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## Influence of Burnable Gadolinia Poison on Coolant Void Reactivity in a Pressure-Tube-Type Heavy Water Reactor

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**Abstract**—The influence of burnable gadolinia poison in fuel assemblies on coolant void reactivity for a pressure-tube-type boiling light-water-cooled heavy water reactor is investigated in critical experiments using the Deuterium Critical Assembly (DCA) and theoretical analyses by the WIMS-D4/CITATION code system. The experimental and the calculated void reactivities agree within  $\pm 0.2$  %.

A number of gadolinia-poisoned fuel assemblies are dispersively loaded in the central region of the DCA core together with unpoisoned fuel assemblies. Each gadolinia-poisoned assembly is composed of three or four  $Gd_2O_3$ -poisoned  $UO_2$  fuel rods as well as unpoisoned fuel rods. The gadolinia concentration is varied from 0.0 to 1.0 wt%.

The void reactivity in the core becomes less negative with the addition of gadolinia but become saturated at a  $Gd_2O_3$  concentration of  $\sim 0.5$  wt%. The void reactivity becomes much less negative with a higher loading ratio of the gadolinia-poisoned assemblies in the core and as the gadolinia-poisoned fuel rods are arranged in the outer layers of the assembly. When the fissile nuclide in the pellets of the unpoisoned fuel assembly is changed from uranium to plutonium, the incremental positive shift of the void reactivity can be reduced because of the increase in the 0.3-eV thermal resonance absorption of  $^{239}Pu$  and  $^{241}Pu$ .

### I. INTRODUCTION

One method to improve the economy of nuclear power plants is to lengthen the period of time the fuel assemblies stay in the reactors; that is, to obtain high fuel burnup. This will be essential in many types of thermal power reactors. Attaining a high burnup means to increase the fissile uranium or plutonium enrichment in the fuel pellets. If such an increase in enrichment could be accomplished without any other considerations, then at the beginning of fuel burnup, not only would a large excess reactivity inevitably be added to the core, but it would also generate a large power peaking or mismatching. To solve these two problems simultaneously, gadolinia ( $Gd_2O_3$ ) is commonly added to several fuel rods in a fuel assembly.

Because the thermal neutron capture cross section of gadolinium is so large, the negative reactivity worth introduced by gadolinium tends to saturate at a low

gadolinia concentration. If gadolinia were added to many fuel rods in each fuel assembly in order to limit the excess reactivity, the local power peaking (maximum fuel rod power in an assembly) would become excessive with the diminution of gadolinia accompanied by fuel burning. Therefore, the number of gadolinia-poisoned fuel rods per assembly is generally limited. For this reason, the arrangement of gadolinia-poisoned rods in a fuel assembly must be determined according to the nuclear characteristics of each type of reactor.<sup>1,2</sup> These rods coexist with fissile and neutron absorber materials in high concentrations during the beginning cycle of a core designed for higher fuel burnup. For a pressure-tube-type boiling light-water-cooled heavy water reactor (HWR) using mainly plutonium for the fissile material, problems in nuclear calculation accuracy or nuclear characteristics (shift in coolant void reactivity, power mismatching, etc.) would result from the utilization of gadolinia in the reactor core, because the

lattice becomes more heterogeneous with the addition of gadolinia to the fuel rods.

The lattice cell of the HWR is more heterogeneous than that of a boiling water reactor (BWR), and the HWR core characteristics are different from those of a BWR because of the dual moderation by a heavy water moderator and by a light water coolant. The thermal conditions of a heavy water moderator never change, even when the coolant void fraction changes with reactor power. The coolant void reactivity (called void reactivity for short) of an HWR is very important in evaluating the characteristics for operation and control of the reactor because the sign of the void reactivity changes easily with the lattice condition. Thus, the neutron behavior for the void reactivity in an HWR core should be clarified in detail. It is possible for an HWR to have a negative void reactivity when plutonium is used, and the void reactivity of Japanese HWR power reactors is designed to have a value of nearly zero.

The ordinary neutron absorbers, boric acid and control rods, are used in the moderator to control the excess reactivity or the power distribution in an HWR, and it has been confirmed that these neutron absorbers affect the void reactivity, causing a less negative shift.<sup>3</sup> When gadolinia poison is added to fuel pellets, it is very important to investigate whether the gadolinia shows the same effect on void reactivity as ordinary neutron absorbers.

## II. EXPERIMENTS AND ANALYSES

### II.A. Evaluation Method

The influence of a gadolinia poison on the void reactivity is studied from an experiment in the Deuterium Critical Assembly (DCA) and from theoretical analyses by a nuclear code system for an HWR. The following parameters are considered:

1. gadolinia concentration in fuel rods in a gadolinia-poisoned fuel assembly
2. loading ratio of the gadolinia-poisoned assemblies in the core
3. type of fissile nuclide in a normal fuel assembly without gadolinia poison (reference assembly).

The WIMS-D4 and CITATION codes<sup>4,5</sup> are used for lattice calculations based on the collision probability method and for core calculations based on the diffusion theory, respectively. The calculational accuracy of the code system for the void reactivity of a core containing gadolinia-poisoned assemblies was evaluated by experimental analyses of a DCA core in which a number of gadolinia-poisoned assemblies were dispersively loaded. Here, gadolinia was added uniformly to the pel-

lets of a few fuel rods in a cluster-type HWR fuel assembly (called a cluster for short).

In the lattice calculation, the collision probability in each mesh region is calculated after 69 groups of a nuclear data library are collapsed into 11 groups. The 11-group constants are further collapsed into 3 groups to obtain the cell-average group constants of the fast group ( $>5.53$  keV), the epithermal group (5.53 keV to 0.625 eV), and the thermal group ( $<0.625$  eV) for the core calculation. The void reactivity is obtained with a three-energy-group diffusion calculation. To investigate the influence of the three parameters mentioned earlier on the void reactivity of a core containing gadolinia-poisoned assemblies, the components of the void reactivity in each fuel region are calculated with a perturbation method. Using the three-energy-group constants obtained from the lattice calculation and both the neutron flux and the adjoint neutron flux obtained from the diffusion calculation, exact perturbation analyses for the void reactivity are carried out with the PERKY code.<sup>6</sup>

To clarify the calculational accuracy of the nuclear code system, void reactivities for a DCA core containing a few gadolinia-poisoned assemblies are measured by adjusting the critical moderator level. The void reactivity is the reactivity that arises when the coolant void fractions in all the pressure tubes of a core are changed from light water (0% void fraction) to air (100% void fraction). The void reactivity  $\rho_{0 \rightarrow v}$  (in dollars) calculated by this method is defined as

$$\frac{\rho_{0 \rightarrow v}}{\beta_{eff}} = \int_{B_{zv}^2}^{B_{z0}^2} \left( \frac{\partial \rho}{\partial B_z^2} \right)_v dB_z^2, \quad (1)$$

where

$\beta_{eff}$  = effective delayed neutron fraction of the core with 100% void fraction

$(\partial \rho / \partial B_z^2)_v$  = reactivity coefficient on axial buckling

$B_{z0}^2, B_{zv}^2$  = critical axial bucklings.

Subscripts 0 and  $v$  indicate 0% and 100% void fractions, respectively. Actually, using the following reactor physics quantities, which are directly measurable, we obtain the experimental void reactivity<sup>3,7</sup> as

$$\frac{\rho_{0 \rightarrow v}}{\beta_{eff}} = \int_{H_0}^{H_v} \left( \frac{\partial \rho}{\partial H} \right)_v dH - \frac{2\eta_v \cdot \delta \lambda_z}{(H_0 + \lambda_{zv})^3}, \quad (2)$$

with

$$\delta \lambda_z = \lambda_{zv} - \lambda_{z0} \quad (3)$$

and

$$\eta_v = \frac{\pi^2 M_z^2}{\beta_{eff} k_{\infty}} \left( 1 + \frac{2\tau L^2}{M^2} B^2 \right), \quad (4)$$

where

$H_0, H_v$  = critical moderator levels

$(\partial\rho/\partial H)_v$  = reactivity coefficient on moderator level

$\lambda_{z0}, \lambda_{zv}$  = axial reflector savings.

The other symbols have their conventional meanings. The gadolinia worth  $\rho_{Gd}$  due to the addition of gadolinia is also measured by adjusting the critical moderator level. Since there was no significant difference in axial reflector savings with varying gadolinia concentration in the fuel rods, the second term on the right side of Eq. (2) becomes zero when obtaining the experimental value of  $\rho_{Gd}$ .

### II.B. Experimental Core Arrangement

The gadolinia-poisoned assemblies used for the experiment are a 28-rod and a 36-rod fuel cluster arranged in three concentric circles, as shown in Fig. 1. Three or four gadolinia-poisoned rods are arranged in the middle layer of the cluster in threefold or fourfold rotation symmetry around the fuel assembly axis, and the oth-

ers are ordinary fuel rods without gadolinia poison (reference rods). The gadolinia is uniformly mixed into the fuel pellets. The gadolinia-poisoned rods in the Japanese HWR power reactor are designed to be placed in the middle layer of a cluster for the three following reasons:

1. Negative reactivity due to neutron absorption of gadolinium and power mismatch between fuel assemblies is not excessive when fresh gadolinia-poisoned or unpoisoned assemblies are contiguously loaded into a core.
2. The rate of gadolinium diminution corresponds to the fuel burnup rate.
3. Local power peaking is not excessive when gadolinium disappears with the fuel burnup.

The specifications of the gadolinia-poisoned and reference rods used for the experiment are shown in Table I. The diameter of all fuel rods in the cluster is 16.7 mm. To investigate the influence of the number of fuel rods in a cluster on the void reactivity, both a 28-rod and a 36-rod cluster are used for the gadolinia-poisoned and reference assemblies. According to the

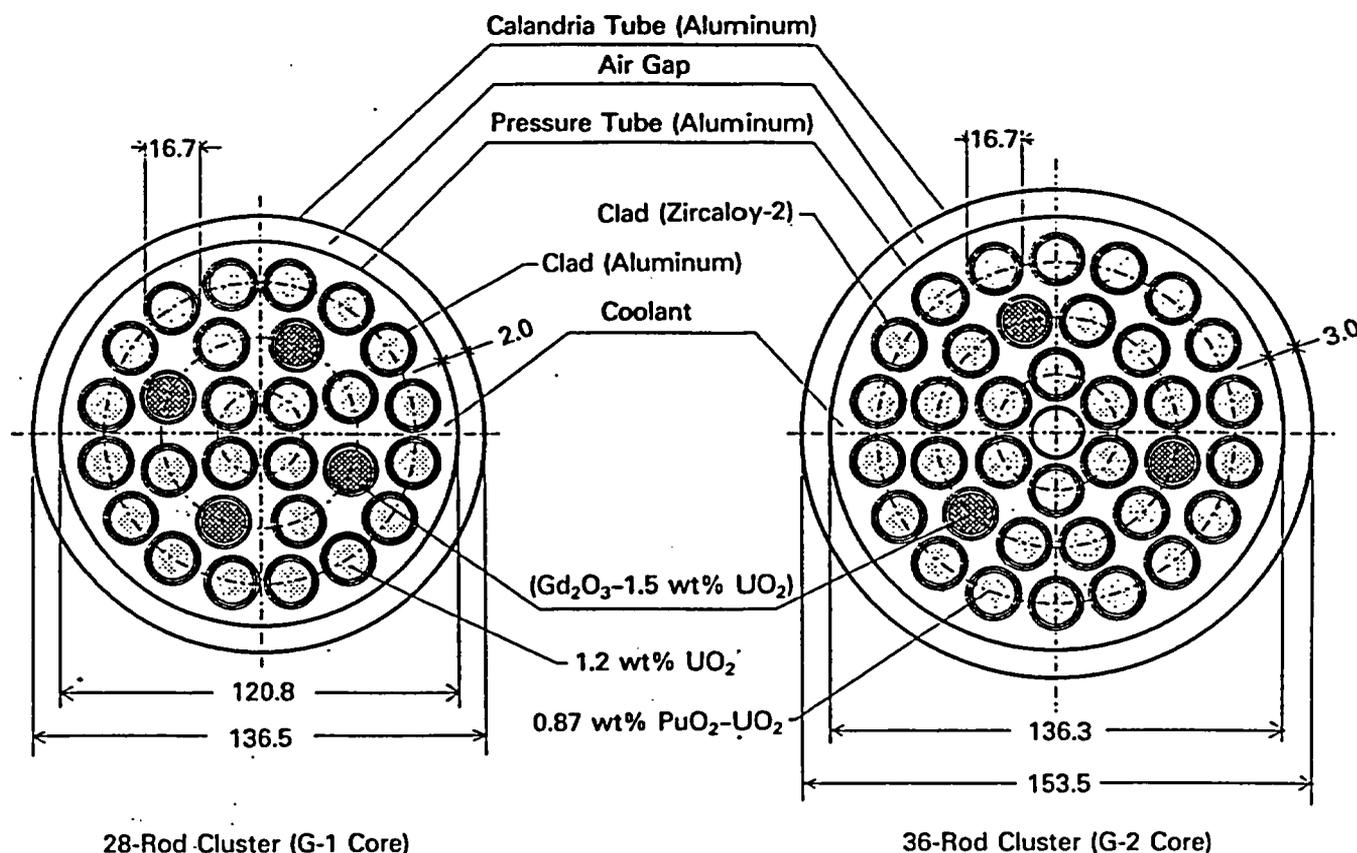


Fig. 1. Cross-sectional view of gadolinia-poisoned fuel cluster with Gd<sub>2</sub>O<sub>3</sub>-UO<sub>2</sub> rods. Dimensions are given in millimetres.

TABLE I  
Specifications for Unpoisoned and Gadolinia-Poisoned Fuel Rods

Specification	Unpoisoned Rod		Gadolinia-Poisoned Rod (Gd <sub>2</sub> O <sub>3</sub> -1.5 wt% UO <sub>2</sub> )			
	UO <sub>2</sub> (in 28-Rod Cluster)	MOX (in 36-Rod Cluster)	0 wt%	0.1 wt%	0.5 wt%	1.0 wt%
			Gd <sub>2</sub> O <sub>3</sub>	Gd <sub>2</sub> O <sub>3</sub>	Gd <sub>2</sub> O <sub>3</sub>	Gd <sub>2</sub> O <sub>3</sub>
<b>Pellet</b>						
Density (g/cm <sup>3</sup> )	10.36	10.17	10.38	10.30	10.30	10.30
Fissile uranium or PuO <sub>2</sub> enrichment (wt%)	1.20	0.87	1.5	1.5	1.5	1.5
Gd <sub>2</sub> O <sub>3</sub> content (wt%)	---	---	0.0	0.1	0.5	1.0
Diameter (mm)	14.80	14.70	14.77	14.78	14.78	14.78
Nuclide content (wt%)						
<sup>235</sup> U	1.057	0.6194	1.317	1.328	1.323	1.316
<sup>238</sup> U	86.793	86.5030	86.563	86.384	86.042	85.612
<sup>238</sup> Pu	---	0.0014	---	---	---	---
<sup>239</sup> Pu	---	0.6849	---	---	---	---
<sup>240</sup> Pu	---	0.0658	---	---	---	---
<sup>241</sup> Pu	---	0.0069	---	---	---	---
<sup>242</sup> Pu	---	0.0005	---	---	---	---
<sup>155</sup> Gd	---	---	0.0	0.0128	0.0634	0.1269
<sup>156</sup> Gd	---	---	0.0	0.0177	0.0881	0.1763
<sup>157</sup> Gd	---	---	0.0	0.0136	0.0675	0.1350
<sup>158</sup> Gd	---	---	0.0	0.0422	0.212	0.4237
<sup>16</sup> O	12.15	12.12	12.12	12.201	12.205	12.210
<b>Cladding</b>						
Material	Al-Mg alloy	Zircaloy-2	Al-Mg alloy	←	←	←
Density (g/cm <sup>3</sup> )	2.674	6.523	2.674	←	←	←
Inner diameter (mm)	15.03	15.06	15.03	14.98	←	←
Outer diameter (mm)	16.73	16.68	16.73	16.69	←	←

scaling up of reactor power from the Fugen prototype HWR (under operation) to a demonstration reactor (being designed), the number of fuel rods per cluster is designed to be increased from 28 to 36 with an expected increase in the channel power; however, the diameter of the fuel rod will be decreased to retain the heat removable capacity. The fuel material of the 28-rod cluster consists entirely of UO<sub>2</sub>, but that of the 36-rod cluster is mixed oxide (MOX) except for the gadolinia-poisoned rods. However, the only fissile nuclide in the gadolinia-poisoned fuel rods in both clusters is uranium. Meanwhile, MOX fuel clusters will be used for all channels of the core in the Japanese HWR power reactor.

Four 28-rod gadolinia-poisoned assemblies or one 36-rod gadolinia-poisoned assembly, together with reference assemblies, are loaded into a DCA core with a 25.0-cm-pitch square lattice. The void reactivities are measured by changing the gadolinia concentration in the gadolinia-poisoned rods from 0.0 to 0.1, 0.5, and 1.0 wt%. The configurations of the two kinds of experimental cores (G-1 and G-2) loaded with 28-rod or 36-rod gadolinia-poisoned assemblies, respectively, are

28-rod gadolinia-poisoned assemblies are loaded in the four corner channels in the central region of (3 × 3) channels of the G-1 core, and one 36-rod gadolinia-poisoned fuel is in the center channel of the G-2 core. In the channels adjacent to the gadolinia-poisoned assemblies, 1.2 wt% UO<sub>2</sub> clusters are loaded in the G-1 core as the reference assembly, and 0.87 wt% PuO<sub>2</sub>-enriched PuO<sub>2</sub>-UO<sub>2</sub> (0.87 wt% MOX) clusters are similarly loaded in the G-2 core. The <sup>10</sup>B concentration in the heavy water moderator and the heavy water purity are, however, slightly different in each core, as shown in Table II.

### III. RESULTS

#### III.A. Calculation Accuracy of the Nuclear Code System

The dependence of the measured gadolinia worth  $\rho_{Gd}$  on the Gd<sub>2</sub>O<sub>3</sub> concentration for the G-1 core is shown in Fig. 3 with values calculated by the code system. Figure 3 reveals that even the addition of only a 0.1 wt% Gd<sub>2</sub>O<sub>3</sub> concentration causes a large reactivity

TABLE II  
Core Conditions for Void Reactivity Measurement

	Core G-1	Core G-2
Gadolinia-poisoned fuel cluster		
Loading in core	4	1
Location of clusters	Corners of central (3 × 3) channels	Center
Gadolinia-poisoned rod	1.5 wt% UO <sub>2</sub> + Gd <sub>2</sub> O <sub>3</sub>	1.5 wt% UO <sub>2</sub> + Gd <sub>2</sub> O <sub>3</sub>
Position and number of gadolinia-poisoned rods in cluster	Middle layer, 4	Middle layer, 3
Reference rod in cluster	1.2 wt% UO <sub>2</sub>	0.87 wt% PuO <sub>2</sub> -UO <sub>2</sub>
Total rods in cluster	28	36
Reference fuel cluster		
Loading in core	28 rods: 1.2 wt% UO <sub>2</sub>	36-rod cluster 0.87 wt% PuO <sub>2</sub> -UO <sub>2</sub> 28-rod cluster 1.2 wt% UO <sub>2</sub>
Reference rod in cluster		0.87 wt% PuO <sub>2</sub> -UO <sub>2</sub>
Total rods in cluster		Eighty-eight 28-rod clusters
Loading in core	93	Eight 36-rod clusters
Reference rod in cluster		Eighty-eight 28-rod clusters
Total rods in cluster		
Lattice pitch (cm)	25.0	25.0
Soluble <sup>10</sup> B content in D <sub>2</sub> O (ppm)	2.64	0.0
Purity of D <sub>2</sub> O moderator (mol%)	99.2	99.4

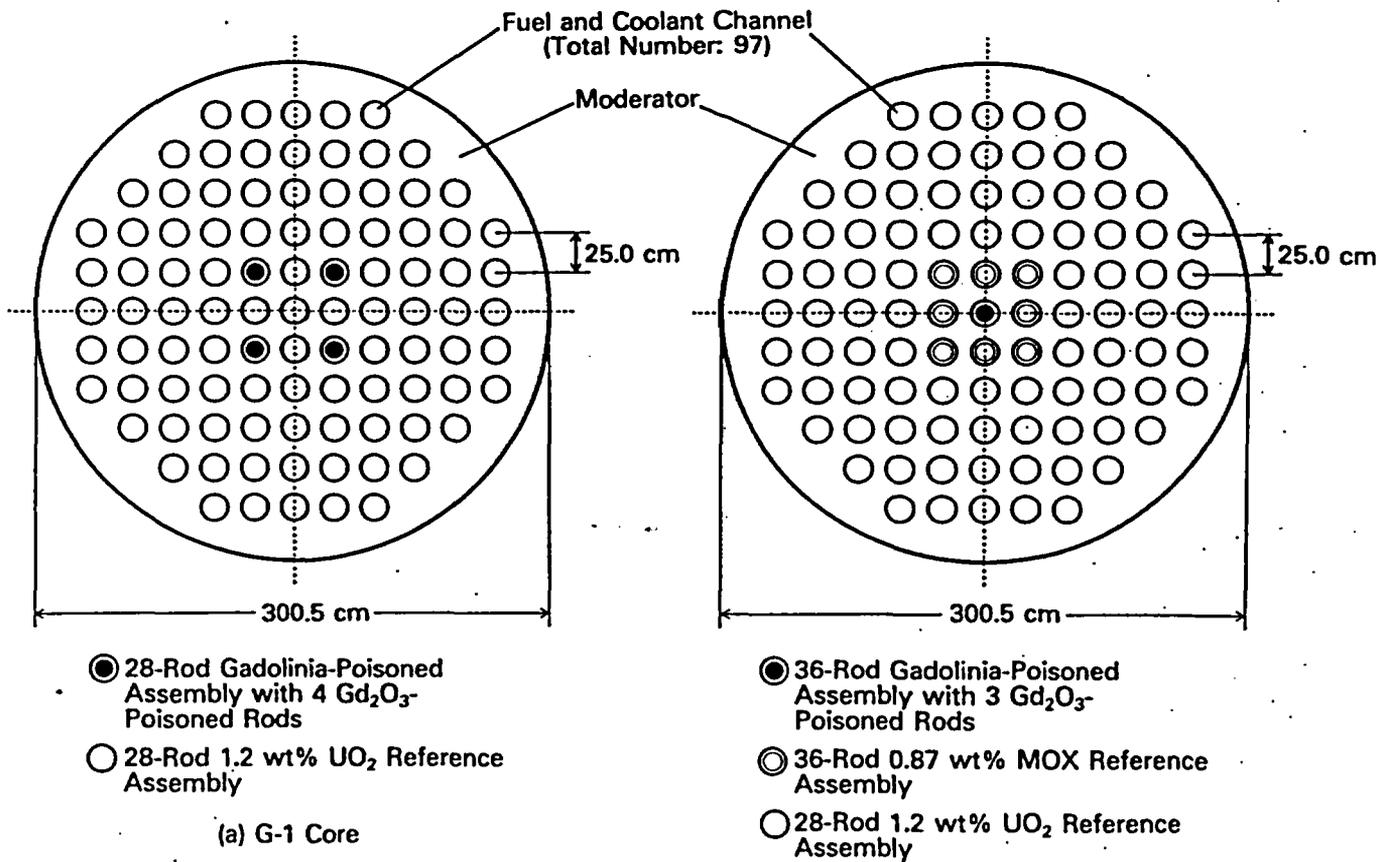


Fig. 2. Configurations of experimental cores with gadolinia-poisoned fuel clusters.

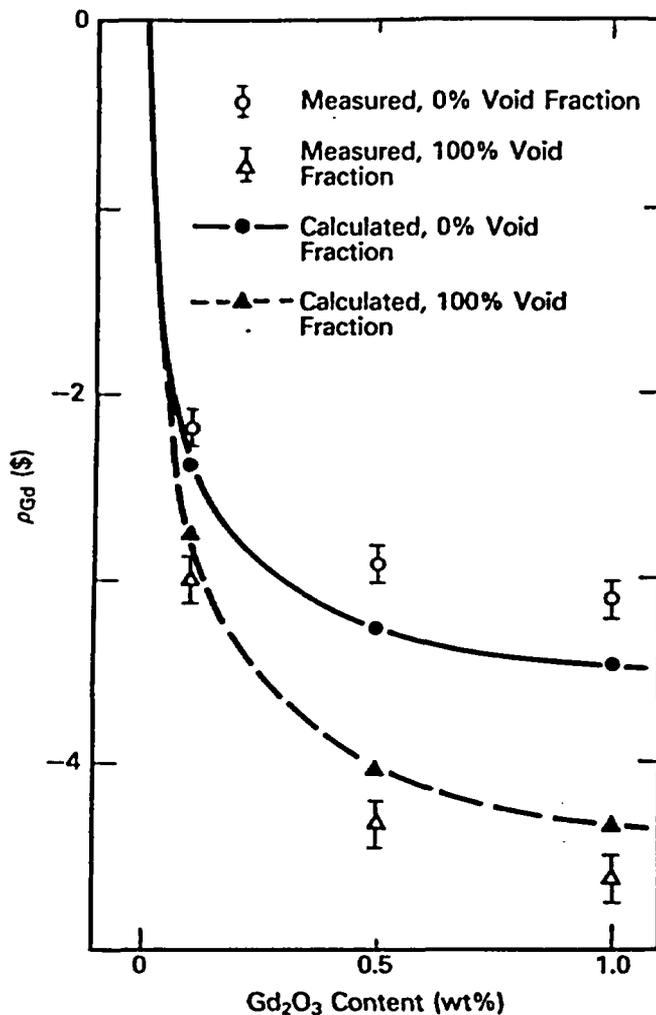


Fig. 3. Calculated and measured gadolinia worths as a function of  $Gd_2O_3$  content in the G-1 core with four 28-rod gadolinia-poisoned fuel clusters.

concentration. The calculated values of  $\rho_{Gd}$  underestimate the experimental ones for the unvoided core but overestimate for the core with a 100% void fraction. The experimental and calculated values agree within  $\pm 0.4$  \$ (relative value  $\pm 11.6\%$ ). The experimental  $\rho_{Gd}$  for the unvoided core is 40 to 50% lower than that for a 100% void fraction. This is because coolant with a higher void fraction lessens the thermal neutron shielding effect and causes the thermal neutron absorption of the gadolinium in the fuel pellets to increase.

The dependence of the experimental and calculated void reactivities on the  $Gd_2O_3$  concentration in the G-1 and G-2 cores is shown in Tables III and IV and in Figs. 4 and 5. The experimental results are shown for the core with the poisoned rods of the gadolinia-poisoned assemblies arranged only in the middle layer of the cluster, but the calculated values are also represented for cores with poisoned rods in the inner or outer

layer of the fuel assembly (only for the G-1 core). As shown in Tables III and IV, the experimental and calculated values agree within  $\pm 0.2$  \$.

### III.B. Dependence of Void Reactivity on $Gd_2O_3$ Concentration and Location of Gadolinia-Poisoned Rods

Both the G-1 and G-2 cores show the same effect on  $\rho_{0 \rightarrow v}$  of  $Gd_2O_3$  concentration as shown in Figs. 4 and 5. Regardless of where the gadolinia-poisoned rods are placed in the cluster,  $\rho_{0 \rightarrow v}$  shifts suddenly to a less negative value when the  $Gd_2O_3$  concentration is increased from 0 to 0.1 wt% and saturates at  $\sim 0.5$  wt%. This tendency is the same as that of the gadolinia reactivity described in Sec. III.A. Since the thermal absorption cross section of gadolinium is extremely large (several tens of thousands of barns), the addition of a slight amount of gadolinia affects the neutron importance and the thermal neutron spectrum in the reference fuel region. In other words, the addition of 0.1 wt%  $Gd_2O_3$  rapidly shifts  $\rho_{0 \rightarrow v}$  toward the less negative side, but when more than 0.1 wt%  $Gd_2O_3$  is added, the thermal absorption cross section reaches the saturated value and  $\rho_{0 \rightarrow v}$  is hardly affected by the gadolinia concentration.

The incremental positive shift of  $\rho_{0 \rightarrow v}$  with a 0.1 wt% addition of gadolinia becomes larger when poisoned rods are placed in the outer layer and when the number of poisoned rods is increased but is negligibly small when they are placed in the inner layer. This is because gadolinium and the fuel nuclide have large thermal neutron absorption cross sections, so that the reduction of the thermal neutron shielding effect due to coolant voiding is larger when the poisoned rods are placed in the outer layer of a cluster nearer the heavy water moderator. When the poisoned rods are placed in the inner layer, the thermal neutron flux in the inner layer is lower than that in the middle or the outer layer, so that the reduction of the thermal neutron shielding effect due to coolant voiding is small compared with the case when the poisoned rods are in the outer layer.

The calculational accuracies of the gadolinia and void reactivities in cores with gadolinia-poisoned assemblies have been clarified. In the following sections, the effect of gadolinia concentration on  $\rho_{0 \rightarrow v}$  is described for the G-1 core in which gadolinia-poisoned rods are arranged in the middle layer of the clusters, including the result of perturbation analyses.

### III.C. Effect of Loading Ratio of Gadolinia-Poisoned Assembly on Void Reactivity

It can be estimated from the results in Sec. III.A that the void reactivity becomes less negative even if the area of lattice with gadolinia-poisoned assemblies (poisoned fuel region) in the core is increased by increasing loading ratio of the gadolinia-poisoned assembly,

TABLE III  
Void Reactivities in the G-1 Core with Four 28-Rod Gadolinia-Poisoned Fuel Clusters

Gadolinia-Poisoned Fuel Rod		Void Reactivity (\$)		$\beta_{eff}$ (%) at Voided Core
Gd <sub>2</sub> O <sub>3</sub> Concentration (wt%)	Location (Number)	Experiment	Calculation	
0.0	Middle (4)	3.48 ± 0.19	3.31	0.783
	Outer (4)	---	3.26	0.783
	Inner (2)	---	3.35	0.783
0.1	Middle (4)	3.88 ± 0.14	3.90	0.784
	Outer (4)	---	4.47	0.784
	Inner (2)	---	3.46	0.783
0.5	Middle (4)	3.71 ± 0.13	3.89	0.784
	Outer (4)	---	4.65	0.784
	Inner (2)	---	3.35	0.784
1.0	Middle (4)	3.67 ± 0.12	3.87	0.784
	Outer (4)	---	4.65	0.784
	Inner (2)	---	3.33	0.784

TABLE IV  
Void Reactivities in the G-2 Core with One 36-Rod Gadolinia-Poisoned Fuel Cluster

Gadolinia-Poisoned Fuel Rod		Void Reactivity (\$)		$\beta_{eff}$ (%) at Voided Core
Gd <sub>2</sub> O <sub>3</sub> Concentration (wt%)	Location (Number)	Experiment	Calculation	
0.0	Middle (3)	-6.48 ± 0.24	-6.35	0.653
	Outer (3)	---	-6.50	0.655
	Inner (6)	---	-6.41	0.657
0.1	Middle (3)	---	-5.73	0.660
	Outer (3)	---	-5.35	0.665
	Inner (6)	---	-4.44	0.674
0.5	Middle (3)	---	-5.47	0.664
	Outer (3)	---	-4.86	0.670
	Inner (6)	---	-3.84	0.682
1.0	Middle (3)	-5.62 ± 0.22	-5.41	0.664
	Outer (3)	---	-4.77	0.671
	Inner (6)	---	-3.74	0.683

as is the case when the gadolinia concentration in the fuel pellets is increased. To determine the phenomena that cause the less negative shift when the poisoned fuel region is increased, the gadolinia-poisoned assemblies are dispersively distributed not to be adjacent to each other, and the dependence of  $\rho_{0-v}$  on gadolinia concentration is calculated for cores in which 4, 8, 12, 16, and 21 reference assemblies of 1.2 wt% UO<sub>2</sub> are re-

placed by gadolinia-poisoned assemblies in fourfold rotation symmetry around the core axis (core G-1A). An example of the configuration of core G-1A with 12 gadolinia-poisoned assemblies is shown in Fig. 6. Figure 7a for core G-1A shows that an increase in the loading ratio of the gadolinia-poisoned assembly further causes a less negative shift in  $\rho_{0-v}$  as is the case for an increase in gadolinia concentration.

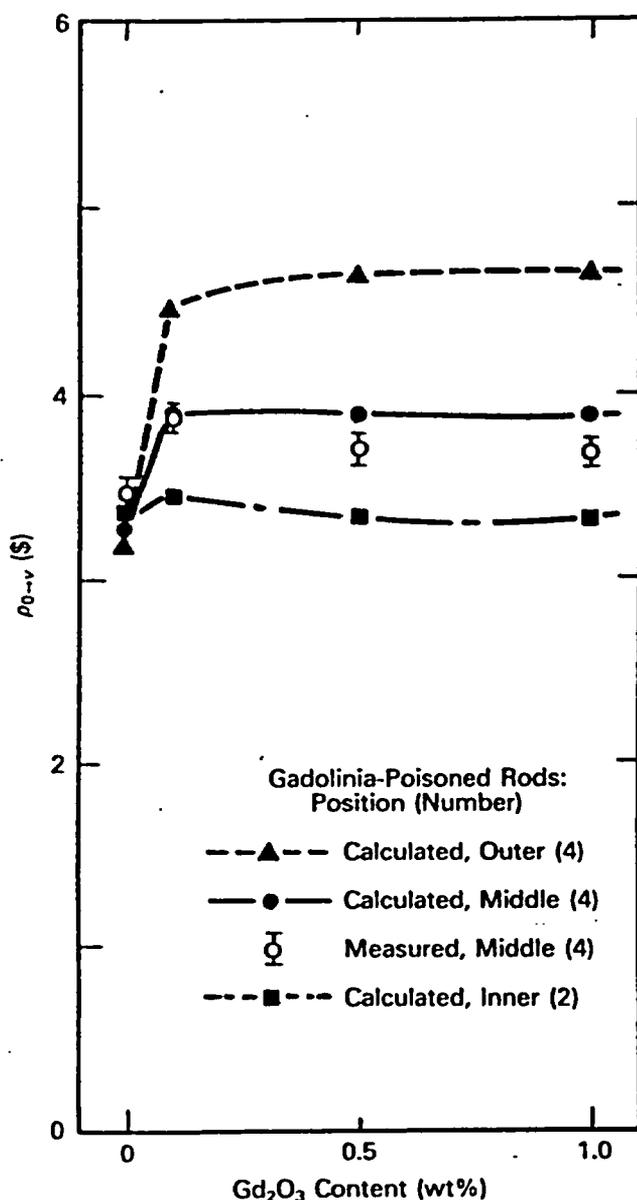


Fig. 4. Calculated and measured void reactivities as a function of  $Gd_2O_3$  content in the G-1 core with four 28-rod gadolinia-poisoned fuel clusters.

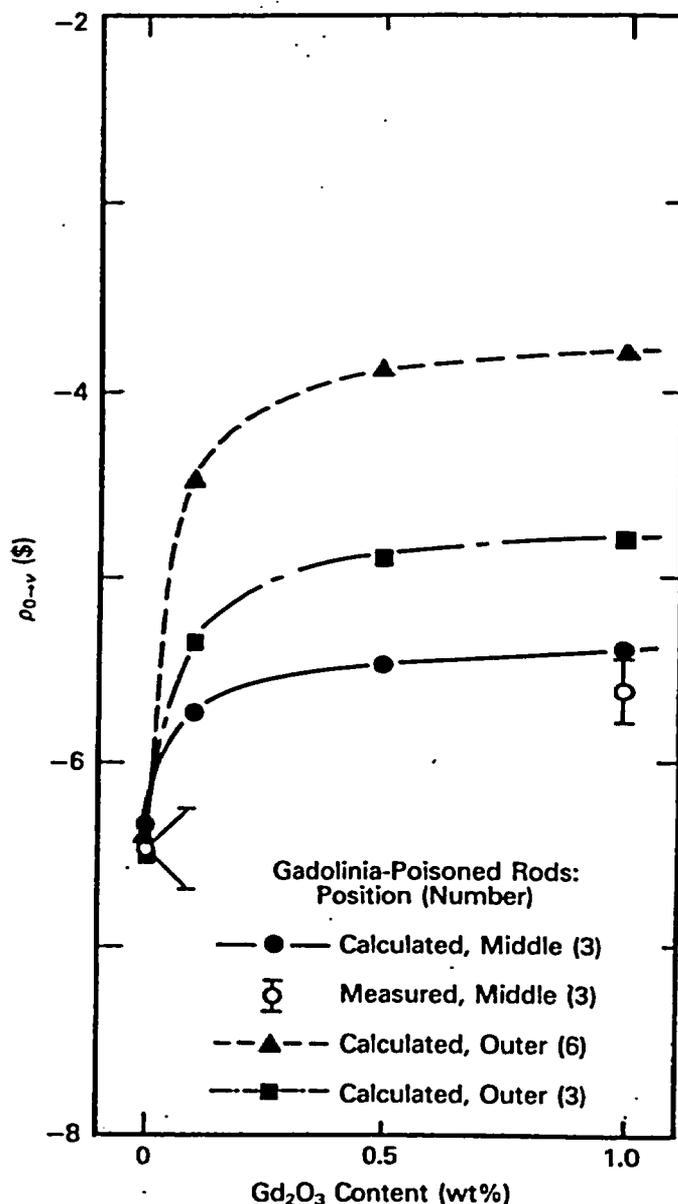


Fig. 5. Calculated and measured void reactivities as a function of  $Gd_2O_3$  content in the G-2 core with one 36-rod gadolinia-poisoned fuel cluster.

### III.D. Effect of the Fissile Nuclide in the Reference Fuel on Void Reactivity

To study the effect of the fissile nuclide in the reference assembly on  $\rho_{0 \rightarrow v}$  in a core in which gadolinia-poisoned assemblies are dispersively loaded, a new core (core G-1B) is formed by replacing reference 1.2 wt%  $UO_2$  assemblies with 0.54 wt%  $PuO_2$ -enriched  $PuO_2$ - $UO_2$  (0.54 wt% MOX) having the same fuel rod shape and the same ratio of fissile nuclide as 1.2 wt%  $UO_2$ . The dependence of  $\rho_{0 \rightarrow v}$  on gadolinia concentration

for core G-1B was calculated by changing the loading ratio of the gadolinia-poisoned assembly same as in Sec. III.C, and the result is shown in Fig. 7b. The dependence of  $\rho_{0 \rightarrow v}$  on gadolinia concentration does not change even if the reference assemblies are changed from  $UO_2$  to MOX, but the incremental positive shift of  $\rho_{0 \rightarrow v}$  is restrained for core G-1B, and this tendency of  $\rho_{0 \rightarrow v}$  increases as increasing gadolinia concentration. Therefore, plutonium acts to more severely restrain  $\rho_{0 \rightarrow v}$  compared with uranium, even in the core with gadolinia-poisoned assemblies.

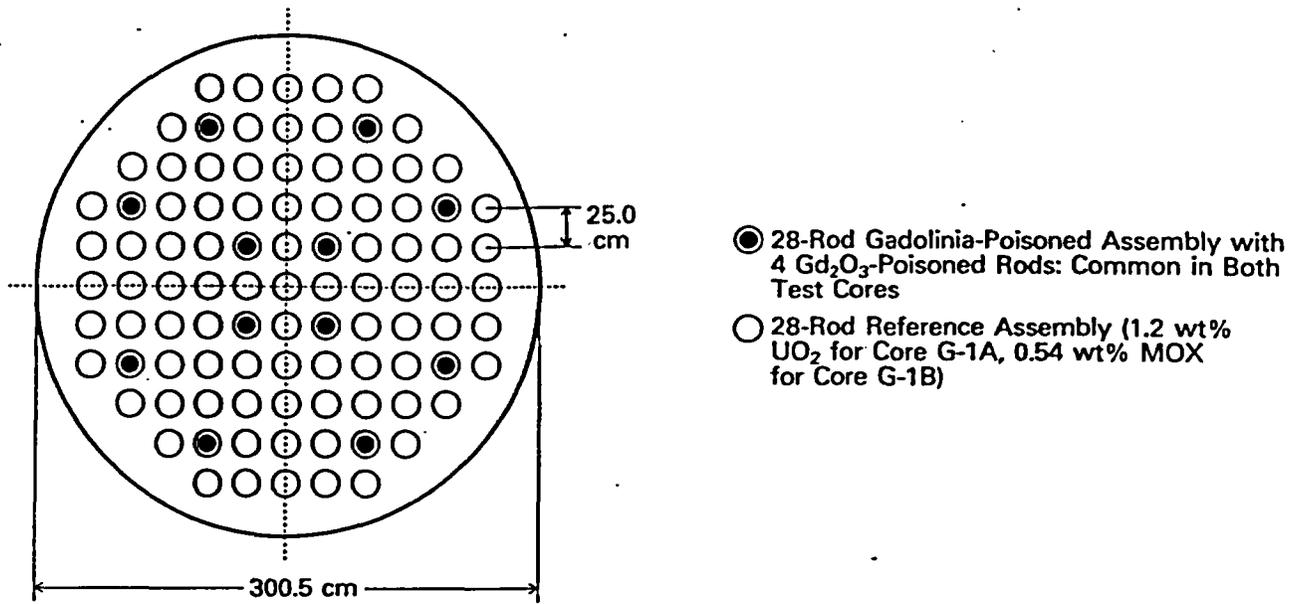


Fig. 6. Example of test cores G-1A and G-2B in which 12 gadolinia-poisoned fuels are dispersively loaded.

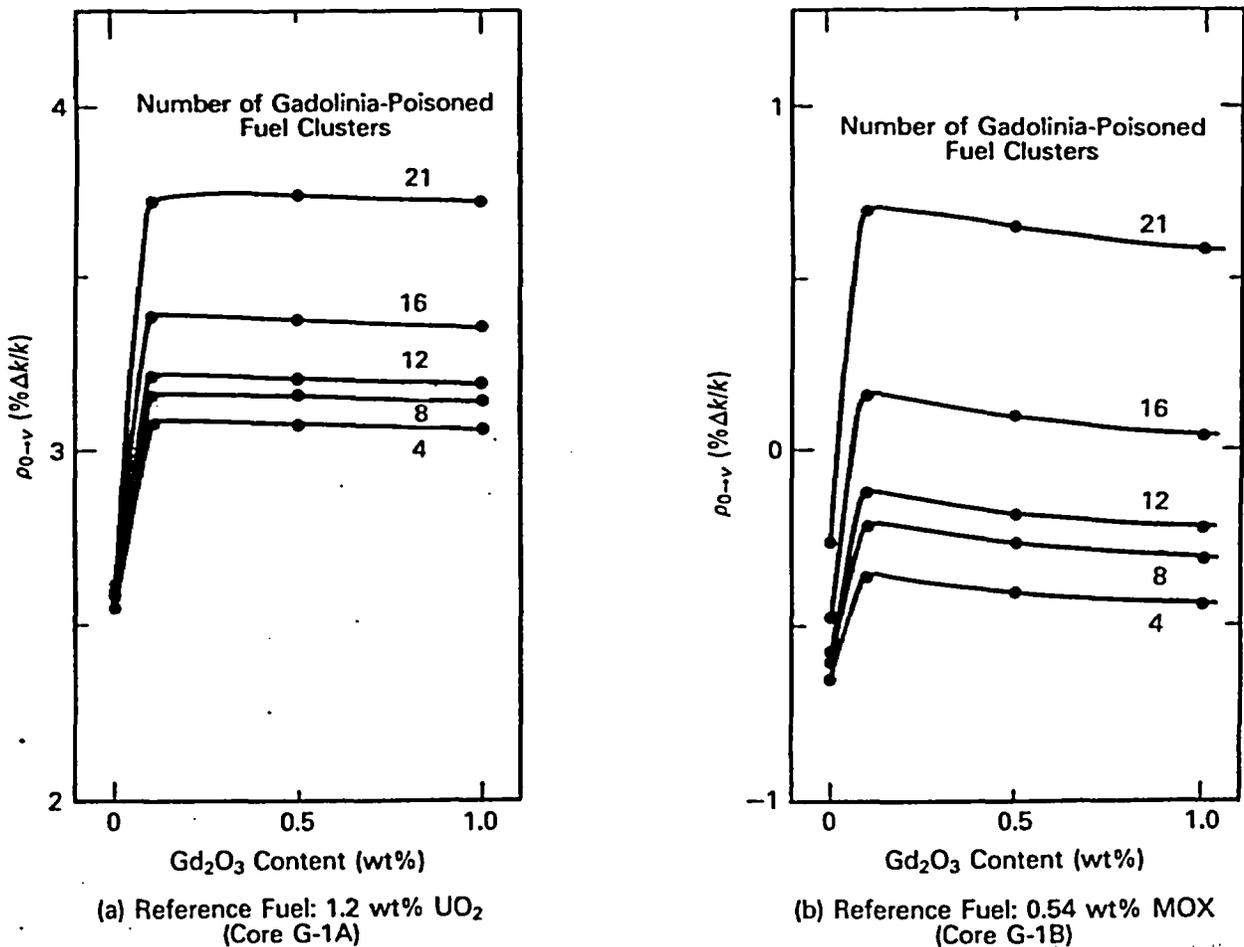


Fig. 7. Calculated void reactivity as a function of  $Gd_2O_3$  content and number of loaded gadolinia-poisoned fuel clusters.

### III.E. Result of Perturbation Analysis

Exact perturbation analyses are performed for the G-1A and G-1B cores fueled with 1.2 wt%  $\text{UO}_2$  or 0.54 wt% MOX as the reference assemblies. Components  $\rho_v^R$  and  $\rho_v^G$  of  $\rho_{0 \rightarrow v}$  at every fuel region of the reference or gadolinia-poisoned assembly are shown in Fig. 8. Superscripts *G* and *R* indicate the fuel regions of the lattices with gadolinia-poisoned and reference assemblies, respectively. Leakage components  $\rho_{v,1}^R$  and  $\rho_{v,1}^G$  and nonleakage components for each fuel region are also obtained. Here, the nonleakage component of  $\rho_{0 \rightarrow v}$  is divided into two components:  $\rho_{v,r}$  and  $\rho_{v,f}$ . The component  $\rho_{v,r}$  corresponds to the change in the re-

moval cross section  $\Sigma_r^{\epsilon}(\Sigma_a^{\epsilon} + \Sigma_s^{\epsilon} - \sum_{g'=1}^{\epsilon-1} \Sigma_s^{g'-\epsilon})$ , and the  $\rho_{v,f}$  is the change in the fission yield cross section  $\nu \Sigma_f$ . The  $\rho_{v,r}$  is regarded as the absorption effect of  $\rho_{0 \rightarrow v}$  corresponding mainly to a change in the absorption cross section. The  $\rho_{v,f}$  is similarly regarded as the fission effect. The relation between these components can be represented as

$$\rho_{0 \rightarrow v} = \rho_v^R + \rho_v^G,$$

$$\rho_v^R = \rho_{v,r}^R + \rho_{v,f}^R + \rho_{v,l}^R,$$

and

$$\rho_v^G = \rho_{v,r}^G + \rho_{v,f}^G + \rho_{v,l}^G.$$

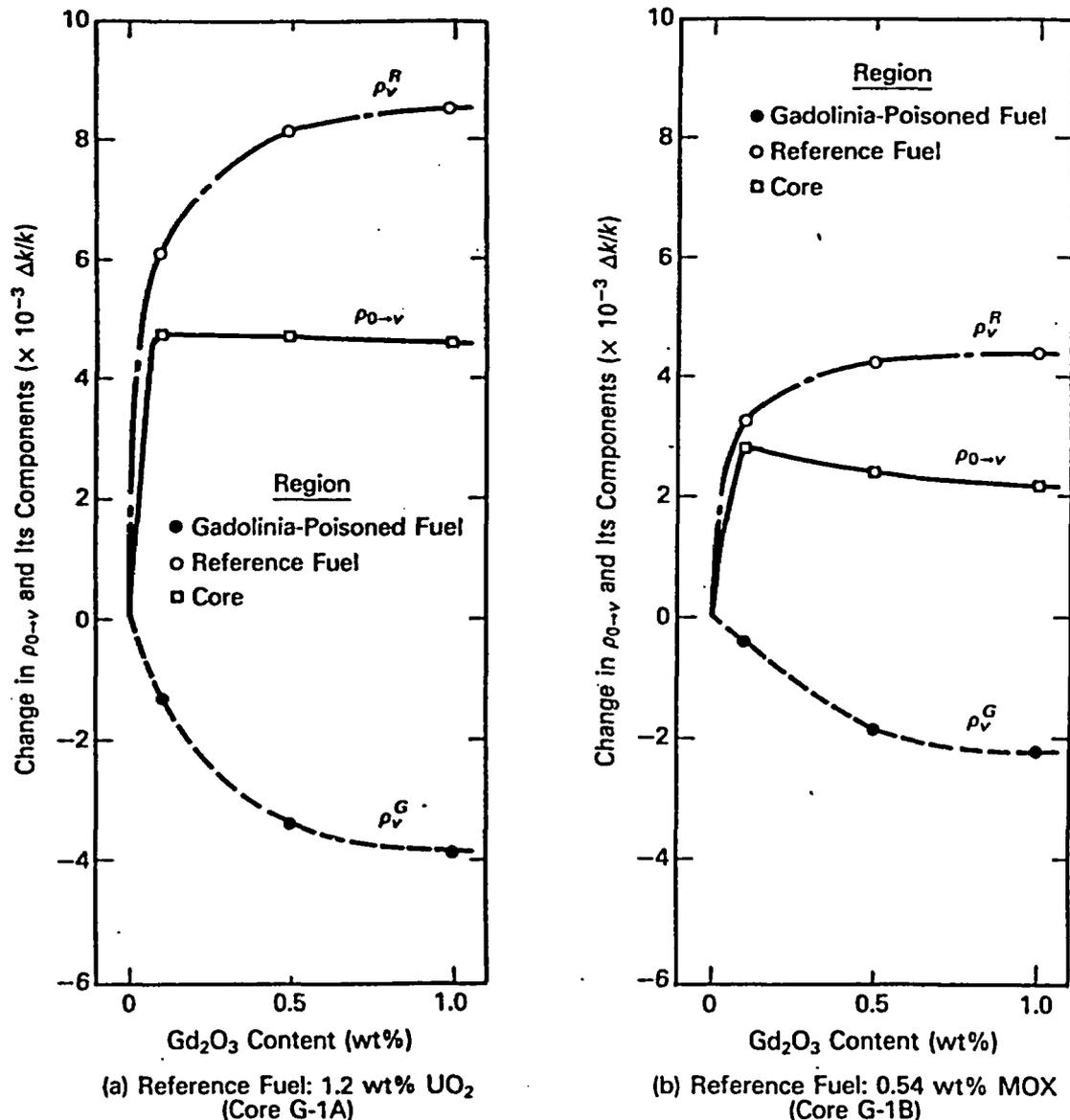


Fig. 8. Deviation of void reactivity and its components with the addition of  $\text{Gd}_2\text{O}_3$  into the middle layer of the fuel assembly in a core including four 28-rod gadolinia-poisoned fuel clusters.

The nonleakage and leakage components are shown in Fig. 9. To study in detail the effect of plutonium enrichment in the reference assemblies on  $\rho_{0-v}$  in a core in which the gadolinia-poisoned assemblies are dispersively loaded, components  $\rho_{v,r}$ ,  $\rho_{v,f}$ , and  $\rho_{v,l}$  are also obtained for another core (core G-1C) in which the 1.2 wt%  $UO_2$  reference assemblies are replaced with 0.87 wt% MOX, which has a higher plutonium enrichment than 0.54 wt% MOX. The result for core G-1C is shown in Fig. 9c. Here, the void reactivities and its components are shown as deviations from the values for 0 wt%  $Gd_2O_3$ . The void reactivities obtained by the perturbation method agree with the ones from the eigenvalue calculation within  $\pm 5\%$ . The effect on the void reactivity of the gadolinia concentration calculated by the perturbation method, as shown in Fig. 8a, is the same as that using the eigenvalue calculation (Fig. 4).

The following items were clarified by the perturbation analyses for the void reactivity.

1. The dependences of components  $\rho_v^R$  and  $\rho_v^G$  in each fuel region on  $Gd_2O_3$  concentration show opposite tendencies. The gadolinia-poisoned fuel lattice itself tends to shift the void reactivity to the negative side, but the reference fuel lattice causes the void reactivity shift to be less negative because of the gadolinia-poisoned assemblies. The addition of gadolinia, therefore, makes the void reactivity less negative because of the stronger effect of the less negative component in the reference fuel region.

2. The dependence of  $\rho_{v,r}^R$  in the reference fuel region on the gadolinia concentration strongly depends on the fissile nuclide composition of the reference assemblies, unlike that of  $\rho_{v,r}^G$  in the poisoned fuel region. The  $\rho_{v,r}^R$  largely shifts to the less negative side

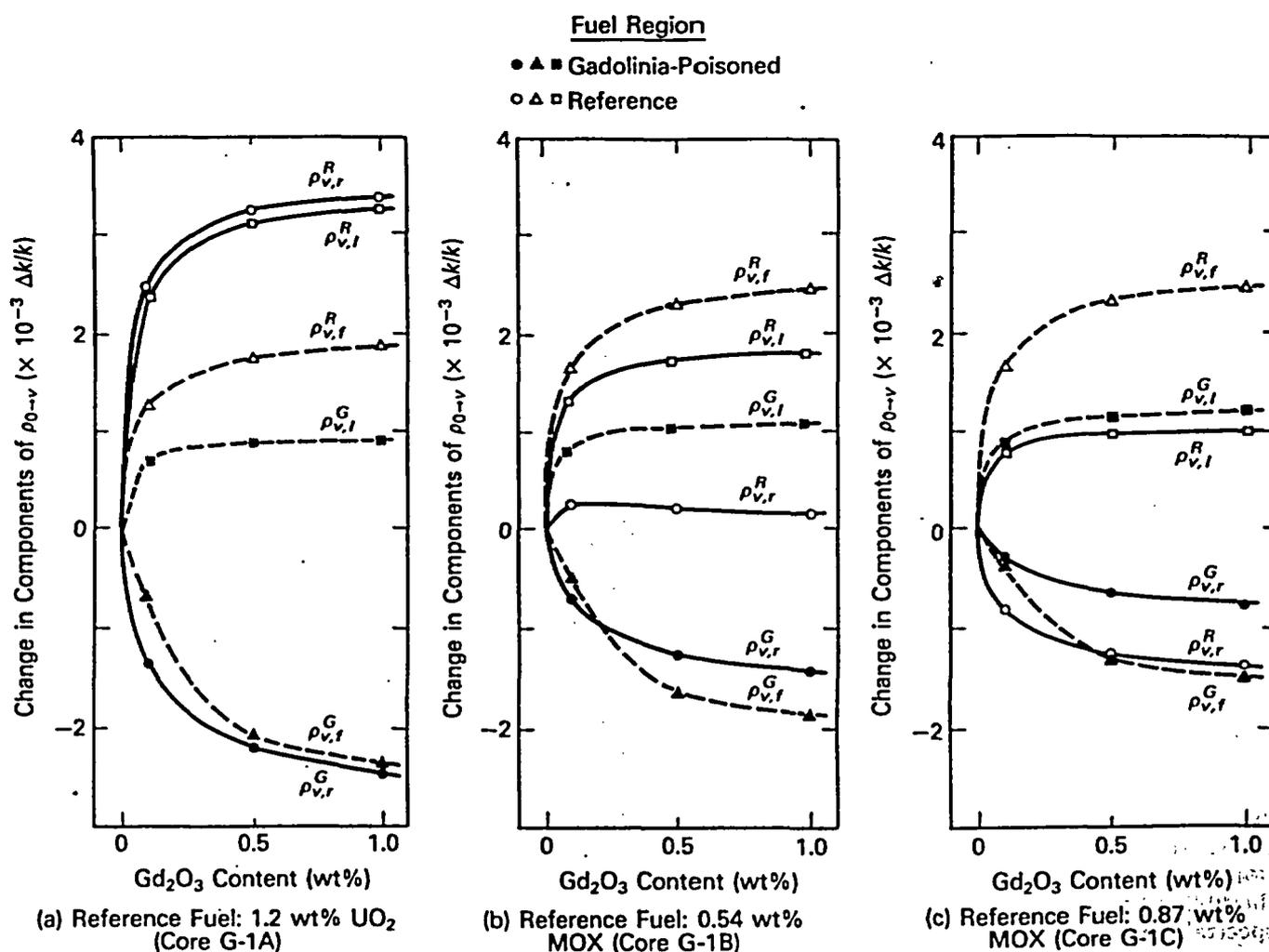


Fig. 9. Deviation of the components of void reactivity with addition of  $Gd_2O_3$  into the middle layer of the fuel assembly in a core including four 28-gadolinia-poisoned fuel clusters.

with the addition of gadolinia for the  $\text{UO}_2$  reference assembly, but the less negative shift can largely be reduced by changing the reference fuel composition from  $\text{UO}_2$  to MOX. Conversely,  $\rho_{v,r}^R$  shifts to the negative side by the addition of gadolinia for higher plutonium enrichment in the MOX reference assembly. On the other hand,  $\rho_{v,f}^R$  always shifts to the less negative side with the addition of gadolinia and is only slightly affected by the fuel nuclides of the reference assembly.

3. Substituting the reference  $\text{UO}_2$  assemblies with MOX reduces the negative shift of  $\rho_v^G$  with increasing addition of gadolinia; however, the less negative shift of  $\rho_v^R$  largely decreases. As a result, the addition of gadolinia causes a negative void reactivity shift because of the stronger effect of  $\rho_v^R$  compared with that of  $\rho_v^G$ .

4. The nonleakage components  $\rho_{v,r}^G$  and  $\rho_{v,f}^G$  in the poisoned fuel region always shift to the negative side with the addition of gadolinia; this negative shift reduces with increasing plutonium enrichment of the MOX reference assembly.

#### IV. DISCUSSION

It is found from the results of experiments and analyses that an increase in the gadolinia concentration in gadolinia-poisoned rods or in the loading ratio of gadolinia-poisoned assemblies in a core indirectly shifts the void reactivity to a less negative side, which differs from the neutron behavior in a core with more common neutron absorbers used in the moderator, such as soluble boron or control rods.<sup>3</sup> To clarify the effect of gadolinia on void reactivity, neutron behavior due to coolant voiding is discussed here.

##### IV.A. Neutron Behavior in Lattices Due to Coolant Voiding

In the HWR lattice, the coolant voiding greatly reduces the effects of neutron moderation and scattering due to light water as well as the thermal neutron absorption of light water itself. As a result, the thermal neutron spectra in the fuel rods are hardened, and the thermal neutron shielding effect of light water for the fuel rods decreases, leading to a flat thermal neutron distribution in the fuel assembly.

If this neutron behavior in lattices due to coolant voiding is assumed to arise from changes in the  $f$  and  $\eta$  values among the four factors of reactor physics, the following explanation is deduced: The flattened thermal neutron flux distribution due to coolant voiding increases the  $f$  value, indicating thermal neutron utilization, but slightly decreases the  $\eta$  value, indicating a thermal neutron spectral index due to thermal neutron spectral hardening. Accordingly, since the rate of increase in the  $f$  value due to coolant voiding is greater than the rate of decrease in the  $\eta$  value, the  $\rho_{0-v}$  value of the HWR lattice becomes increasingly less negative.

The effects of fissile nuclides (uranium and plutonium) on void reactivity in two kinds of fuel lattices consisting of unpoisoned reference rods with the same fissile content are discussed mainly from the viewpoint of the change in the thermal neutron spectra. In the uranium fuel lattice, since the neutron energy dependence of the absorption cross section in the thermal energy region is nearly represented by the  $1/v$  law, the degree of thermal neutron spectral hardening is greater than that of the MOX fuel lattice. Consequently, coolant voiding decreases the thermal neutron absorption in the uranium fuel rods, making the  $\rho_{0-v}$  value of the uranium fuel lattice increasingly less negative compared with that in the MOX fuel lattice. On the other hand, plutonium has a greater thermal neutron absorption cross section than uranium and has a resonance absorption in the thermal energy region ( $\sim 0.3$  eV), so the thermal neutron spectrum in the MOX fuel lattice is harder than that in the  $\text{UO}_2$  fuel lattice. Accordingly, the degree of thermal neutron spectral hardening due to coolant voiding is comparatively small in the MOX fuel lattice. However, thermal neutron spectral hardening due to the decrease in the thermal neutron shielding and scattering effects of light water increases the resonance capture and the resonance fission due to the resonance of  $^{239}\text{Pu}$  and  $^{241}\text{Pu}$  near 0.3 eV (Ref. 8). Because the  $\alpha$  value (ratio of neutron capture to fission) is greater in the resonance region than in other thermal energy regions, coolant voiding in the MOX fuel lattice enhances neutron capture rather than fission. In the MOX fuel lattice, therefore, the incremental positive shift of  $\rho_{0-v}$  is smaller than in the  $\text{UO}_2$  fuel lattice.<sup>9</sup>

In the gadolinia-poisoned fuel lattice, because the thermal absorption cross section is extremely large, it is hardly affected by thermal neutron spectral hardening due to coolant voiding. The decrease in the thermal neutron shielding and the scattering effects of light water due to coolant voiding, however, increase the thermal absorption of gadolinium in the fuel, thereby resulting in an increase in the cell-average thermal absorption cross section. In the gadolinia-poisoned fuel lattice, therefore, coolant voiding indirectly enhances thermal neutron spectral hardening (the  $\eta$  value decreases), making  $\rho_{0-v}$  shift toward the negative side. As in the reference fuel lattice, coolant voiding increases the  $f$  value in the gadolinia-poisoned fuel lattice, in which the increase in the  $f$  value is slower than that in the reference fuel lattice because the increase in thermal neutron absorption of gadolinium is more remarkable than the fuel itself in the reference fuel lattice (i.e., the incremental positive shift of  $\rho_{0-v}$  is restrained).

##### IV.B. Neutron Behavior in a Core with Gadolinia-Poisoned Assemblies

From Figs. 8 and 9, the following three items can be pointed out as the effects of gadolinia on the  $\rho_{0-v}$

of a core in which gadolinia-poisoned assemblies are dispersively loaded:

1. The predominant factor of shifting of  $\rho_{0 \rightarrow v}$  toward the less negative side in a core with gadolinia-poisoned assemblies is the fact that the fission effect  $\rho_{v,f}^R$  in the reference fuel region shifts greatly toward the less negative side with the addition of gadolinia.

2. If highly enriched MOX is used for the reference fuel, the incremental positive shift of  $\rho_{0 \rightarrow v}$  with the addition of gadolinia is restrained to some extent. This is because  $\rho_{v,r}^R$  shifts greatly toward the negative side.

3. The fission effect  $\rho_{v,f}^G$  and the absorption effect  $\rho_{v,r}^G$  for the poisoned fuel region shift toward the negative side with the addition of gadolinia, regardless of the type of fissile nuclide in the reference assembly.

In a core in which gadolinia-poisoned assemblies are dispersively loaded, the neutron importance in the poisoned fuel region is lower than that in the adjacent reference fuel region, because the thermal neutron flux in the gadolinia-poisoned assembly is essentially low, and coolant voiding, as described in Sec. IV.A, increases the thermal neutron absorption rate. On the contrary, in the reference fuel region, coolant voiding enhances the relative increase in neutron importance together with thermal neutron spectral hardening. Figure 10 shows the radial distribution of the statistical weight (neutron flux  $\times$  adjoint neutron flux) of the thermal energy group ( $<0.625$  eV) in the 45-deg direc-

tion of the G-1 core calculated by the code system. These radial distributions indicate the weighting factors on each fuel region for void reactivity of the core and are normalized in the poisoned fuel region. Figure 10 shows that the increase in thermal neutron absorption rate due to coolant voiding, especially in the poisoned fuel region, increases the decrease in thermal neutron flux. If the loading of the gadolinia-poisoned assembly enhances both the increase in neutron importance and thermal neutron spectral hardening due to coolant voiding in the reference fuel region, then, as described in Sec. IV.A, the thermal neutron absorption rate decreases in  $\text{UO}_2$  fuel, the resonance absorption rate increases in MOX fuel, and the fission rate increases in both  $\text{UO}_2$  and MOX fuels.

If coolant voiding enhances thermal neutron spectral hardening in the reference assembly, then neutron absorption simply decreases and  $\rho_{v,r}^R$  shifts toward the less negative side with increasing gadolinia concentration, as shown in Figs. 9a and 9b, in the  $\text{UO}_2$  fuel, because of the absence of resonance absorption by uranium in the thermal energy region. In 0.54 wt% MOX fuel containing plutonium, coolant voiding increases 0.3-eV resonance capture, so the incremental positive shift of  $\rho_{v,r}^R$  becomes smaller than that of the  $\text{UO}_2$  fuel. In 0.87 wt% MOX fuel containing more plutonium, thermal neutron spectral hardening due to coolant voiding further increases 0.3-eV resonance capture. Accordingly, as shown in Fig. 9c,  $\rho_{v,r}^R$  shifts toward the negative side with increasing gadolinia concentration. These facts suggest that the incremental positive shift of  $\rho_{0 \rightarrow v}$  with the addition of gadolinia can be restrained as plutonium enrichment becomes higher.

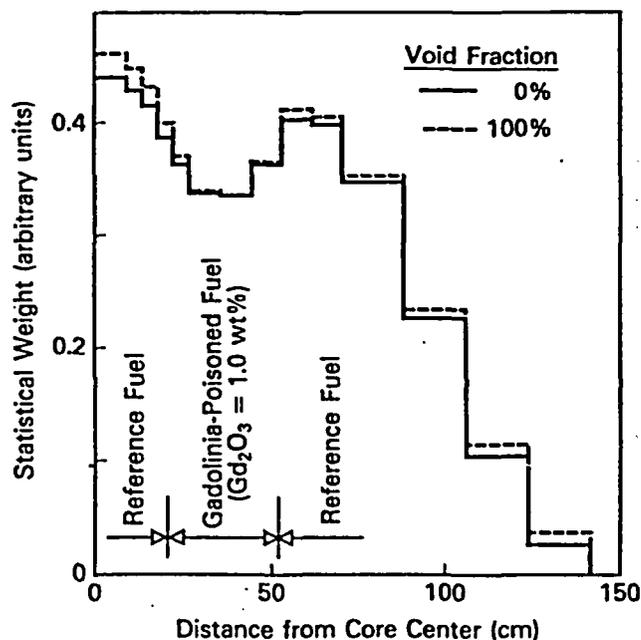


Fig. 10. Thermal statistical weight distributions across the gadolinia-poisoned fuel cluster in the G-1 core.

## V. CONCLUSION

The effect of gadolinia poison added to fuel rods on void reactivity of a pressure-tube-type heavy water reactor was clarified by a series of experiments using the Deuterium Critical Assembly and by theoretical analyses.

When gadolinia-poisoned fuel assemblies are dispersively loaded into a core, the void reactivity rapidly shifts toward the less negative side at  $\sim 0.1$  wt%  $\text{Gd}_2\text{O}_3$  concentration, reaching a saturated value at a very low concentration. The incremental positive shift of void reactivity with the addition of gadolinia increases when the gadolinia-poisoned fuel rods are placed in the outer layers of the fuel cluster and as the loading ratio of the gadolinia-poisoned fuel assemblies in the core becomes greater. The incremental positive shift, however, is negligibly small when the gadolinia-poisoned fuel rods are placed in the inner layer, and it can then be reduced by changing the fissile nuclide in the unpoisoned fuel assembly from uranium to plutonium.

It was confirmed that gadolinia has a very strong influence on the neutron behavior in the unpoisoned

fuel lattice. According to the results of the perturbation analyses, although the gadolinia-poisoned fuel lattice itself has a negative void reactivity component, the addition of gadolinia causes a less negative shift in the void reactivity in a core with both unpoisoned and gadolinia-poisoned fuel assemblies. The main reason for the less negative shift of the void reactivity is that the remarkable increase in the thermal neutron absorption of the gadolinia-poisoned fuel assemblies due to coolant voiding enhances the increase in neutron importance in the unpoisoned fuel region adjacent to the poisoned fuel region and results in an enhancement of the fission yield component of void reactivity in the unpoisoned fuel region. When the fissile nuclide of the unpoisoned fuel is changed from  $\text{UO}_2$  to MOX or the plutonium enrichment of the MOX fuel is raised, however, the incremental positive shift of the void reactivity with the addition of gadolinia can largely be restrained by the increase in the absorption component of the void reactivity arising from 0.3-eV thermal resonance absorption of  $^{239}\text{Pu}$  and  $^{241}\text{Pu}$ .

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