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Heavy Water Critical Experiments

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June, 1976

Abstract

The following parameters have been measured in the Deutrium Critical Assembly (DCA) in a core with a 22.5 cm square lattices fueled with 0.87 wt % PuO_2-UO_2:

(i) material buckling;

(ii) thermal flux distribution;

(iii) lattice parameters;

(iv) coolant void reactivity;

(v) local power peaking factor.

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1. Introduction

A series of critical experiments with plutonium fueled lattices have been carried out in the Deuterium Critical Assembly (DCA). The summary of early reactor physics studies on plutonium lattices made in the DCA was already given in 1975[1].

The early studies were concerned with low enrichment plutonium mixed oxide fuels, viz, 0.54 % PuO_2-UO_2. This report is a summary of reactor physics studies on higher enrichment plutonium mixed oxide fuels, viz, 0.87 wt % PuO_2-UO_2.

2. DCA Core Configuration

In order to find out the effect of the fissile content in plutonium on nuclear characteristics, two kinds of plutonium mixed oxide fuels were used in the experiments: one enriched with standard grade plutonium (91 wt % Pu fissile) and the other with reactor grade plutonium (74 wt % Pu fissile).

The isotopic content of plutonium is shown in Appendix (Table 1). The dimensions of lattices are listed in Appendix (Table 2). The core configuration of DCA and the configuration of the fuel assembly are shown in Appendix (Figs. 1 and 2).

The coolants in the cluster used in the experiment were as follows:

(i) light water (0 % void);

(ii) air (100 % void).

3. Experiment

The following parameters have been measured.

(i) material buckling;

(ii) thermal flux distribution;

(iii) lattice parameters;

(iv) coolant void reactivity;

(v) local power peaking factor.

The experiment results are as follows.

(i) Material buckling

The progressive substitution method was used to measure material buckling, using a small amount of test fuels and a well-known reference lattice.

The fuel clusters in the central part of the reference 1.2 wt % enriched uranium oxide core were progressively replaced with 1, 5, 9 up to 25 clusters of PuO_2-UO_2 fuel. Substituted fuels were arranged around the core axis with four fold rotation symmetry. Critical moderator heights were converted to axial buckling by extrapolation length obtained by the copper wire activation method in a core uniformly fueled with 1.2 wt % enriched uranium oxide.

In order to obtain material buckling, the change of axial buckling caused by substitution was analysed by the formula derived from the second order perturbation theory. Both flux distortion due to the substitution and spectrum mismatch between the test and reference lattices can be directly taken into account by using the second order perturbation theory.

Measured material bucklings are shown in Fig. 3.

(ii) Thermal flux distribution

Intra cell thermal neutron flux distributions were measured by the dysprosium foil activation method.

Thermal neutron fluxes in the fuel pins were measured by using four foils set in asymmetrical positions in a cluster.

Distribution in the coolant region was done by using sector foils which set between the fuel pins.

Fluxes on the calandria tube and pressure tube were obtained by using foils which set at two identical positions around each surface.

Flux distribution in the D_2O moderator region was obtained by using foils arranged in two directions, viz. the direction towards an adjacent cluster (0 degree) and the direction towards the space between two adjoining clusters (45 degrees).

(iii) Lattice parameters

Measured lattice parameters and their definitions are:

$E_{Cd} = .42$ eV.

$$\delta^{28} \equiv \frac{\underset{i}{\mathrm{Sum}}\, Vi\left[\int_0^\infty (\Sigma_f \phi)^{28} dE\right]_i}{\underset{i}{\mathrm{Sum}}\, Vi\left[\int_0^\infty (\Sigma_f \phi)^{25} dE\right]_i}$$

$$\rho^{28} \equiv \frac{\underset{i}{\mathrm{Sum}}\, Vi\left[\int_{Ecd}^\infty \sigma_c^{28}(E)\phi(E)dE\right]_i}{\underset{i}{\mathrm{Sum}}\, Vi\left[\int_0^{Ecd} \sigma_c^{28}(E)\phi(E)dE\right]_i}$$

$$\delta^{25} \equiv \frac{\underset{i}{\mathrm{Sum}}\, Vi\left[\int_{Ecd}^\infty (\Sigma_f \phi)^{25} dE\right]_i}{\underset{i}{\mathrm{Sum}}\, Vi\left[\int_0^{Ecd} (\Sigma_f \phi)^{25} dE\right]_i}$$

$$\delta^{49} \equiv \frac{\underset{i}{\mathrm{Sum}}\, Vi\left[\int_{Ecd}^\infty (\Sigma_f \phi)^{49} dE\right]_i}{\underset{i}{\mathrm{Sum}}\, Vi\left[\int_0^{Ecd} (\Sigma_f \phi)^{49} dE\right]_i}$$

$$\delta_{25}^{49} \equiv \frac{\underset{i}{\mathrm{Sum}}\, Vi\left[\int_0^\infty (\Sigma_f \phi)^{49} dE\right]_i}{\underset{i}{\mathrm{Sum}}\, Vi\left[\int_0^\infty (\Sigma_f \phi)^{25} dE\right]_i},$$

where V_i indicates the volume of each fuel ring of a cluster.

These parameters were obtained by using the foil activation method.

The specifications of detector foils are tabulated in Appendix (Table 3). A NaI(Tl) scintillation detector and a Ge(Li) detector were used respectively to detect γ-rays emitted from fission products and ^{239}Np produced by capture reactions of ^{238}U.

The following conclusions were reached by this experiment:

(i) the measured values of δ^{28} increase with the increase of plutonium fissile content.

(ii) the measured values of δ^{28} increase with the increase of plutonium fissile content.

(iii) the measured values of δ^{25} and δ^{49} increase as the plutonium fissile content increases.

(iv) the measured values of δ^{49}_{25} increase with the increase of plutonium fissile content.

(iv) Coolant void reactivity

Coolant void reactivity was measured by using the plused neutron source technique in a core partially loaded with plutonium lattices.

When evaluating void reactivity from measured prompt neutron decay constants, corrections were made for the neutron generation time of a largely subcritical system.

Measured void reactivity is shown in Fig. 10.

The following conclusions are formed from this study:

(i) the increase of fissile content in plutonium makes void reactivity move to the more negative side;

(ii) void reactivity gradually moves to the negative side if more PuO_2-UO_2 fuel is loaded.

(v) Local power peaking factor

In order to obtain the local power peaking factor, measurements on power distribution in a fuel cluster were made by detecting -rays emitted from ^{140}La.

When evaluating the local power peaking factor, corrections were made for the difference in yield of ^{140}La and in energy release per fission between plutonium and uranium.

The local power peaking factor was measured by using fuel clusters consisting of 0.87 wt % PuO_2-UO_2 fuel rods for the inner two fuel rings and 0.54 wt % PuO_2-UO_2 fuel rods for the outer fuel ring.

Measured local power distributions are shown in Fig. 11. → 12.

References

(1) Miyawaki, Y., Shiba, K., Heavy Water Critical Experiments on Plutonium Lattice, N941 75-41 (1975)

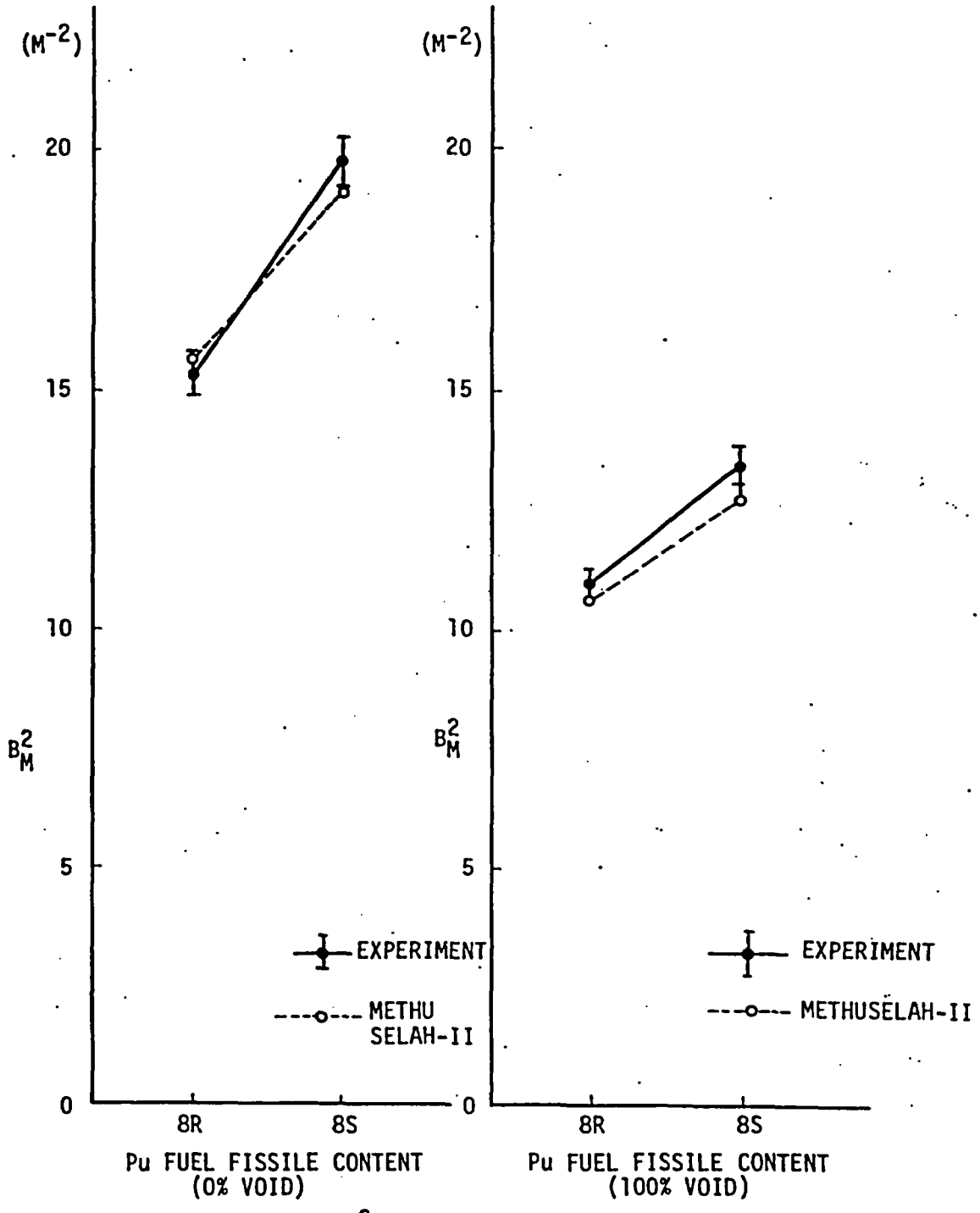


FIG.3 B_M^2 Vs. Pu FUEL FISSILE CONTENT

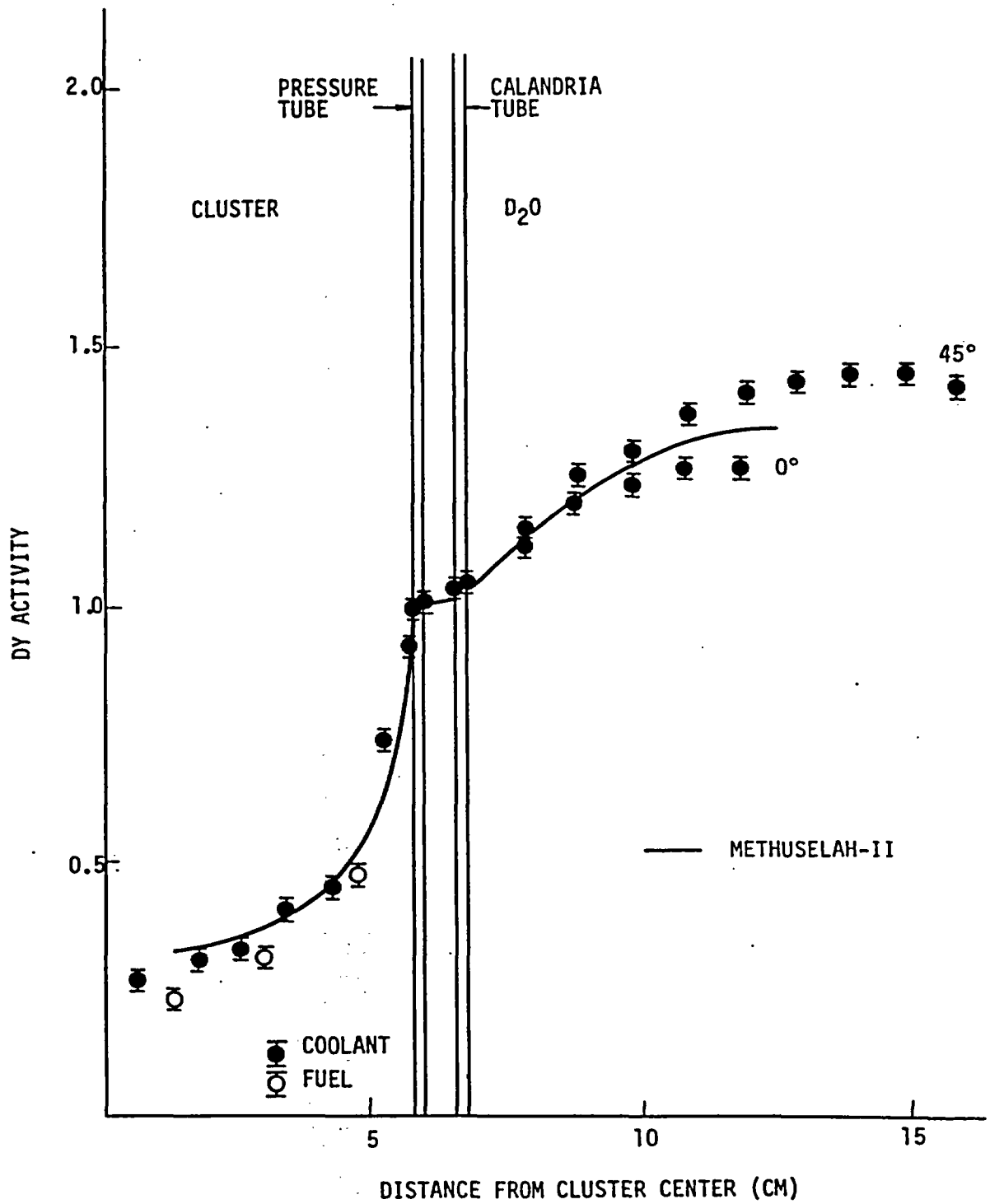


FIG.4 THERMAL FLUX DISTRIBUTION
(0.87W/O (S) PuO_2-UO_2, 0% VOID)

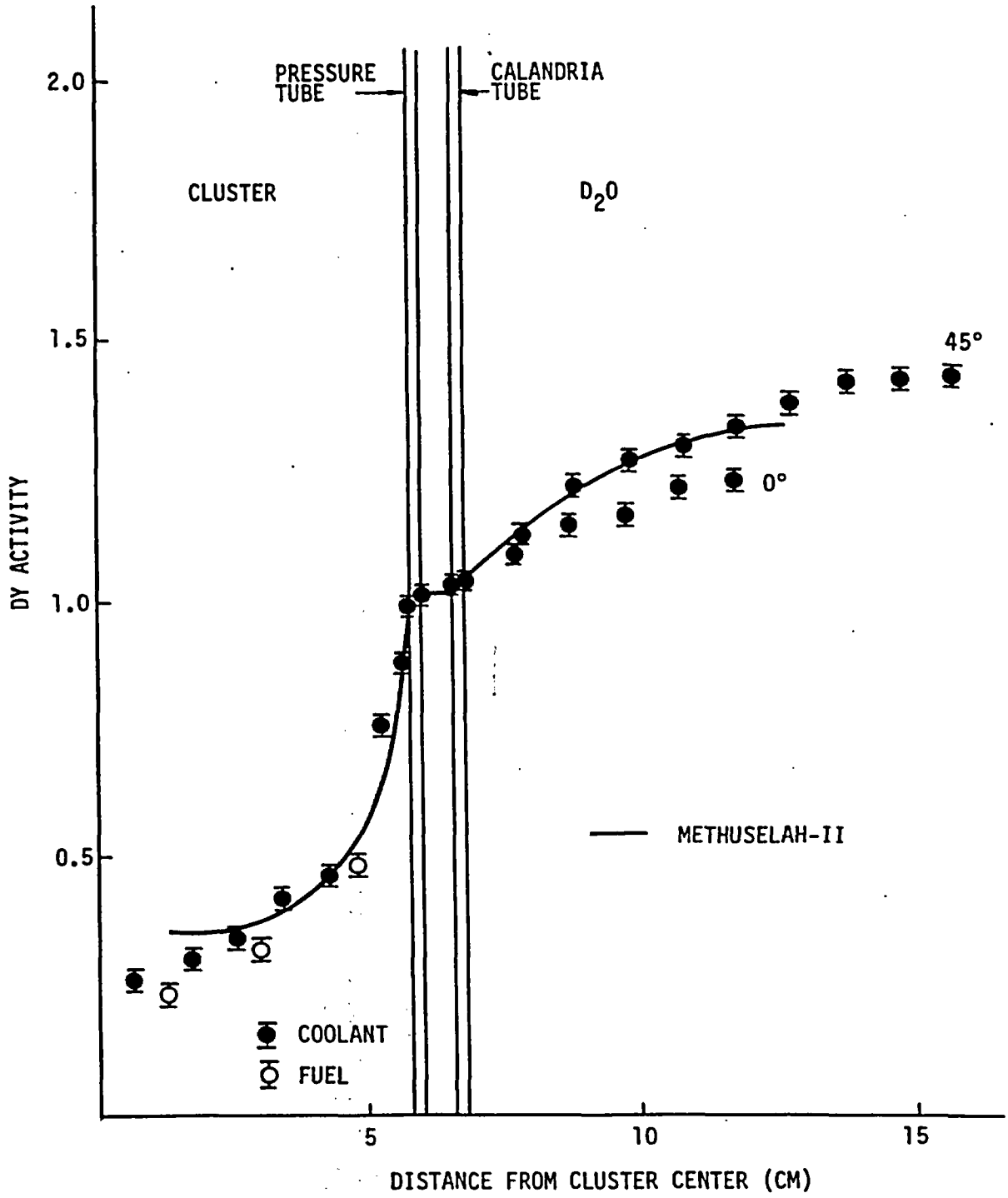


FIG.5 THERMAL NEUTRON FLUX DISTRIBUTION
(0.87W/O (R) PuO_2-UO_2, 0% VOID)

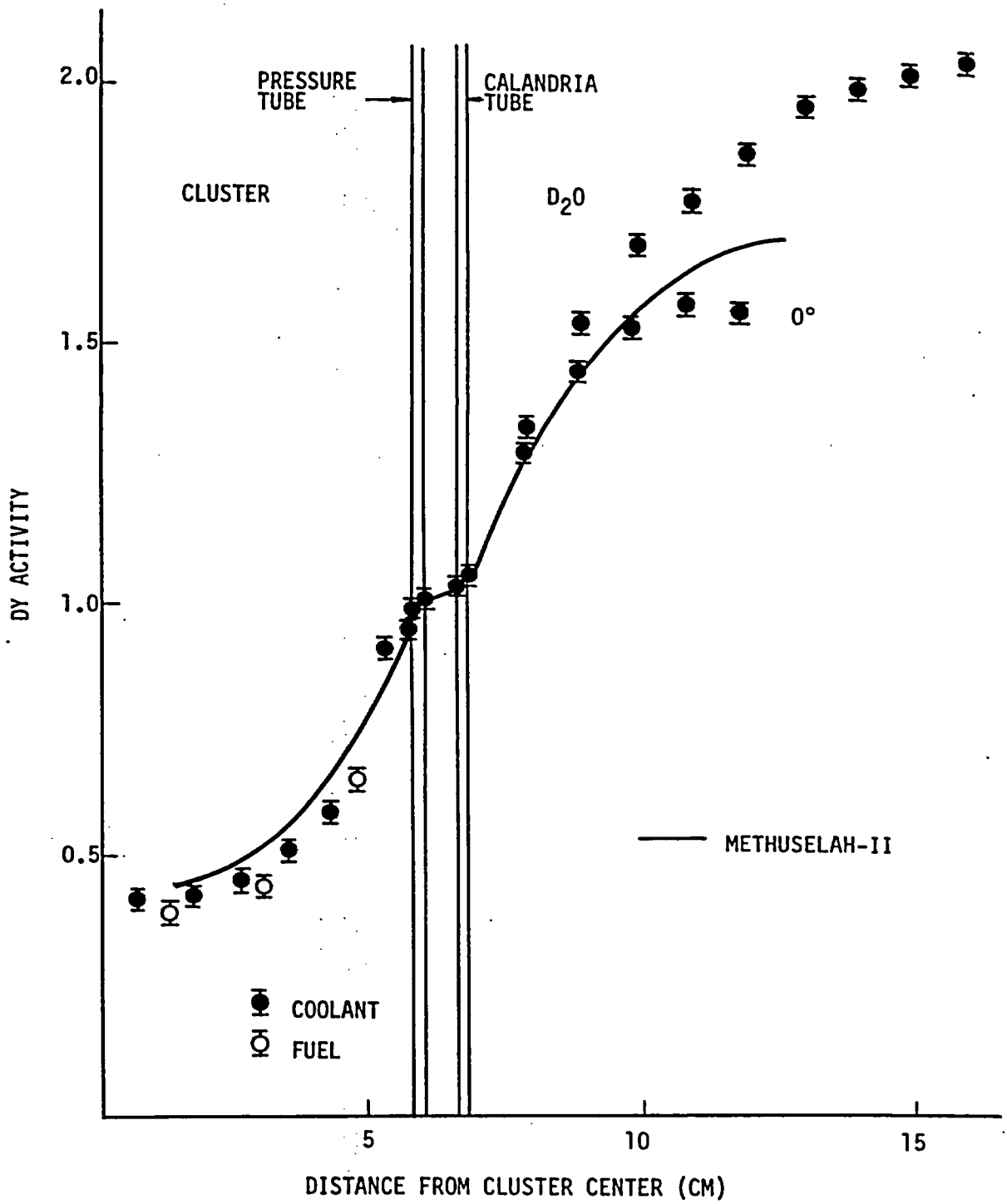


FIG.6 THERMAL NEUTRON FLUX DISTRIBUTION
(0.87W/O (S) PuO_2-UO_2, 100% VOID)

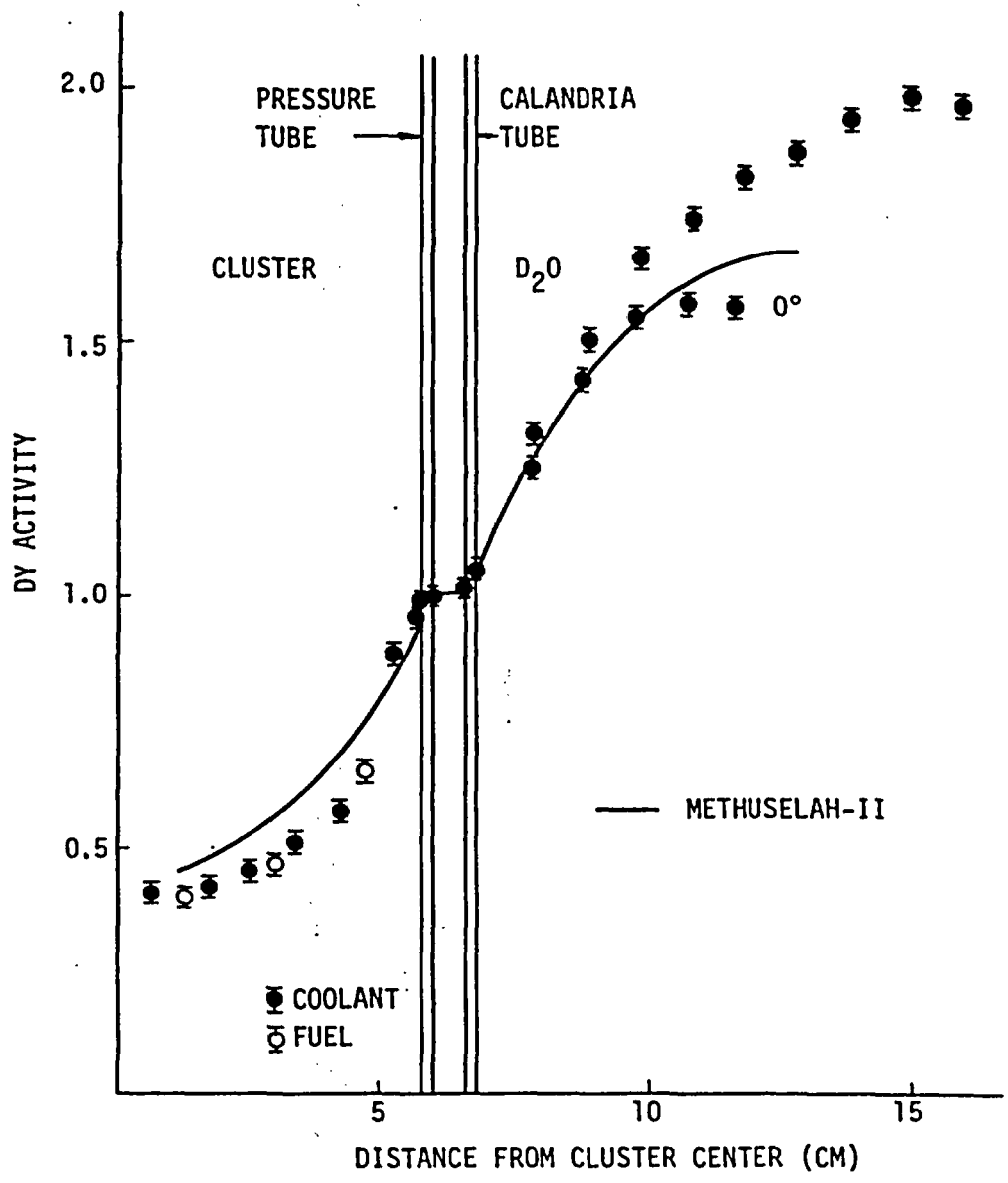


FIG.7 THERMAL NEUTRON FLUX DISTRIBUTION
(0.87W/O (R) PuO_2-UO_2, 100% VOID)

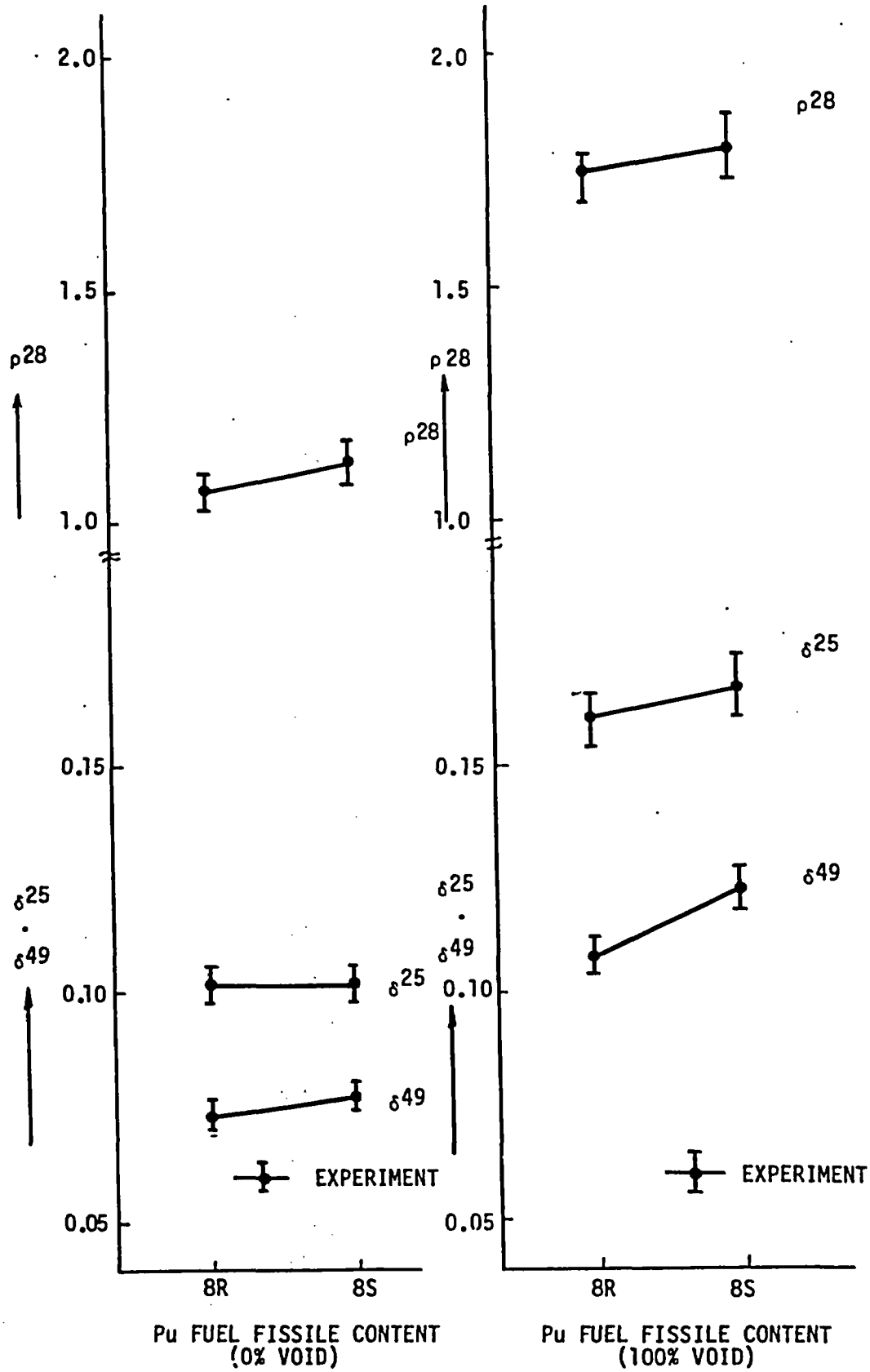


FIG.8 δ^{49}, δ^{25} & ρ^{28} Vs. Pu FUEL FISSILE CONTENT

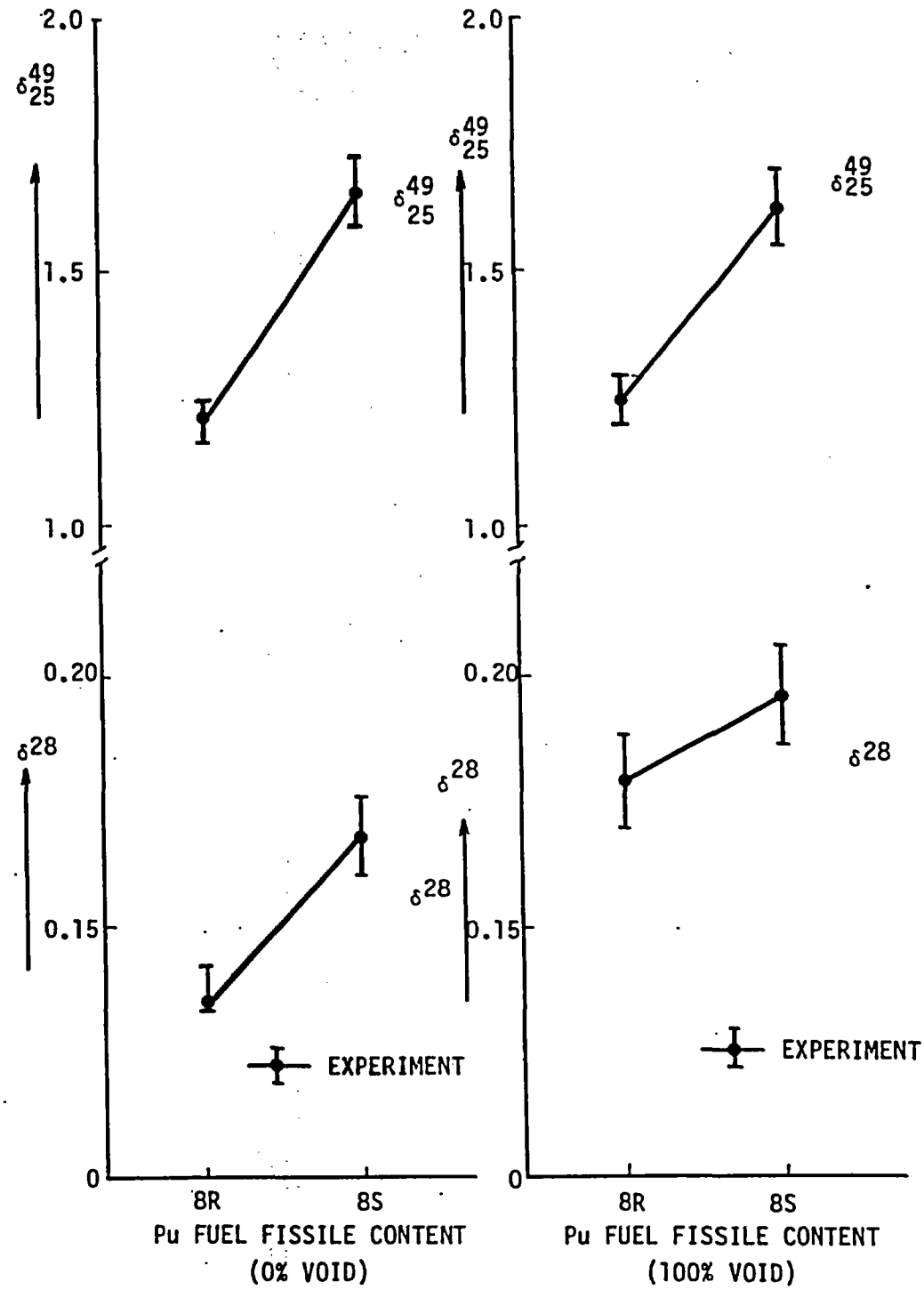
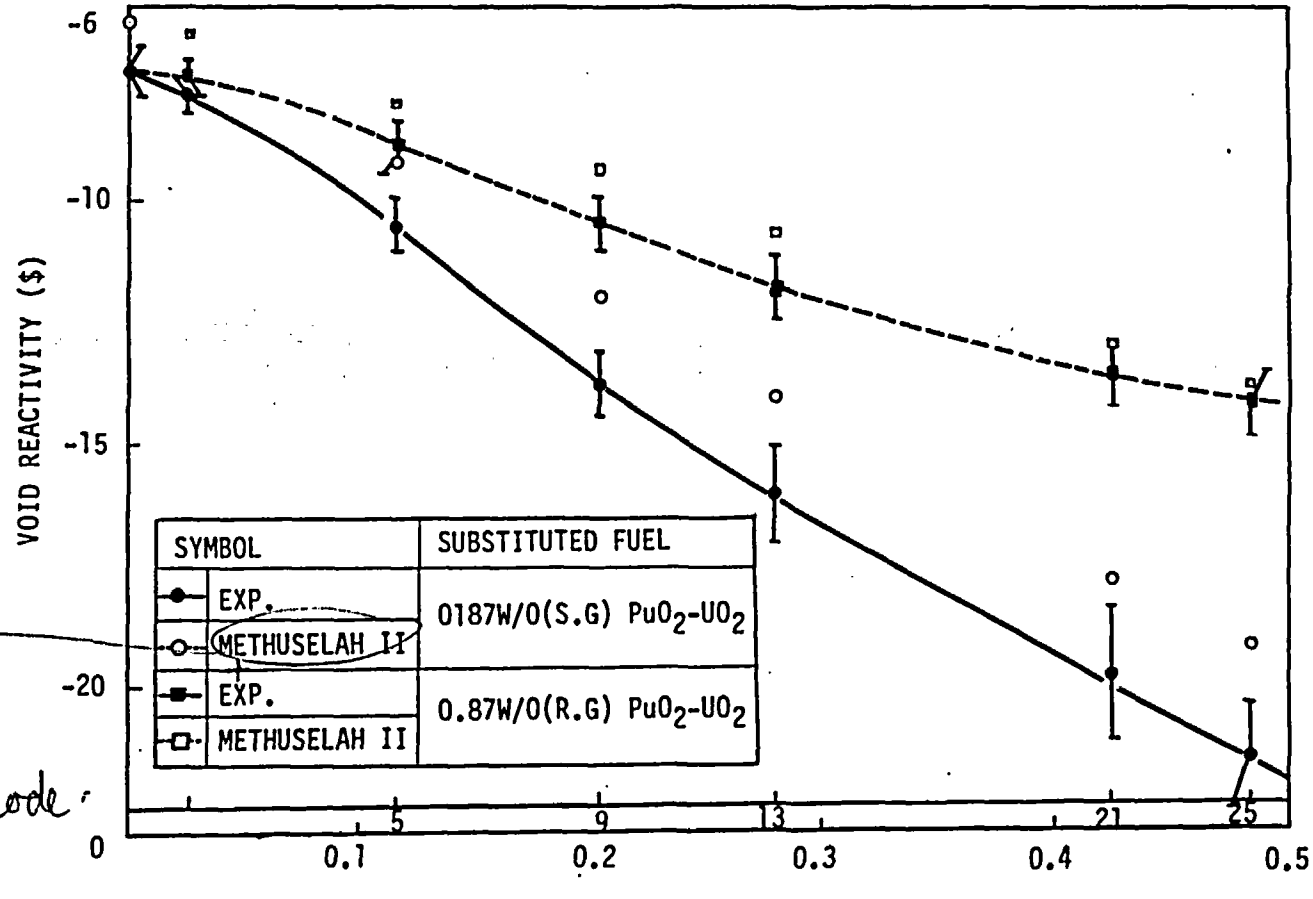


FIG.9 δ^{49}_{25} & δ^{28} - Vs. Pu FUEL FISSILE CONTENT



THE NUMBER OF SUBSTITUTED PuO_2-UO_2 FUEL ASSEMBLIES (UPPER AXIS)
STATISTICAL WEIGHT:Wo (LOWER AXIS)

FIG.10 VOID REACTIVITY IN PuO_2-UO_2 FUEL LOADED CORE

plus CITATION used in X-Y mode.

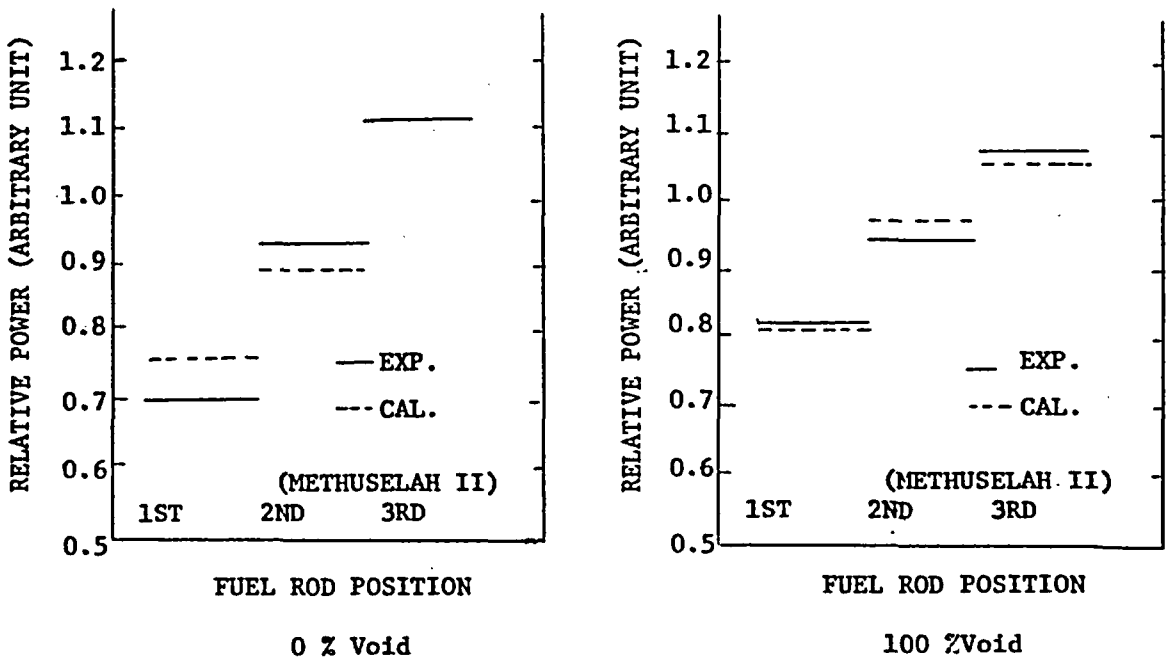


FIG. 12 LOCAL POWER DISTRIBUTION
in a mixed oxide fuel assembly
with 0.87 % Pu for the outer rings
and 0.54 % Pu for the middle
and the innermost rings.

Appendix

TABLE 1 ISOTOPIC CONTENT OF PLUTONIUM[11]

(1) Analytical Results of PuO_2-UO_2 Powder

	Isotope	0.54w/o PuO_2-UO_2 (Standard grade)	0.87w/o PuO_2-UO_2 (Standard grade)	0.87w/o PuO_2-UO_2 (Reactor grade)
Pu	^{238}Pu	0.021 w/o	0.019 w/o	0.84 w/o
	^{239}Pu	90.360 w/o	90.314 3/o	64.92 w/o
	^{240}Pu	8.640 w/o	8.682 w/o	21.77 w/o
	^{241}Pu	0.915 w/o	0.918 w/o	9.46 w/o
	^{242}Pu	0.064 w/o	0.067 w/o	3.01 w/o
U	^{235}U	0.711 w/o		
	^{238}U	99.289 w/o		
Date of Analysis		23 August 1971	23 August 1971	16 June 1973

(2) Atomic Number Density of Fuel Pellet

(i) 0.87 w/o Enriched PuO_2-UO_2 Fuel (Reactor Grade)

Composition		w/o in Pu	w/o in Fuel Pellet	Atomic No. Density ($10^{24}/cm^3$)
Pellet	^{235}U		0.6194	0.0001627
	^{238}U		86.493	0.02243
	^{238}Pu	0.84	0.00641	0.00000166
	^{239}Pu	64.92	0.4953	0.0001279
	^{240}Pu	21.77	0.1661	0.00004272
	^{241}Pu	9.46	0.07217	0.0000184
	^{242}Pu	3.01	0.02296	0.000005856
	O		12.13	0.04680

(ii) 0.87 w/o Enriched PuO_2-UO_2 Fuel (Standard Grade)

Composition		w/o in Pu	w/o in Fuel Pellet	Atomic No. Density ($10^{24}/cm^3$)
Pellet	^{235}U		0.6194	0.0001615
	^{238}U		86.503	0.02226
	^{238}Pu	0.019	0.000145	0.000000037
	^{239}Pu	90.314	0.6849	0.0001755
	^{240}Pu	8.682	0.06584	0.00001680
	^{241}Pu	0.918	0.006960	0.000001769
	^{242}Pu	0.067	0.000510	0.0000001291
	O		12.12	0.04641

(iii) 0.54 w/o Enriched PuO_2-UO_2 Fuel (Standard Grade)

Composition		w/o in Pu	w/o in Fuel Pellet	Atomic No. Density ($10^{24}/cm^3$)
	^{235}U		0.6214	0.0001620
	^{238}U		86.782	0.02233
	^{238}Pu	0.021	0.000102	0.000000026
	^{239}Pu	90.360	0.4304	0.0001103
	^{240}Pu	8.640	0.04115	0.00001050
	^{241}Pu	0.915	0.004359	0.000001108
	^{242}Pu	0.064	0.000303	0.0000000767
	O		12.12	0.04640

(iv) 1.2 w/o UO_2 Fuel

Composition		w/o in Fuel Pellet	Atomic No. Density ($10^{24}/cm^3$)
Pellet	^{235}U	1.057	0.0002806
	^{238}U	86.793	0.02275
	O	12.150	0.04738

TABLE 2 DIMENSIONS OF LATTICE[11]

1. Fuel Assembly

(i) 28 Elements/Assembly in 3 Circular Rings

Ring	No. of Elements	Pitch Circle Dia. of Elements Centers (cm)
1	4	2.625
2	8	6.000
3	16	9.515

(ii) Fuel Element

(1) 0.87 w/o Enriched PuO_2-UO_2 Fuel (Reactor Grade)

	Inner Dia. (cm)	Outer Dia. (cm)	Material	Density (g/cm^3)
Fuel Pellet	---	1.468	0.874 w/o Enriched PuO_2-UO_2	10.25
Gap	1.468	1.506	Helium	---
Fuel Sheath	1.506	1.668	Zry-2	6.523

(2) 0.87 w/o Enriched PuO_2-UO_2 Fuel (Standard Grade)

	Inner Dia. (cm)	Outer Dia. (cm)	Material	Density (g/cm^3)
Fuel Pellet	---	1.472	0.862 w/o Enriched PuO_2-UO_2	10.17
Gap	1.472	1.506	Helium	---
Fuel Sheath	1.506	1.668	Zry-2	6.523

(3) 1.2 w/o Enriched UO_2 Fuel

	Inner Dia. (cm)	Outer Dia. (cm)	Material	Density (g/cm^3)
Fuel Pellet	----	1.480	1.203 w/o enriched UO_2	10.36
GapGap	1.480	1.503	Helium	---
Fuel Sheath	1.503	1.673	Aluminum Alloy	2.674

(iii) Hanger Wire

No. in Assembly	Pitch Circle Dia. of Hanger Wire Center (cm)	Outer Dia. (cm)	Material	Density (g/cm3)
4	10.60	0.20	Aluminum Alloy	2.674

Composition	w/o in Wire	Atomic No. Density ($10^{24}/cm^3$)
Al	96.98	0.05788
Mg	2.60	0.00172

(iv) Spacer

No. in Assembly	Pitch Circle Dia. of Hanger Wire Center (cm)	Outer Dia. (cm)	Material	Density (g/cm^3)
2 *1	11.44	0.30	Aluminum Alloy	2.674

Composition	w/o in Spacer	Atomic No. Density ($10^{24}/cm^3$)
Al	96.98	0.05788
Mg	2.60	0.00172

*1 The positions are 70 cm and 140 cm from the lowest end of fuel.

2. Fuel Cahnnel

	Inner Dia. (cm)	Outer Dia. (cm)	Material	Density (g/cm^3)
Pressure Tube	11.68	12.08	Aluminum Alloy	2.674
Air Gap	12.08	13.25	Air	0.001205
Calandria Tube	13.25	13.65	Aluminum Alloy	2.674

Composition		w/o in Al	w/o in Air	Atomic No. Density ($10^{24}/cm^3$)
Al		96.98		0.05788
Mg		2.60		0.00172
Air	O		23.5204	0.00001067
	N		76.4796	0.00003962

3. Moderator

(1) Density of D_2O (99.50 mol/o) 1.1045

Material	w/o in Moderator	Density (g/cm^3)
D_2O	99.55	1.10504
H_2O	0.45	0.99777

Composition	w/o in D_2O	Atomic No. Density ($/cm^3 x10^{24}$)
H	0.05036	0.0003323
D	20.0223	0.06613
O	79.9283	0.03323

4. Coolant

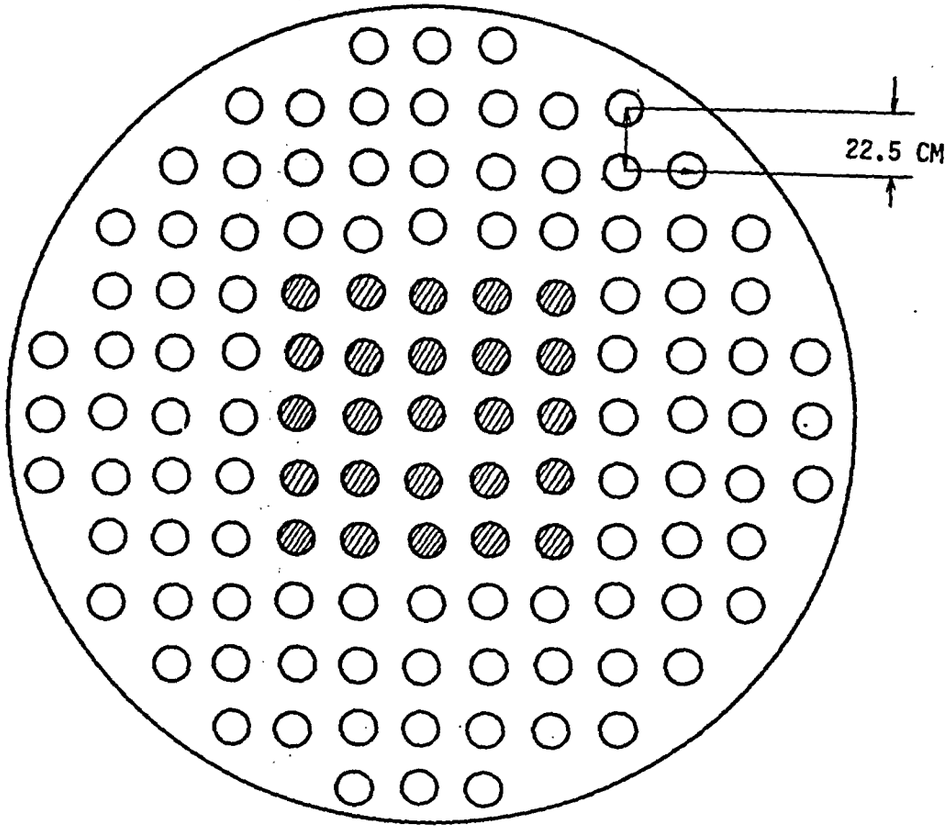
Simulated Void Fraction (%)	w/o in Coolant		Density (g/cm^3)
	H_2O	Air	
0	100		0.99777
100		100	0.000001
Density (g/cm^3)	0.99777	0.000005	

Composition	w/o in Coolant	
	0 % Void	100 % Void
H	11.1901	
O	88.8099	23.5204
N		76.4796

Composition	Atomic No. Density ($10^{24}/cm^3$)	
	0 % Void	100 % Void
H	0.06671	
O	0.03335	0.00001067
N		0.00003962

TABLE 3 SPECIFICATIONS OF DETECTOR FOILS

Foils	Contents	Dimension (mm)	
		Diameter	Thickness
Pu-Al Alloy	$\frac{Pu}{Pu\text{-}Al}$: 5.16 wt/o ^{238}Pu : 0.01 wt/o ^{239}Pu : 94.02 wt/o ^{240}Pu : 5.63 wt/o ^{241}Pu : 0.319 wt/o ^{242}Pu : 0.019 wt/o	14.8	0.1
Eu-Al Alloy	$\frac{U}{U\text{-}Al}$: 8.53 wt/o $\frac{^{235}U}{U}$: 89.84 wt/o	14.8	0.1
Depleted U Metal	$\frac{^{235}U}{U}$: 274 ppm	14.8	0.1
Dy-Al Alloy	$\frac{Dy}{Dy\text{-}Al}$: 4 wt/o	14.8 & 7	0.1



PLUTONIUM FUEL ASSEMBLY

URANIUM FUEL ASSEMBLY

FIG.1 CORE CONFIGURATION COMPRISING 25 PLUTONIUM FUELS

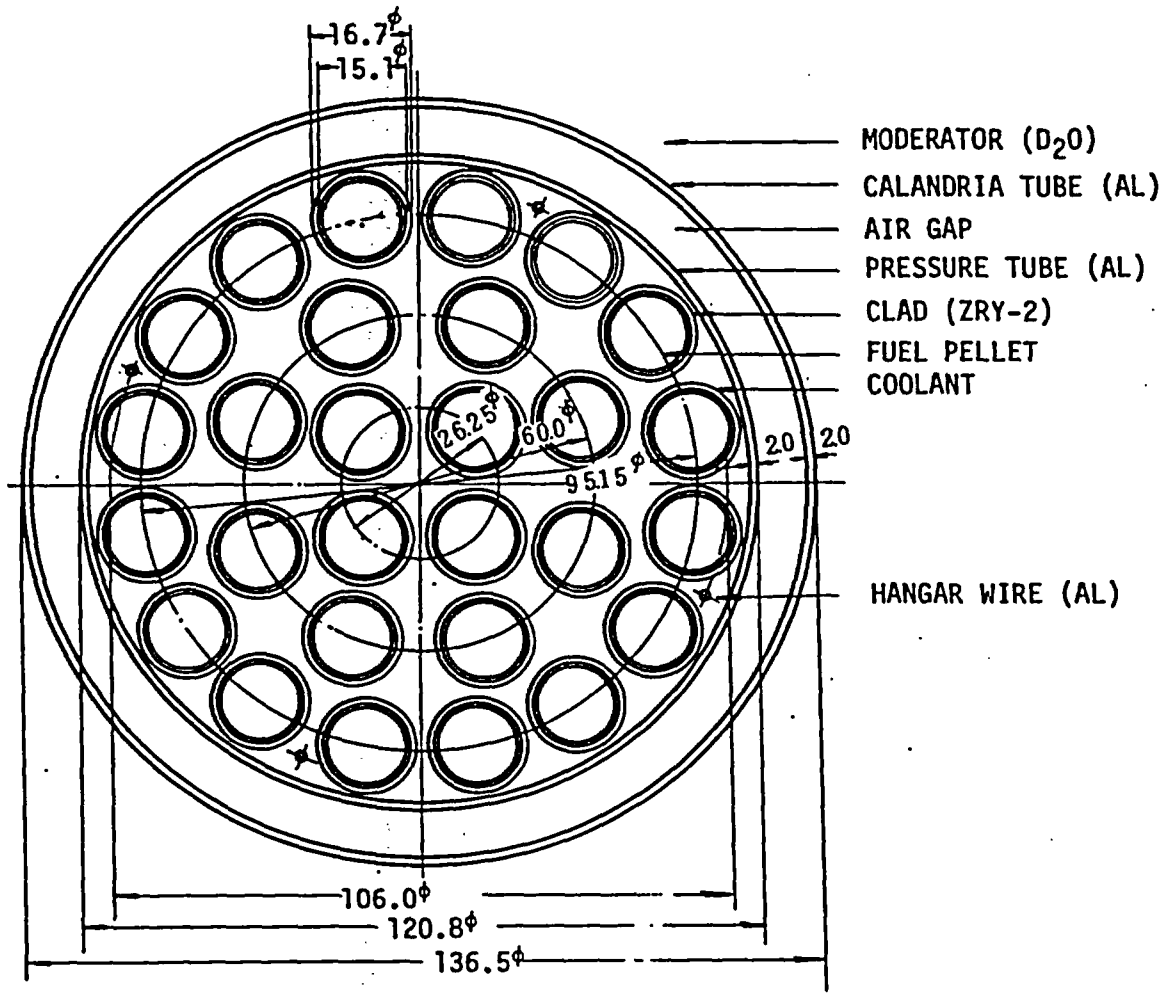


FIG.2 CONFIGURATION OF FUEL ASSEMBLY