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HEAVY- WATER CRITICAL EXPERIMENT
FOR FUGEN (I)
VOID REACTIVITY IN PLUTONIUM LATTICE

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A b s t r a c t

Effect of plutonium on void reactivity has been studied. By means of pulsed neutron source, the coolant void reactivities were measured in Deuterium Critical Assembly's core having 22.5 cm square lattice pitch, by changing effective coolant void fraction from 0% to 30%, 70%, 86.7% and 100%. Plutonium-uranium mixed oxide fuel assemblies were progressively loaded from core center, being surrounded by uranium oxide fuel region. It is resulted from the experiment that void reactivity changes to more negative side regularly, when the number of the mixed oxide fuel loading is increased. The experimental results were compared with calculational ones by METHUSELAH-CITATION system. The following are concluded from the comparison.

- (1) Negative shift of the void reactivity with loading of more plutonium fuels can be well predicted qualitatively by the METHUSELAH-CITATION code system.
- (2) Calculational accuracy of the METHUSELAH-CITATION code system for reactivity change caused by loss of coolant is about the same for both uniform oxide and partial mixed oxide loaded cores.

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1. Introduction

The advanced thermal reactor FUGEN is a heavy water moderated, boiling light water cooled, plutonium fueled, pressure tube type reactor.⁽¹⁾ It is known that this type of reactor tends to have positive coolant reactivity when less enriched fuel is used. It was experimentally shown by Briggs & Jhonstone⁽²⁾ that plutonium has a favorable character to decrease the positive coolant void reactivity in the similar type of reactor, namely SGHWR.

The effect of plutonium on void reactivity was studied through the design calculation⁽³⁾ which showed that the same tendency as the previous experiment. It is planned that 96 plutonium uranium mixed oxide fuel assemblies are loaded FUGEN, being surrounded by 128 enriched uranium fuel assemblies. Experimental little study has been done on the effect of plutonium on void reactivity, together with many calculational works.

In order to make experimental study on effect of plutonium, the coolant void reactivities have been measured in DCA core having 22.5 cm square lattice pitch, by changing effective coolant void fraction from 0% to 30%, 70%, 86.7% and 100%. The mixed oxide fuel assemblies were progressively loaded from core center, being surrounded by the 1.2 w/o enriched uranium oxide fuel region.

2. Experimental Procedure

The composition of coolants used in this measurement is listed in Table 1. Fully voided coolant was simulated by air. The decrease of slowing down power caused by voiding was simulated by using proper mixtures of light and heavy water. A bit of boric acid was added to the mixtures to make their absorption for thermal neutrons equal to that of actually voided coolants. Several cross sections of the simulated coolants are compared in Table 2, with those of the actually voided coolants. The comparison shows that neutron cross sections other than transport cross section have a good agreement between the mixtures and actually voided coolants. It is natural that absorption cross section of heavy water does not agree with that of the coolant of which void fraction is 86.7%, since the boric acid was not added in this case.

The composition of the mixed oxide fuel is listed in Table 3. The content of plutonium oxide in fuel pellet was determined so that number density of fissile atoms in the mixed oxide was nearly equal to that in

the 1.2 w/o enriched uranium oxide. As shown in Table 4, the content of plutonium fissile is high, that is, 91.28 w/o, while the content of plutonium 240 is markedly low.

Void reactivities were measured in the various cores with mixed oxide fuel assemblies progressively loaded with 1, 5, 9 up to 25 assemblies by substitution. The mixed oxide fuel assemblies were loaded around the core axis with four fold rotation symmetry. As an example, the configuration of a core comprising 25 mixed oxide fuel assemblies is shown in Fig. 1. The schematic drawing of DCA is shown in Fig. 2. The core tank, the upper and lower grid plates are made from aluminium. The absorber sandwich of boron plate is placed under the lower grid plate, to block the return of neutrons reflected by floor of the reactor room. In this measurement, it was managed to level the moderator and the coolant heights.

A Cockcroft-Walton type neutron generator was used to carry out pulsed neutron experiments for reactivity measurement. Neutron bursts were produced at tritium target bombarded by pulsed deuteron beam. Accelerating voltage of deuteron was about 170 KV. The pulsed deuteron beam was 1.1 m/sec wide and the repetition rate was changed from 10 Hz to 0.1 Hz. Neutron decay in a pulsed core was observed by BF_3 counters which were 13 mm in diameter. Time analysis of signals from the counters were performed by the 1024 channel time analyser. When evaluating decay constants of neutron density by fitting to $A + B \exp(-\alpha t)$, early part of the neutron decay was discarded to eliminate contamination of the spacial higher modes. Obtained decay constants were converted to reactivity in dollars by Simmons & King's method,⁽⁴⁾ namely by using the following equation.

$$\rho(\$) = \alpha/G(\alpha) - 1 \quad (1)$$

where $G(\alpha)$ is defined by

$$G(\alpha) = \beta_{\text{eff}} K_{\text{eff}} / \ell_p \quad (2)$$

where β_{eff} : effective delayed neutron fraction,

K_{eff} : effective multiplication factor,

ℓ_p : prompt neutron life time.

$G(\alpha)$ can be approximated as follows,

$$G(\alpha) \approx \alpha_c [1 + \beta_{\text{eff}} \rho(\$) - \ell_{\text{pc}}^{-1} (\partial \ell_p / \partial B_z^2) (B_z^2 - B_{z_c}^2)] \quad (3)$$

where α_c : decay constant at critical,

ℓ_{pc} : prompt neutron life time at critical.

In a largely subcritical system, a simple substitution of $G(\alpha)$ with α_c should result in marked error in reactivity, since $G(\alpha)$ cannot be approximated by α_c in such a system due to large deviation of K_{eff} and l_p from values at critical.

Therefore, corrections were made for $G(\alpha)$ in such system, by iterative procedure based on the equation (1) and (3). First, an approximated value of $\rho(\$)$ is obtained from the equation (1) by substituting $G(\alpha)$ with α_c , then new $G(\alpha)$ can be evaluated from this $\rho(\$)$ value using the equation (3). With this new value of $G(\alpha)$, new approximate $\rho(\$)$ value can be obtained from the equation (1) similarly.

This procedure is repeated until converged value is obtained on $\rho(\$)$. In the equation (2), calculated values were used for the effective delayed neutron fraction β_{eff} and for the prompt neutron life time ℓ_p . Dependence of the neutron life time on axial buckling was also estimated theoretically. These values were evaluated from five energy group constants obtained from cell calculation by METHUSELAH code.⁽⁵⁾ The correction to the neutron generation time accounted up to 5% maximum.

3. Results

In Fig. 3, obtained void reactivities are shown as a function of void fraction. The errors of void reactivity measurement were estimated about 5% up to 7% when the mixed oxide fuels were partially loaded.

When the number of the mixed oxide fuel loading is increased, as shown in this figure, the void reactivity changes to more negative side regularly.

In the case of loading five assemblies of mixed oxide, the void reactivity changes to positive side at 100% void fraction, but this cannot be considered significant because the change is not so large compared with the experimental error.

Then it is concluded that the plutonium fuel strongly influences the void reactivity in FUGEN type lattice.

4. Comparison with Calculation and Discussion

By using CITATION code in X-Y geometry, theoretical void reactivities were evaluated from five energy group constants obtained from cell calculation by METHUSELAH code,⁽⁵⁾ which is used in the design calculation of FUGEN reactor. In the cell calculation of mixed oxide lattice, METHUSELAH code was utilized on the same condition as in that of uranium oxide lattice. The configuration of a unit cell is shown in Fig. 4. Calculation of void reactivity was done for a core model consisting of three parts, namely, the central lattice region fueled with mixed oxide, surrounding lattice of uranium oxide fuel and the outer layer of heavy water. The heavy water layer of which mean thickness is about 10 cm, is unavoidably produced on the results that square lattices are arranged in the round core tank.

Calculated void reactivities are compared with the experiments in Fig. 5. The calculated void reactivities in $\% \Delta k/k$ unit were converted to in dollar unit by using the effective delayed neutron fraction evaluated from the calculated distribution of fission events. The calculated void reactivities are largely shifted to the negative side with loading of more mixed oxide fuel. This large negative shift is same as in the experimental results. At void fractions of 30%, 70% and 86.7%, agreement with the experiments in the case of the uniform core is fairly good, but the partial loading of mixed oxide fuel makes the agreement worse. At the 100% void fraction, there is a large disagreement with the experiments in the case of the uniform oxide core as well as in the partially loaded cores with mixed oxide.

The discrepancy between the calculation and experiment is by about 40% in the case of the uniform core: the value is lower in experiment. This discrepancy is not increased by the partial loading of the mixed oxide fuel. Though the check is done only in the case of the uniform core, the discrepancy cannot be reduced very much even when the Benoist option is utilized in the METHUSELAH code, as shown in Fig. 6. This option can take the anisotropy in neutron diffusion.

5. Concluding Remarks

The following are concluded from these facts.

- (1) Negative shift of the void reactivity with loading of more plutonium fuels can be well predicted qualitatively by the METHUSELAH-CITATION calculation system, although quantitative prediction is poor.

- (2) Calculational accuracy of the METHUSELAH-CITATION system for reactivity change caused by loss of coolant is about the same for both uniform oxide and partial mixed oxide loaded cores.

It is confirmed from the present studies that the coolant void reactivity is largely improved to the negative side with use of plutonium fuel.

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Table 1. COMPOSITION OF COOLANTS

VOID FRACTION (%)	CONTENT (W/o)				DENSITY (gr/cm ³)
	H ₂ O	D ₂ O	H ₃ BO ₃	AIR	
0	100.00	—	—	—	0.9978
30	63.17	36.82	0.00921	—	1.0359
70	18.07	81.91	0.02150	—	1.0866
86.7	0.45	99.55	—	—	1.1078
100	—	—	—	100.00	0.0012

Table 2 COMPARISON
OF
NEUTRON CROSS SECTIONS

VOID FRACTION (%)	RATIO OF CROSS SECTION				
	THERMAL REGION			EPI-THERMAL REGION	
	ABSORPTION	SCATTERING	TRANSPORT	SLOWING DOWN POWER	TRANSPORT
30	1.0000	1.0008	1.0203	0.9998	1.1634
70	0.9998	1.0042	1.1103	0.9994	1.8896
86.7	0.0376	1.0112	1.3108	1.0091	2.3514

$$\text{RATIO} = \frac{\text{CROSS SECTION OF SIMULATED COOLANT}}{\text{CROSS SECTION OF ACTUALLY VOIDED COOLANT}}$$

Table 3 COMPOSITION
OF
MIXED OXIDE FUEL

NUCLEID	CONTENT IN FUEL PELLETT (w/o)
²³⁵ U	0.6214
²³⁸ U	86.782
²³⁸ Pu	0.000102
²³⁹ Pu	0.4304
²⁴⁰ Pu	8.642
²⁴¹ Pu	0.004359
²⁴² Pu	0.000303
O	12.12

$$\frac{\text{PuO}_2}{\text{PuO}_2 + \text{UO}_2} \times 100 = 0.54 \text{ w/o}$$

Table 4 ISOTOPIC CONTENT
OF
PLUTONIUM

NUCLEID	CONTENT (w/o)
^{238}Pu	0.021
^{239}Pu	90.360
^{240}Pu	8.640
^{241}Pu	0.915
^{242}Pu	0.064

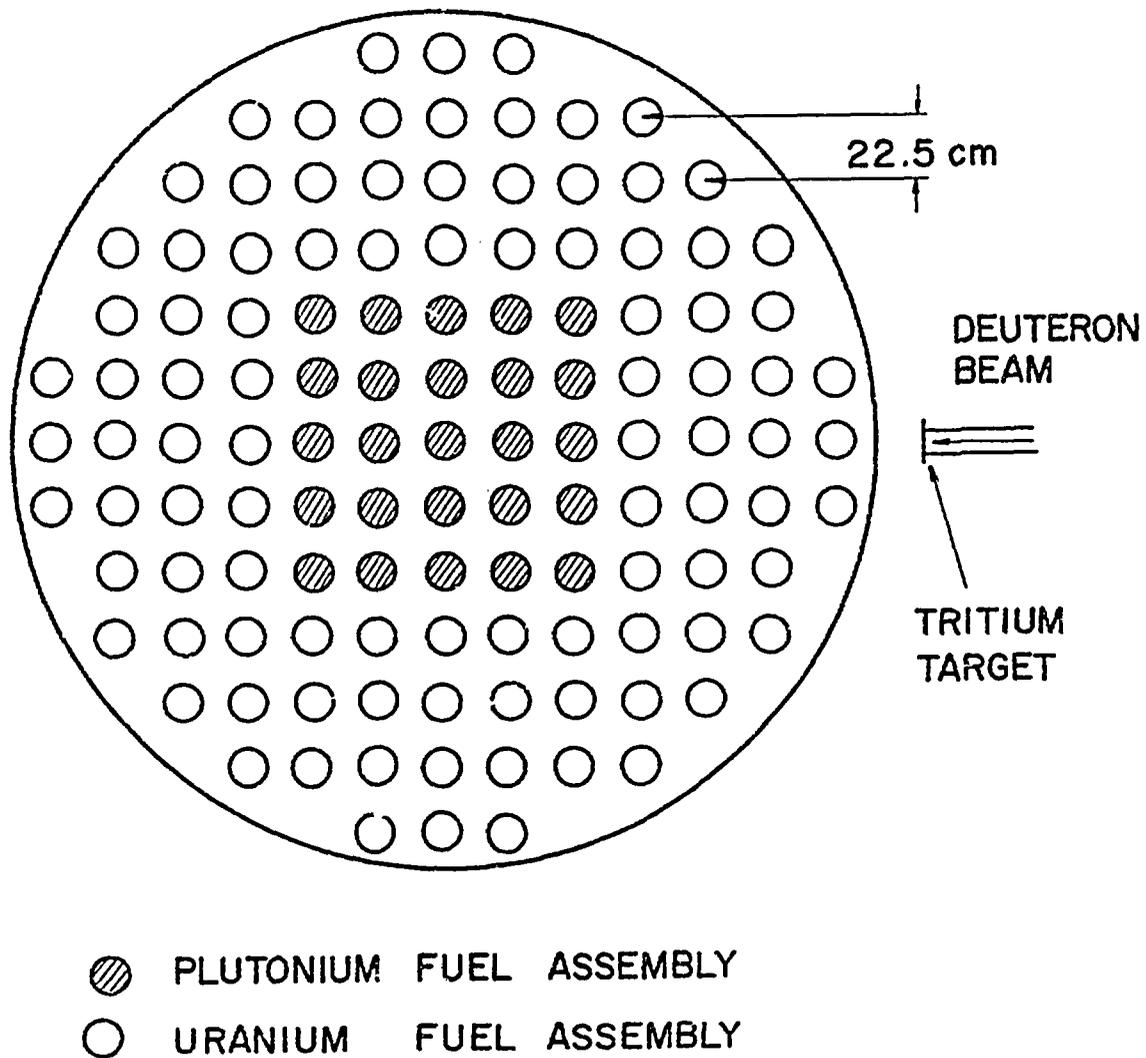


Fig.1 CONFIGURATION OF THE CORE
COMPRISING 25 PLUTONIUM FUEL ASSEMBLIES

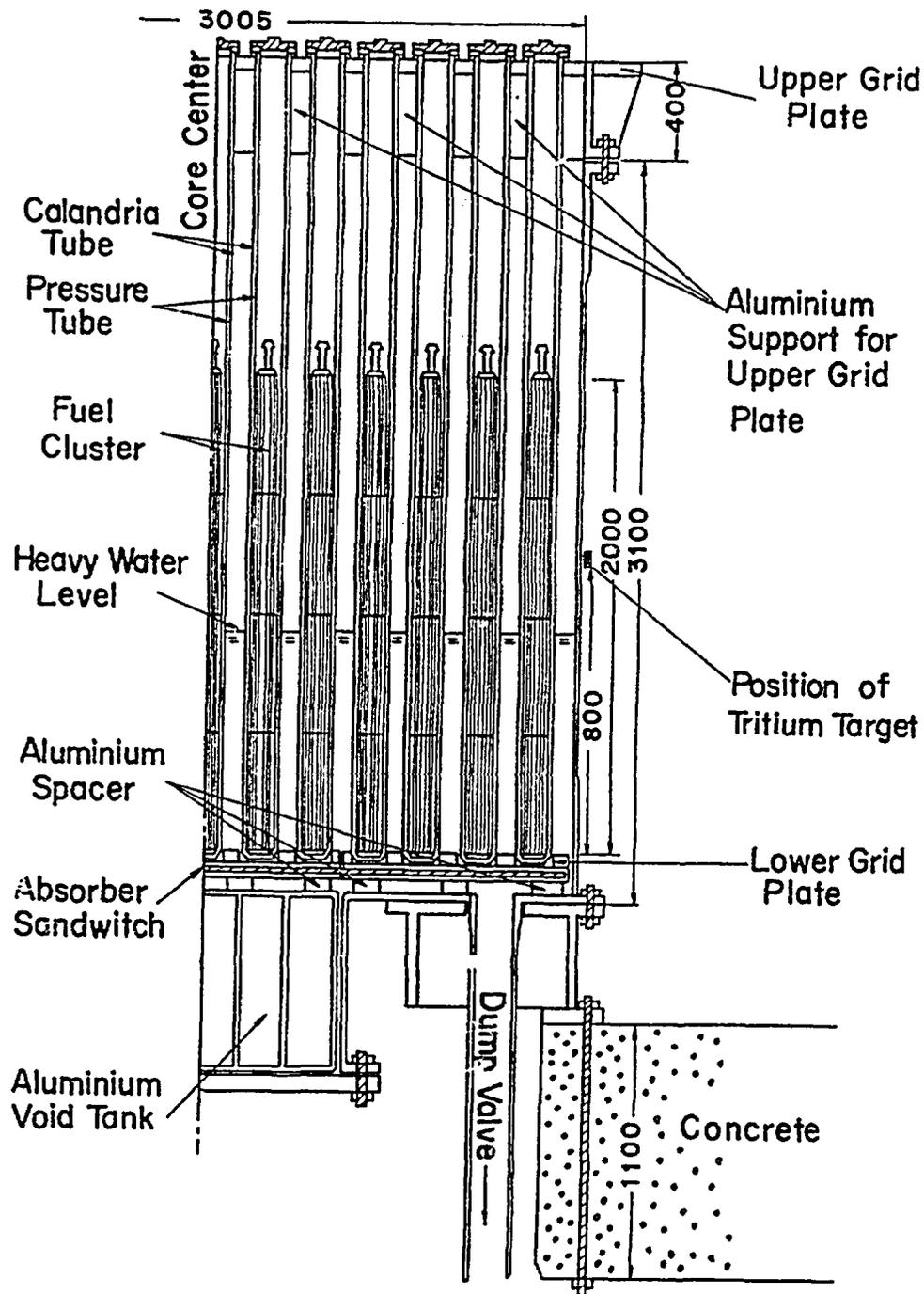


Fig. 2 SCHEMATIC DRAWING OF THE CORE CONFIGURATION OF DEUTERIUM CRITICAL ASSEMBLY

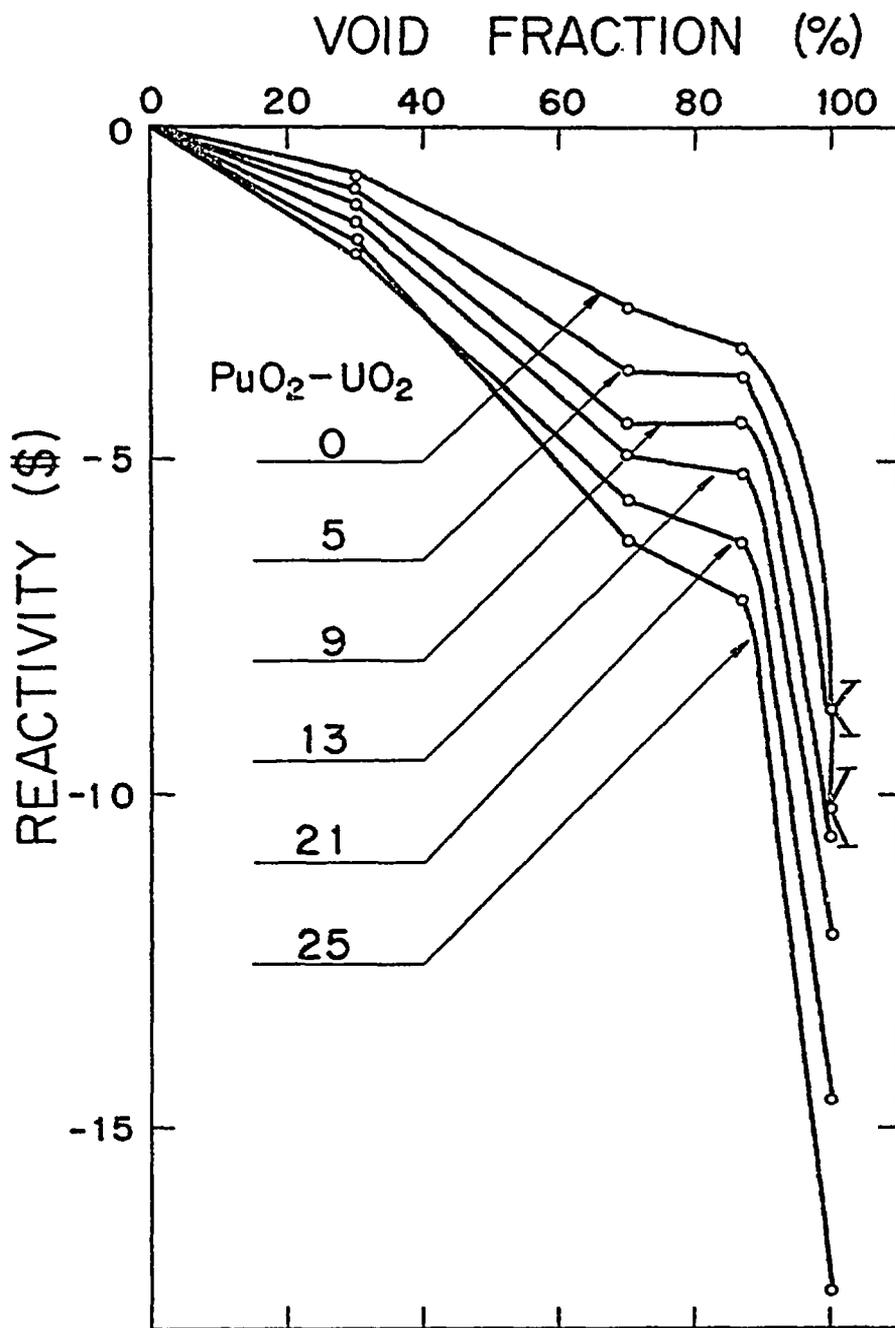


Fig. 3 MEASURED VOID REACTIVITIES

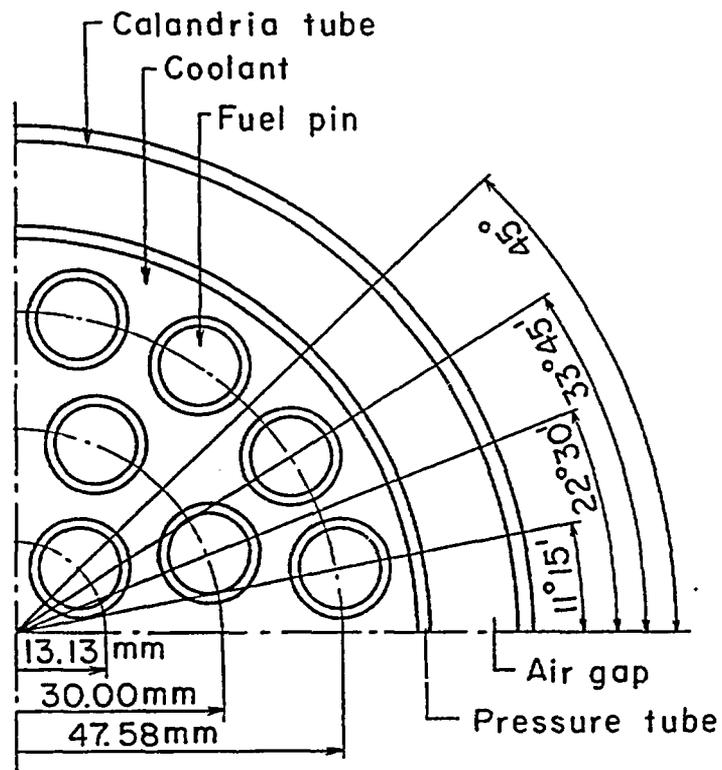


Fig. 4. CONFIGURATION OF FUEL ASSEMBLY

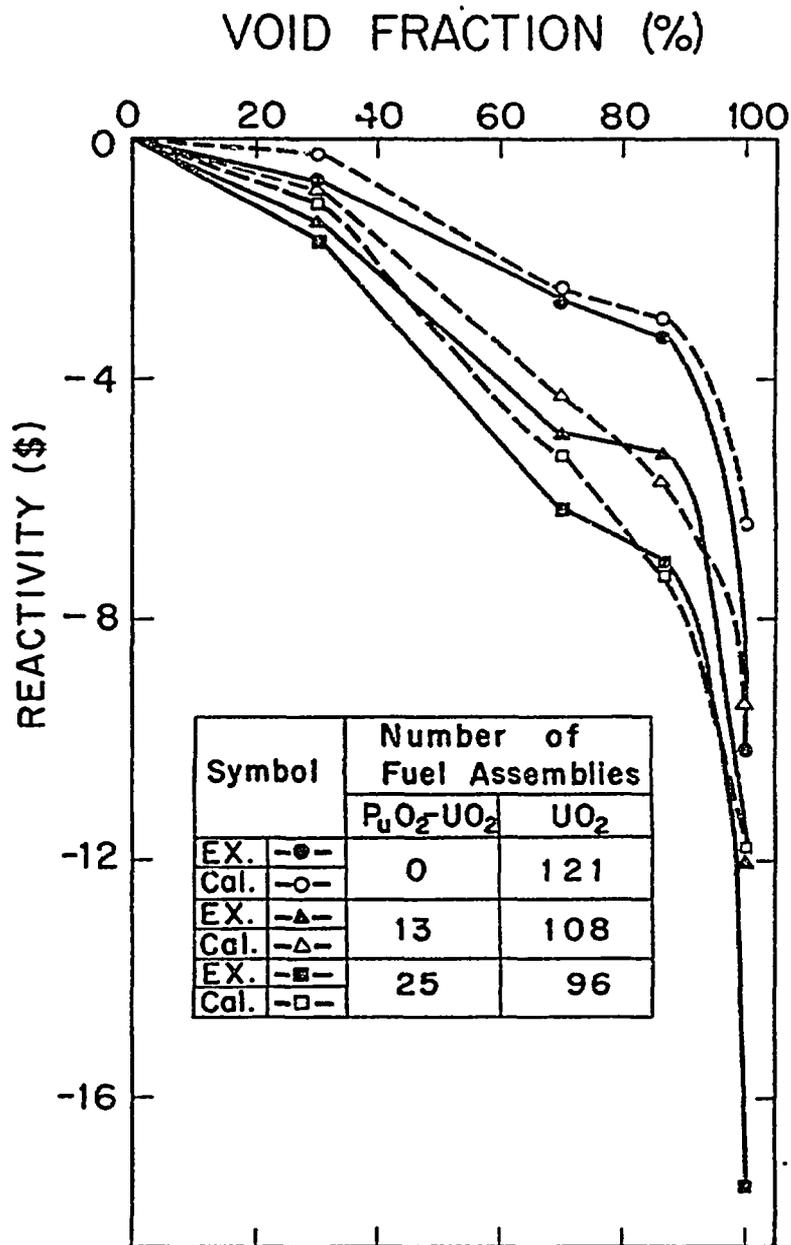


Fig.5 COMPARISON BETWEEN MEASURED AND CALCULATED VOID REACTIVITIES

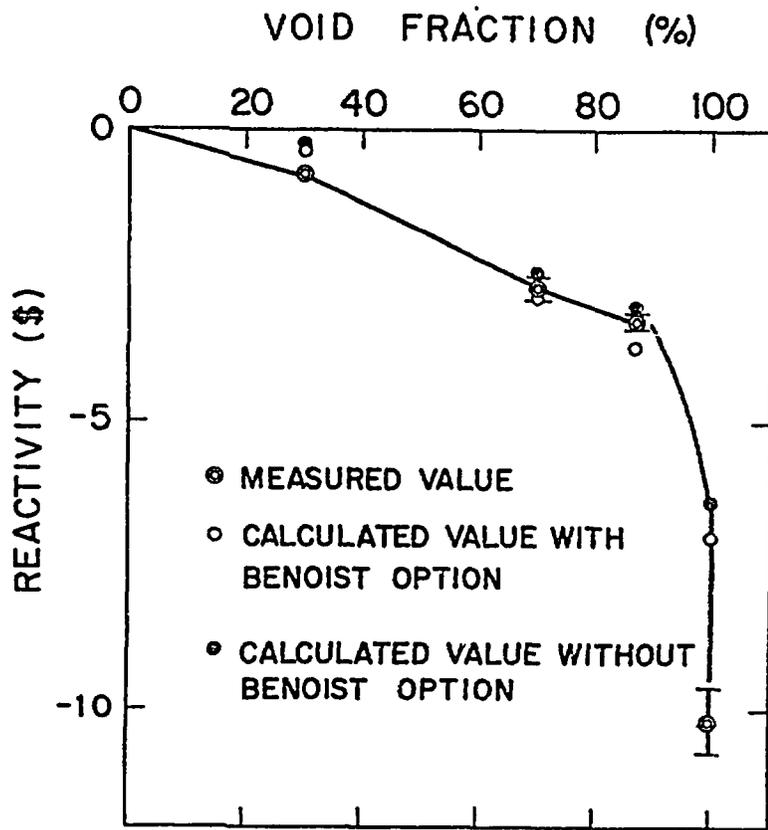


Fig.6 EFFECT OF BENOIST OPTION ON CALCULATED COOLANT VOID REACTIVITIES