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Measurements of Reactivity Change Due to Gd_2O_3-UO_2 Fuel Pins in Cluster-Type Fuel Assembly

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Abstract

The physical behaviors of the gadolinium burnable poison fuel pins in cluster-type fuel assembly, especially those concerning reactivity effects and coolant void reactivity have been studied by the single-rod citical experiments.

The following were found from this experiment.

(1) Excess content of poison beyond 0.5 wt% makes no increase in reactivity change. This may be attributed to the self-shielding effect of Gd in the fuel pin.

(2) The reactivity change depends on the position of poisoned pins inserted in the cluster; that is, the change decreases according as the inserted position approaches to the center of the cluster. The reactivity change is proportionate to the change in ^{235}U reaction rates in the cluster.

(3) When distance between the two poisoned pins is sufficiently large, reactivity change induced in the same fuel ring layer is in proportion to the number of the pins.; When the two poisoned pins are inserted contiguously, on the other hand, the reactivity change

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induced is smaller by 15 % than that for the isolated pins. This behavior suggests that poisoned pins inserted contiguously interfere markedly with each other.

(4) Reactivity change due to the poisoned pins is larger in the case of air-filled (100 % void fraction) lattice than in the H_2O-filled (0 % void fraction) lattice. This means that neutron absorption of the poisoned pin increases in the air filled lattice owing to the smaller depression of neutron flux because the thermal neutron self-shielding effect of the H_2O coolant disappears in this air filled lattice. The present result suggests that the use of burnable poison in fuel pins yields the advantage in coolant void reactivity.

1. Introduction

Burnable poison mixed in fuel pellets has been successfully applied to reduce initial excess reactivity of light water power reactors and to improve fuel economy of this type of reactors. This suggests us that use of burnable poison is also probably effective in reducing the initial excess reactivity of boiling-light-water-cooled pressure-tube-type heavy water reactor (HWR) and improving power distribution in fuel clusters of this type of HWR.

Since D_2O cell of clustered fuel has high heterogeneity, neutron behavior in this cell is more complicated than in regular H_2O cell of single fuel pin. Especially, thermal neutron flux is highly depressed in fuel cluster(1). Consequently, it is anticipated that effect of the burnable poison on D_2O lattice of fuel clusters intricately depends on various parameters, like concentration of poison in fuel pellets, number of poisoned pins in a cluster, their configuration in it and coolant voiding(2).

It is clear that information of this dependence is essentially important to a utilization of the burnable poison in D_2O lattice of clustered fuel pins. There has been, however, only a little amount of experimental study about this dependence. This fact is one of the reasons that wide use of burnable poison in fuel pellets is prevented in a pressure-tube-type HWR. Single-rod experiment has been, therefore, performed to investigate the effect of the burnable poison on the D_2O lattice of 54-pin cluster.

We measured reactivity changes that were induced by substitutions of poisoned fuel pins with unpoisoned ones; then, we try to infer from these reactivity changes how the above mentioned parameters influence reducing the initial excess reactivity by use of burnable poison.

Experimental results were compared with calculation by the use of code WIMS[3][4][5] and CITATION.

2. Experimental Procedure

The 54-pin cluster is fuelled with 1.5 wt% enriched UO_2. The fuel pins lie with their centers on three concentric layers. The schematic drawing of the 54-pin cluster is given in Fig. 1. As illustrated in Fig. 2, the 54-pin cluster is placed at the core center of the Deuterium Critical Assembly and is drived by 136 cluster of 28-pin. 28-pin clusters are fuelled with 1.2 wt% enriched UO_2. In 28-pin clusters, fuel pins also lie with their centers on three concentric layers. As known from Fig. 3 and Fig. 4, clusters are separated from D_2O moderator by aluminum pressure tubes, air gaps and aluminum calandria tubes. Pressure tubes are usually filled with air.

To find out the effect of the burnable poison, a few fuel pins of the 54-pin cluster were replaced with 1.5 wt% enriched UO_2 pins which are poisoned with Gd_2O_3. We prepared three types of poisoned pins in which content of Gd_2O_3 ranges from 0.1 wt% to 1.0 wt%. The specifications of unpoisoned and poisoned pins are listed in Table I.

To estimate reactivity changes due to substitutions of poisoned pins with unpoisoned ones, changes in critical D_2O height due to the substitutions were measured as functions of

(i) poison concentration

(ii) number of poisoned pins

(iii) configuration of the cluster with poisoned pins

(iv) coolant void.

Measurements of D_2O height were made to an accuracy of 0.2 mm with the use of a survo manometer in a communicating tube. Measured changes in critical D_2O height were converted to dollar reactivity with the help of reactivity coefficient of D_2O height given by

$$\frac{\partial \rho}{\partial H} = \frac{\alpha}{(H + \delta)^3} \qquad (2\text{-}1)$$

where α is the experimentally determined coefficient, H D_2O height, and δ the effective axial extrapolation distance including reflector saving of the structure. Reactivity change relevant to change in critical D_2O height from h_1 to h_2 were evaluated by the formula

$$\rho = \int_{h_1}^{h_2} \left(\frac{\partial\rho}{\partial H}\right) dH = \left(\frac{\alpha}{2}\right)\left[\frac{1}{(h_1 + \delta)^2} - \frac{1}{(h_2 + \delta)^2}\right] \qquad (2\text{-}2)$$

To determine δ, axial destribution of cupper activation was measured at the center of the unpoisoned 54 pin cluster. Final value of δ was estimated at 14.4 ± 1.5 cm.

In all cores with loading patterns of poisoned pins given in Table II, reactivity coefficients of D_2O height were determined from relations between reactor period and small excess in D_2O height. Values of α were obtained from the measured reactivity coefficients and critical D_2O height on the base of Eq. 2-1.

Finally, all values of α were averaged and the averaged value was used in Eq. 2-2. Error in ρ used in Eq. 2-2 is estimated at ± 4 %.

3. Results and Discussion

Results of reactivity change due to substitutions of unpoisoned pins with poisoned ones were given in Table II. Experimental error in these results is estimated to be ± 4 %. The upper three results in Table II gives reactivity changes due to substitutions of an unpoisoned pin in the 3rd layer with a poisoned pin. These data clearly shows the dependence of the reactivity change on concentration of poison Gd_2O_3 in a pin. As shown in Fig. 5, the reactivity change does not increase apparantly in range of above 0.5 wt% Gd_2O_3 concentration. This behavior of the reactivity change can be well explained by self-shielding effect of Gd in a poisoned fuel pin.

The data at the first, 7-th, 8-th and 9-th column in Table II give the dependence of reactivity change on number of poisoned pins in the cluster. The pictorial expression of this dependence is given in Fig. 6. The reactivity change in the 8-th column, which is due to the substitution with two poisoned pins sufficiently spaced, is in good agreement with the twice of the reactivity change in the first column, which is due to the substitution with the single poisoned pin; on the other hand, the reactivity change in the 7-th column, which is due to the substitution with two poisoned pins closely inserted, is smaller by 15 % than the twice of the reactivity in the first column. Furthermore, the reactivity change in the 9-th column which is due to the substitution with twelve poisoned pins inserted alternate position, is smaller by 39 % than the twelve times of the reactivity in the first column. These behaviors of reactivity change show that two or more poisoned pins largely interfere with each other, especially in the case where space of every two poisoned pins is small. The interferance suggests that a poisoned pin depresses neutron flux in the vicinity of the poisoned pin.

The data in the first, fifth and sixth columns in Table II show the dependence of reactivity change on inserted position of a poisoned pin. As shown in Fig. 7, reactivity change due to substitution decrease as inserted position approaches to the center of the cluster. This behavior can be well explained by thermal neutron flux distribution inside the cluster that depresses toward to the center of the cluster. The reactivity change in the fourth column which is due to substitutions in the air-filled cluster, is larger than the reactivity change in the H_2O-filled cluster given in the first column; furthermore, the same tendency is revealed in the pair of the last two data in Table II. This behavior of reactivity change may be attributable to the fact that neutron absorption in a poisoned pin increases owing to less depression of neutron flux in the air filled cluster, because the self-shielding effect of H_2O disappears in this cluster. As shown in Fig. 8, this result suggests that the use of burnable poison makes loss-of-coolant reactivity of D_2O lattice of cluster shift to the negative side.

Table I shows that the calculation by the codes WIMS-CITATION predicts the experiment to the accuracy of 20 %. For this calculation, neutron cross sections of ^{155}Gd and ^{157}Gd were prepared from ENDF-B/III library.

4. Concluding Remarks

The physical behaviors of the gadolinium burnable poison fuel pins in cluster-type fuel assembly, especially those concerning reactivity effects, thermal neutron flux distribution and coolant void reactivity have been studied by the one-rod citical experiments.

The following were found from this experiment.

(1) Excess content of poison beyond 0.5 wt% makes no increase in reactivity change. This may be attributed to the self-shielding effect of Gd in the fuel pin.

(2) The reactivity change depends on the position of poisoned pins inserted in the cluster; that is, the change decreases according as the inserted position approaches to the center of the cluster. The reactivity change is proportionate to the change in ^{235}U reaction rates in the cluster.

(3) When distance between the two poisoned pins is sufficiently large, reactivity change induced in the same fuel ring layer is in proportion to the number of the pins. When the two poisoned pins are inserted contiguously, on the other hand, the reactivity change induced is smaller by 15 % than that for the isolated pins. This behavior suggests that poisoned pins inserted contiguously interfere markedly with each other.

(4) Reactivity change due to the poisoned pins is larger in the case of air filled (100 % void fraction) lattice than in the H_2O filled (0 % void fraction) lattice. This means that neutron absorption of the poisoned pin increases in the air filled lattice owing to the smaller depression of neutron flux, because the thermal neutron self-shielding effect of the H_2O coolant disappears in this air filled lattice. The present result suggests that the use of burnable

poison in fuel pins yields the advantage in coolant void reactivity.

(5) The calculation by the codes WIMS-CITATION predicts the experiment to the accuracy of 20 %.

It is concluded from this experiment that use of burnable poison in fuel is effective in the reduction if initial excess reactivity of a pressure-tube-type reactor.

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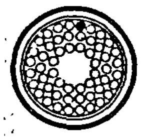
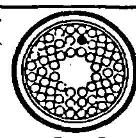
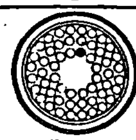
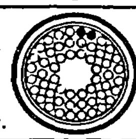
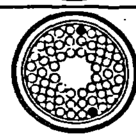
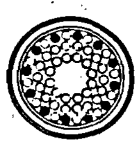
(5) M. J. Roth : "The Estimation of Collision Probabilities in Complicated Geometries" AEEW-M857 (1969)

Table I Specification of Fuel

Fuel Type	1.5wt% UO_2 Fuel	0.1wt% Gd_2O_3 Poisoned Fuel	0.5wt% Gd_2O_3 Poisoned Fuel	1.0wt% Gd_2O_3 Poisoned Fuel
Fuel Pellet				
Density (g/cm_3)	10.38	10.30	10.30	10.30
Diameter (mm)	14.77	14.78	14.78	14.78
UO_2 Enrichment (wt%)	1.5	1.5	1.5	1.5
Gd_2O_3 Enrichment (wt%)	-	0.10	0.496	0.993
Composition (wt%)				
^{235}U	1.317	1.328	1.323	1.316
^{238}U	86.563	86.384	86.042	85.612
O	12.120	12.201	12.205	12.210
^{155}Gd	-	0.01278	0.06335	0.12690
^{157}Gd	-	0.01360	0.06748	0.13509
Other Gd	-	0.06	0.30	0.60
Fuel Pin				
Cladding Material	Aluminum		Aluminum	
Cladding i.d., (mm)	15.03		14.98	
Cladding o.d., (mm)	16.73		16.69	
Gap Material	Air		Air	

Table II Reactivity Change Due to Subsititution of Gadolinia Loaded Fuel Pins

COOLANT	GADOLINIA CONCENTRATION (WT%)	CONFIGURATION	REACTIVITY CHANGE (¢) EXP.	REACTIVITY CHANGE (¢) CAL.
H_2O	1.0		−53.8	−52.8
	0.5		−51.6	−49.8
	0.1		−36.1	−37.0
AIR	1.0		−69.0	−87.7
H_2O	1.0		−40.6	−33.4
H_2O	1.0		−38.4	−30.3
H_2O	1.0		−90.4	−82.5
H_2O	1.0		−107.2	−96.8
H_2O	1.0		−356.4	−308.7
AIR	1.0		−430.8	−496.7

○ 1.5WT% UO_2 FUEL PIN EXPERIMENTAL ERROR : ±4.0%
● Gd_2O_3-UO_2 FUEL PIN

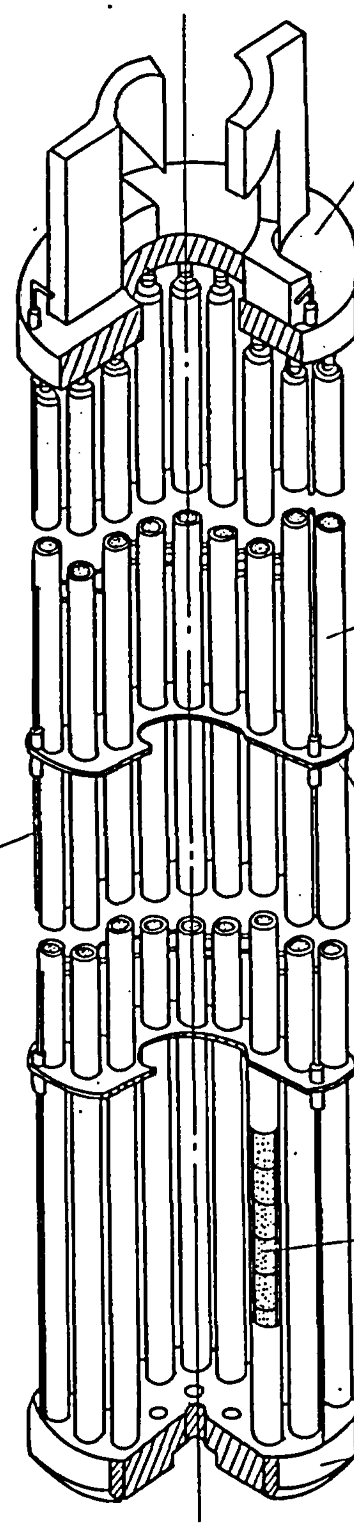
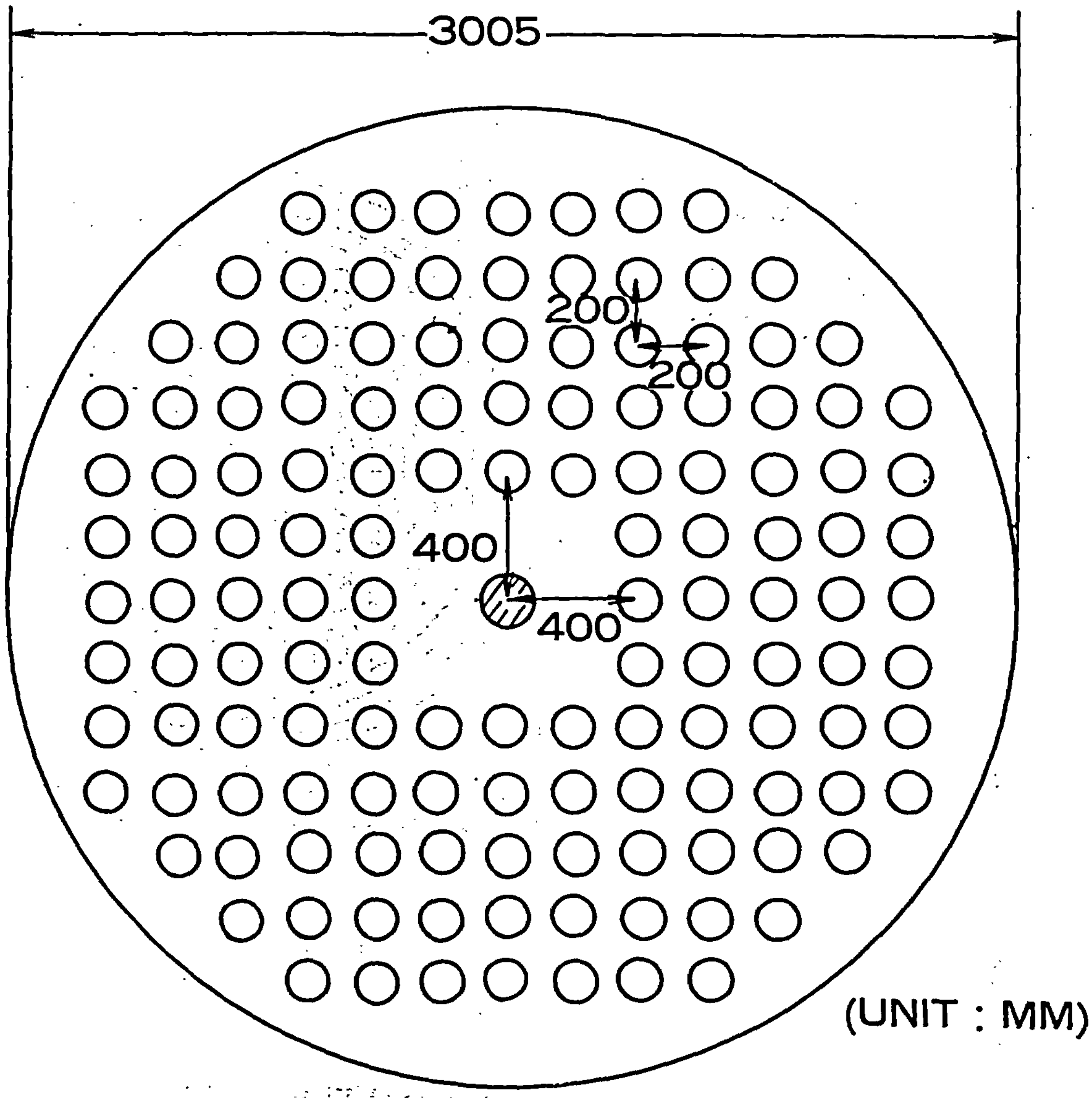


Fig. 1 Schematic View of 54-pin Cluster



TEST FUEL CLUSTER OF 54 PINS

DRIVER FUEL CLUSTER OF 28 PINS

Fig. 2 Layout of Fuel Clusters in DCA

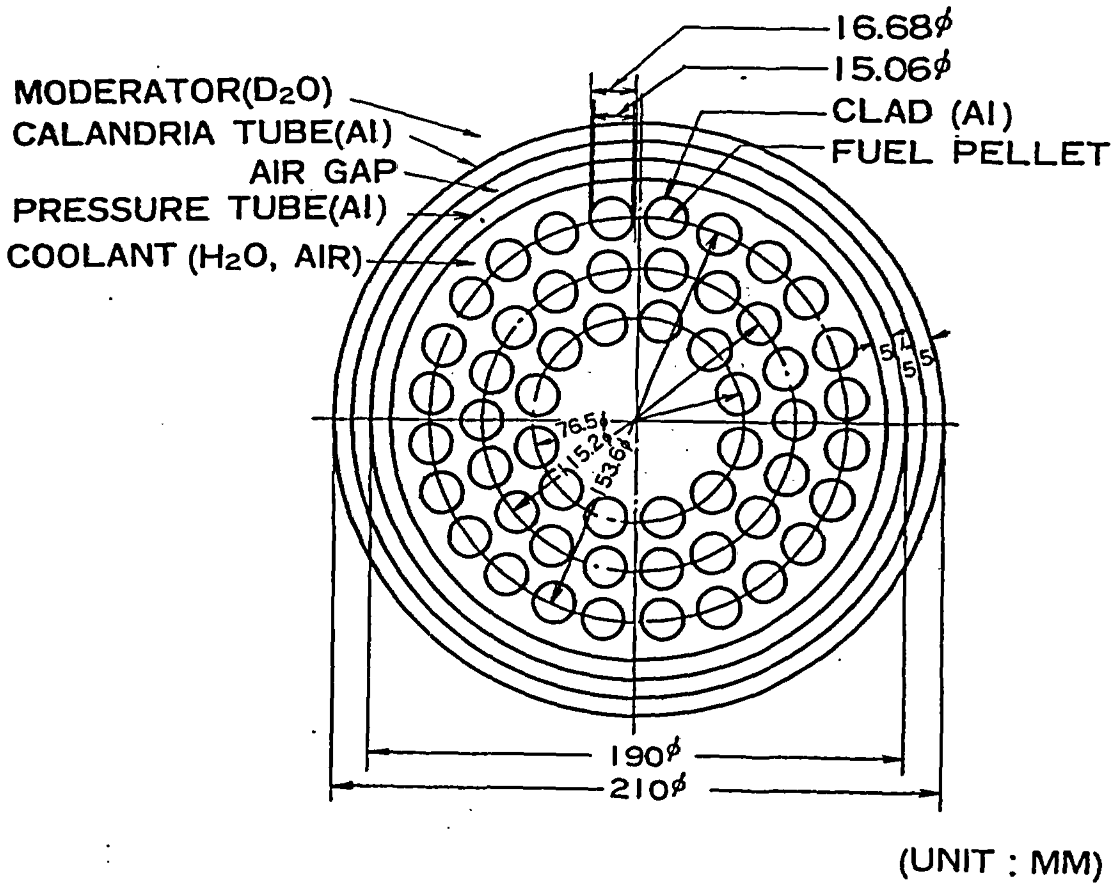


Fig. 3 Cross Sectional View of 54-pin Test Fuel Cluster

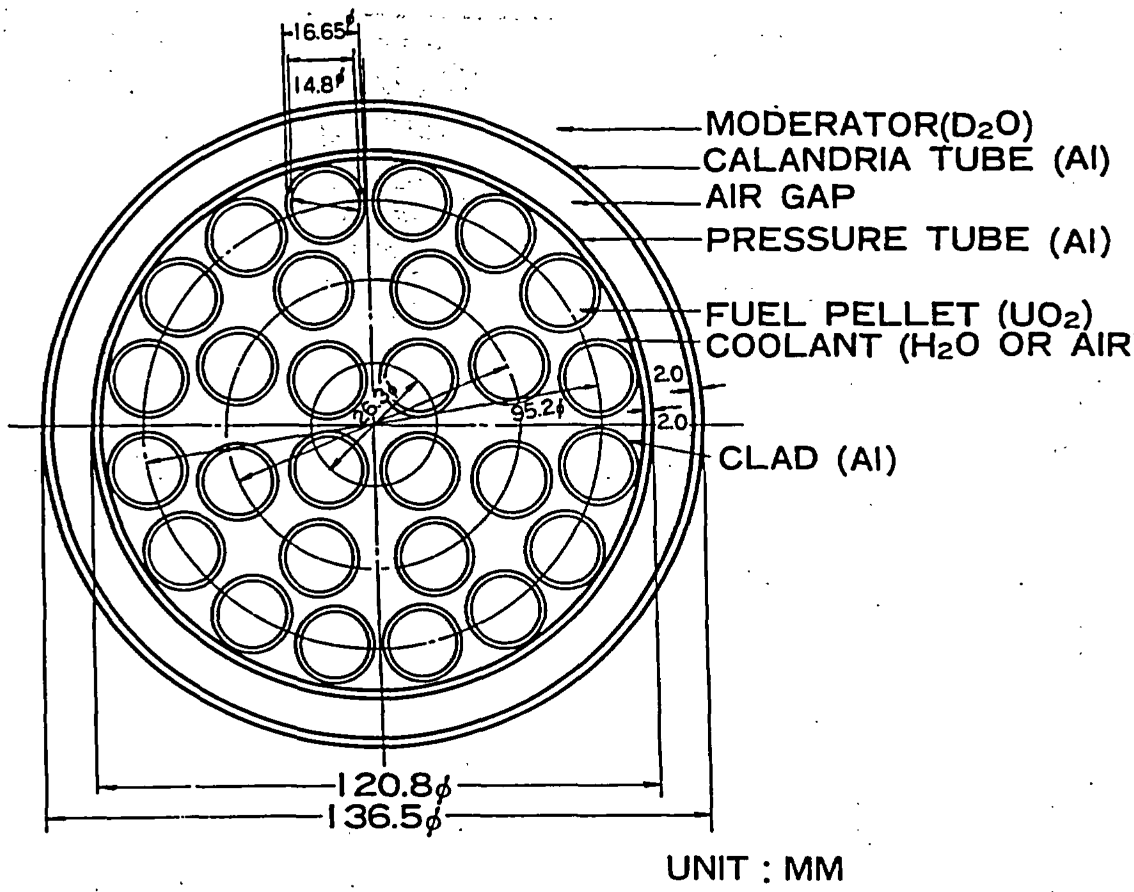


Fig. 4 Cross Sectional View of 28-pin Driver Fuel Cluster

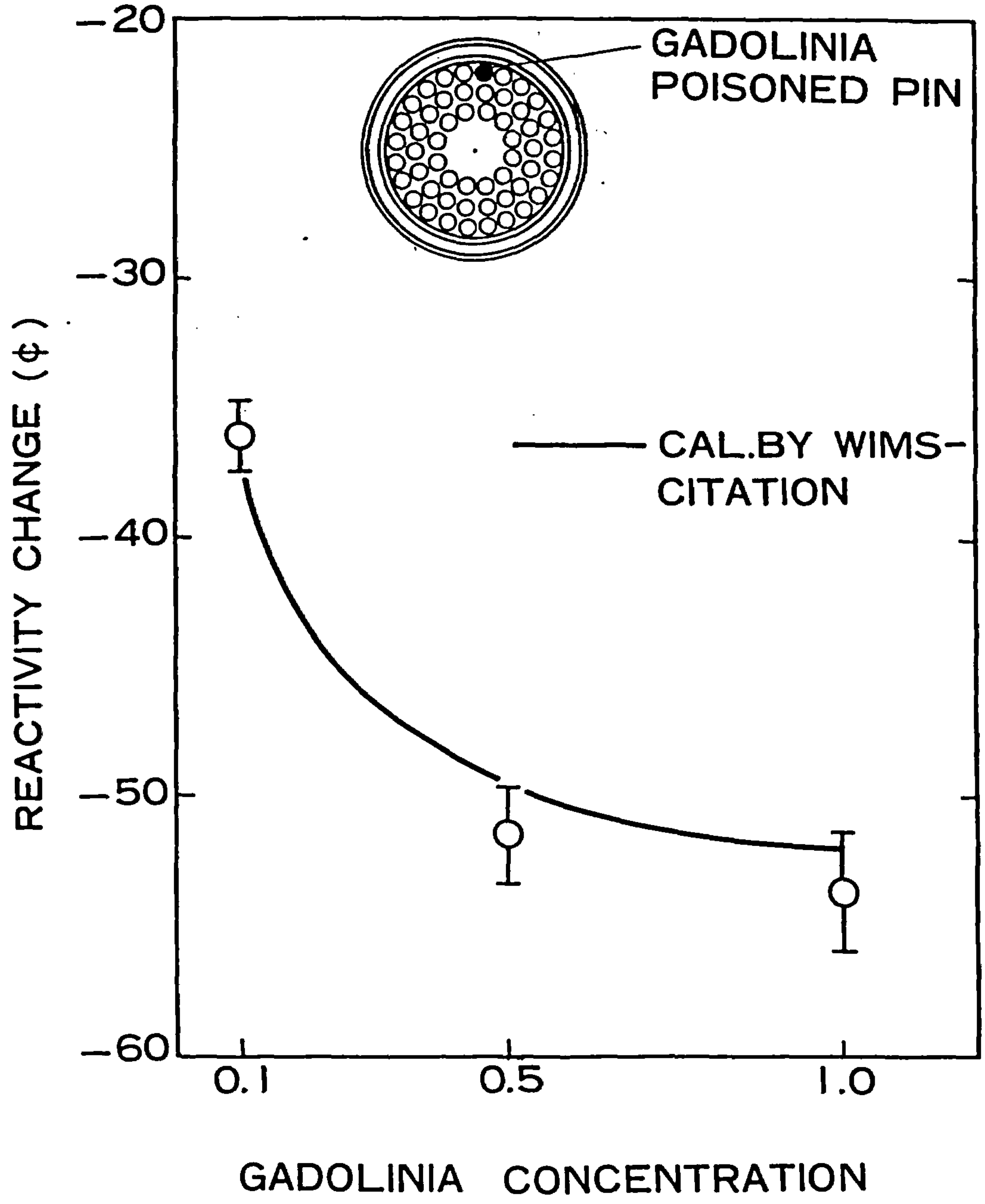


Fig. 5 Dependence of Reactivity Change of Gadolinia Concentration

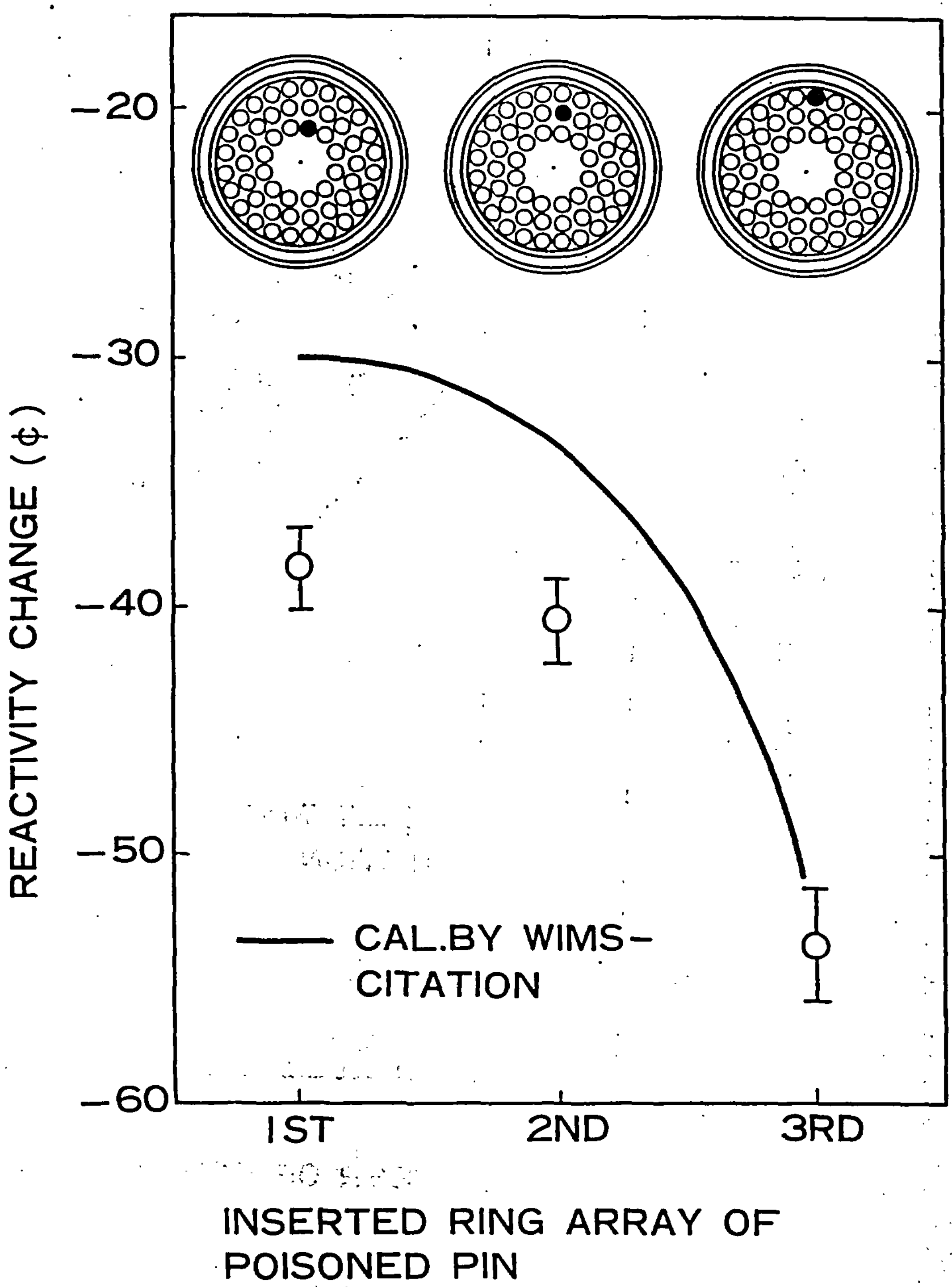


Fig. 6 Dependence of Reactivity Change on Configuration in Fuel Cluster (1.0 WT% Gd_2O_3)

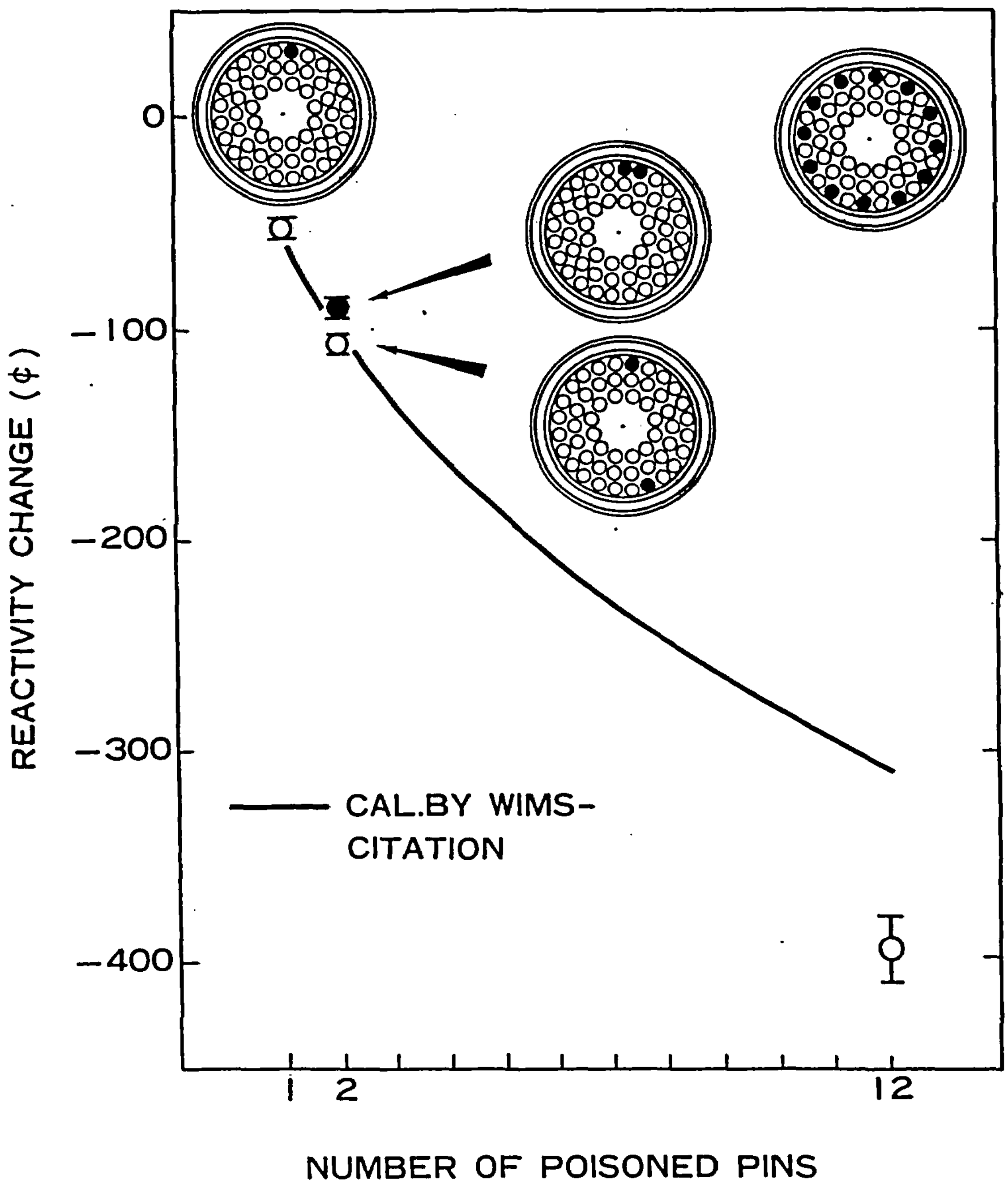


Fig. 7 Dependence of Reactivity Change on the Number of Poisoned Pins (1.0 WT% Gd_2O_3)

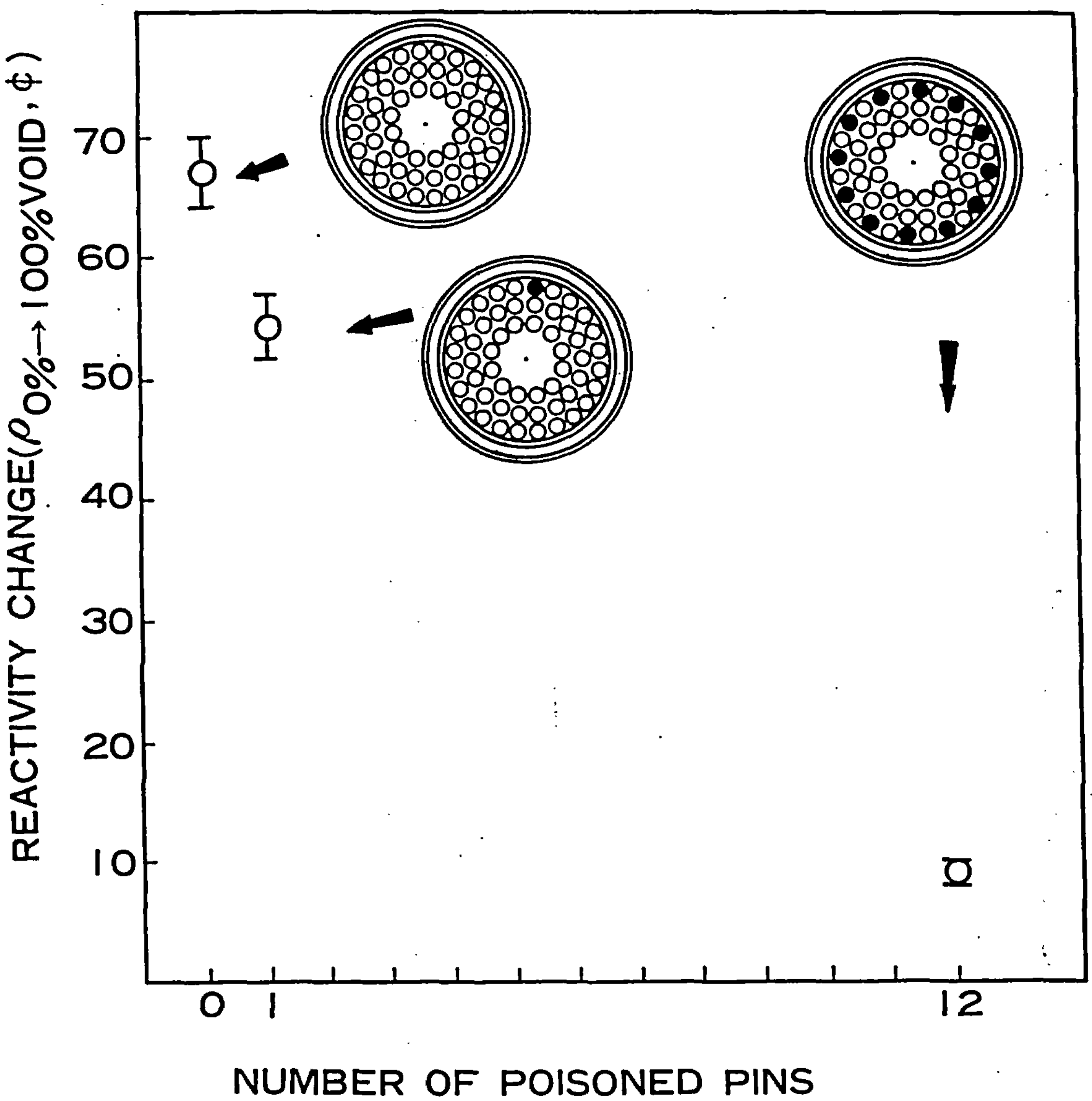


Fig. 8 Dependence of Reactivity Change from 0 % to 100 % Void on the Number of Poisoned Pins (1.0 WT% Gd_2O_3)