-cluster lattice core with $K_{eff}=1$. In order to examine whether the influence of the driver region is effectively nullified in the central unit cell by the 8 buffer cells surrounding the central cell, the lattice parameters at a position (N-3-1) closest to the central cell were also measured. The corresponding position in the central cell is T-3-1. The values for these two positions are almost the same within experimental error (Tables 2 and 3). Except for the lattice parameters larger by about 5 to 10% with PuO_2-UO_2 fuel and void ratio 100%, the values at N-3-1 are 2 to 3% smaller for most of the experimental conditions. This indicates that the moderation of neutrons is large in the driver region; and that this effect is not entirely eliminated even at the position N-3-1. Since, however, the influence is only to this extent at N-3-1, the effect in the central cell should be negligible.

Further, to examine the influence of the driver region, experiments were made in which a water gap of 4.55 cm width was provided between the test and driver regions (equivalent in dimension to 1.5 lattice pitches in the driver region), thereby significantly changing the neutron spectrum entering the test region. This gap caused a change in the Cd ratio of Au from 2.5 to 6.0. The values of δ^{28}, δ^{25} and ρ^{28} measured for the reactor core with the water gap are shown in **Table 4**; all the values in this table are normalized to those of a corresponding core without the gap. As seen from the table, there is no change in the δ^{25} value, but for δ^{28} and ρ^{28} the values are somewhat larger. The Cd ratio of Au in heavy-water is from 2.6 to 3.3, which is close to 2.5, which is the corresponding value in the light-water driver region without the gap, as described earlier. Therefore, it can be considered that the deviation in the characteristic spectrum of the test region, even if existent, should be negligible for an ordinary core configuration without water gap. From the above considerations, the difference in neutron flux distributions between the present two-region core (in the central cell) and the single region D_2O-cluster core with $K_{eff}=1$ will be within measurement error, and hence insignificant.

Table 4 Lattice parameters with light-water gap in driver region

Position \ Parameter	δ^{28}	δ^{25}	ρ^{28}
T-1	1.04±0.03	0.98±0.02	1.05±0.03
T-2	1.04±0.03	1.01±0.02	1.05±0.03
T-3-1	1.04±0.03	0.99±0.02	1.04±0.03
T-3-2	1.03±0.03	1.00±0.02	1.03±0.03
N-3-1	1.10±0.03	0.96±0.02	1.00±0.03

(1) Values given are normalized in reference to a core without water gap.
(2) Lattice pitch 25 cm, void ratio 100%, UO_2 clusters, 4.55 cm water gap between the test and the driver regions.

V. Conclusion

By the present experiments, the lattice parameters δ^{28}, δ^{25}, ρ^{28} and C^* in cluster-type fuel lattices of the ATR were measured as a function of coolant void ratio, lattice pitch and fuel composition. The parameters show strong dependence on the void ratio when the lattice pitch is 22.5 cm, but weak when 25.0 cm, with UO_2 fuel. With PuO_2-UO_2 fuel, (25.0 cm pitch), a similar weak dependence on void ratio is observed. Thermal neutron self-shielding effect, enhanced by the H_2O coolant, is fairly large in the cluster fuel, and this effect changes the void dependence of the parameters quite radically according to the position of the fuel pin. Increase of the lattice

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the present two-region
and the single region
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ence insignificant.

:ters with light-water
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δ^{25}	ρ^{28}
0.98±0.02	1.05±0.03
1.01±0.02	1.05±0.03
0.99±0.02	1.04±0.03
1.00±0.02	1.03±0.03
0.96±0.02	1.00±0.03

ized in reference to a core

ratio 100%, UO_2 clusters,
en the test and the driver

CLUSION

ıents, the lattice param-
" in cluster-type fuel
measured as a function
ce pitch and fuel com-
show strong dependence
.e lattice pitch is 22.5
0 cm, with UO_2 fuel.
5.0 cm pitch), a similar
ɔid ratio is observed.
ling effect, enhanced by
large in the cluster fuel,
ıe void dependence of
cally according to the
ncrease of the lattice

pitch simply diminishes the lattice parameters, irrespective of the presence of H_2O coolant.

The foil handling technique has been developed for studying the lattice parameters in PuO_2-UO_2 fuel pins; the measured values are of almost of the same accuracy as for the UO_2 fuel.

Correction factors to account for the effect of Cd filter and UO_2 buttons were determined to ensure accurate measurement of ρ^{28} and δ^{25}.

Methods were devised for dividing an irradiated U foil into several zones both radially and thicknesswise, and dissolving them in acid for the measurements. These methods, permitted the following measurements to be made: (1) the spatial distribution of ^{235}U fission and ^{238}U capture reaction rates in a fuel pin with good accuracy, (2) the ^{239}Np distribution in an (irradiated) depleted U foil, and consequently its influence on the coincidence counting efficiency for the foil.

In the measurement of lattice parameters with the two-region critical facility, it was also found that equilibrium of neutron flux was obtainable in the central unit cell within experimetal error.

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