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HEAVY WATER CRITICAL EXPERIMENTS ON PLUTONIUM LATTICE

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Heavy Water Critical Experiments on Plutonium Lattice

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Abstract

This report is the summary of physics study on plutonium lattice made in Heavy Water Critical Experiment Section of PNC.

By using Deuterium Critical Assembly, physics study on plutonium lattice has been carried out since 1972. Experiments on following items were performed in a core having 22.5 cm square lattice pitch.

(1) Material buckling
(2) Lattice parameters
(3) Local power distribution factor
(4) Gross flux distribution in two region core
(5) Control rod worth

Experimental results were compared with theoretical ones calculated by METHUSELAH II code.

It is concluded from this study that calculation by METHUSELAH II code has acceptable accuracy in the prediction on plutonium lattice.

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1. Introduction

FUGEN is a heavy water moderated, boiling light water cooled, pressure tube type reactor.[1], [2] Plutonium fuel is partially loaded in FUGEN from initial core to decrease positive coolant void reactivity [3] and to use nuclear fuel effectively. Therefore, accuracies of calculation codes used for the core design must be also checked on the plutonium fueled lattices from various physical points of view in a similar way made on the uranium fueled ones.

For the purpose, a series of critical experiments on the following items have been performed by using Deuterium Critical Assembly's core having 22.5 cm lattice pitch.

(1) Material buckling
(2) Lattice parameters
(3) Local power distribution factor
(4) Gross flux distribution in two region core
(5) Control rod worth

Experimental results were compared with calculational ones by METHUSELAH II and few groups diffusion codes.

This report is the summary of recent reactor physics activities on plutonium fuel lattices made in Heavy Water Critical Experiment Section.

2. Material buckling[4]

Material bucklings of plutonium uranium mixed oxide fuel lattices were measured by means of progressive substitution method. Plutonium enrichment of the mixed oxide fuel was 0.54 w/o. Measurements of critical moderator height were carried out in cores having various test regions surrounded by 1.2 w/o enriched uramium oxide. The test region comprises 1, 5, 9 up to 25 mixed oxide fuel assemblies. Critical moderator heights were converted to axial buckling, by using extrapolation length obtained in a core uniformly fueled with 1.2 w/o enriched uranium oxide.

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

Measured material bucklings are shown in Fig. 1, compared with theoretical ones calculated by METHUSELAH II code. Comparison shows that the disagreement between them will cause the discrepancy in effective multiplication factor by about 1% maximum. This result is considered to be practically acceptable.

3. Lattice parameters [5]

Lattice parameters have been measured in the lattice fueled with 0.54 w/o enriched mixed oxide, by changing coolant void fraction from 0% to 30%, 70% and 100%. Measured lattice parameters are as follows:

δ^{28} : Ratio of ^{238}U fissions to ^{235}U fission,

δ^{25} : Ratio of ^{235}U fissions in epicadmium region to ones in subcadmium,

ρ^{28} : Ratio of ^{238}U captures in epicadmium region to ones in subcadmium region,

δ^{49} : Ratio of ^{239}Pu fissions in epicadmium region to ones in subcadmium region,

δ^{49}_{25} : Ratio of ^{239}Pu fissions to ^{235}U fissions

Detector foils were irradiated in the central unit cell of the mixed oxide fuel region. The mixed oxide fuel region consisting of 25 fuel assemblies was surrounded by 96 fuel assemblies of 1.2 w/o enriched uranium oxide.

NaI (Tl) scintillation detector and Ge (Li) detector were used to count γ-rays emitted from fission products and ^{239}Np produced by capture reaction of ^{238}U , respectively.

Micro parameters measured are shown in Fig. 2 and 3 as a function of fuel position in a cluster. By summing the specific activities in the relevant energy region or of each nuclei for the whole fuel space of a cluster, one ratio for a unit cell was obtained of δ^{28}, δ^{25}, ρ^{28}, δ^{49} and δ^{49}_{25}. The suffix "cell" added to δ and ρ signifies such a cell value, for example, δ^{28}_{cell} and $\delta^{49}_{25\ cell}$.

δ^{25}_{cell} and ρ^{28}_{cell} are compared with experimental ones of 1.2 w/o and 1.5 w/o enriched uranium oxide fuel lattices in Fig.4 and 5. δ^{28}_{cell} multiplied by $^{25}N_{fuel}/^{28}N_{fuel}$ ($^{25}N_{fuel}$ and $^{28}N_{fuel}$ are atomic density of ^{235}U and ^{238}U in a fuel, respectively) is shown in Fig. 6.

Following are found from this comparison

(1) δ^{25}_{cell} and δ^{28}_{cell} ($^{25}N_{fuel}/^{28}N_{fuel}$) are larger than ones of either uranium oxide lattice.

(2) ρ^{28}_{cell} of mixed oxide lattice lays midway between those of the uranium oxide fuel lattices.

These facts suggests that at 6 ev or lower, neutron spectrum in 0.54 w/o enriched mixed oxide fuel is harder than one in either uranium oxide fuel.

Dependences of δ^{49}_{cell} and $\delta^{49}_{25\ cell}$ on coolant void fraction are shown in Fig. 7. The dependences suggest that at 30% void fraction or more, coolant voiding increases the comtribution of epi-thermal neutrons to neutron spectrum and softens sub-cadmium spectrum.

4. Local power distribution factor [6]

Local power distribution factors in 0.54 w/o enriched mixed oxide and 1.2 w/o enriched uranium oxide fuel clusters have been measured by using DCA's core having 22.5 cm square lattice

pitch. In order to obtain the dependence of local power distribution factor on coolant voiding, measurement was done at 0% and 100% void fraction. The central region consisting of 37 mixed oxide fuel clusters was surrounded by 1.2 w/o enriched uramium oxide fuel.

Power of fuel rod was evaluated from intensity of γ-rays emitted from ^{140}La produced by fission. When evaluating power distribution of mixed oxide fuel cluster, corrections were made to the difference in yield of ^{140}La and energy release per fission between plutonium and uranium. Measured results are shown in Fig. 8 and 9, compared with calculation by METHUSELAH code. It is found from these figures that coolant voiding tends to flatten power distribution. This tendency is larger in the uranium oxide fuel than in the mixed oxide fuel. Disagreement of local power distribution factor between calculation and experiment is smaller at the third ring than at the first and second ones.

5. Gross flux distribution in two region core [7]

By means of copper wire activation method, radial flux distribution has been measured in two region core. The central region fueled with 0.54 w/o enriched plutonium uranium mixed oxide was surrounded with 1.2 w/o enriched uranium oxide fuel assemblies as shown in Fig. 10. 0% and 100% void fraction were used in this experiment.

Radial flux distributions measured in the center of a fuel cluster are shown Fig. 11 and 12. Fig. 13 shows the radial flux distribution measured in the center of moderator region and Fig. 14 shows the radial flux distribution measured in the midpoint of the nearest neighbor's fuel cluster. Flux distributions calculated by METHUSELAH and PDQ codes are also compared with experiments in Fig. 11, 12, 13 and 14.

Copper reaction rate at the position r was calculated as follows.

$$\text{Reaction rate of copper} = \sum_{g=1}^{G} \phi_g^{core}(r) \cdot \frac{\phi_g^{cell}(r)}{\bar{\phi}_g^{cell}} \cdot \Sigma_{a,g}^{cu}(r)$$

where

$\phi_g^{core}(r)$: flux of g-th group at r calculated by PDQ code,

$\phi_g^{cell}(r)$: flux of g-th group at r calculated by METHUSELAH code,

$\bar{\phi}_g^{cell}$: flux of g-th group averaged over a unit lattice,

$\Sigma_{a,g}^{cu}(r)$: absorption cross section of copper at r.

Since overlapping model are used in METHUSELAH code to calculate thermal flux in a unit lattice, absorption cross section of copper can be evaluated space-dependently. Calculated flux distributions have a fairly good agreement with experimental results. Flux distribution measured at the center of fuel cluster agrees with calculation slightly better than that measured in moderator region.

6. Control rod worth[8]

By means of critical method, control rod worth has been measured in two region core having 22.5 cm square lattice pitch. The core configuration used in this measurement is the same as mentioned in the previous chaptor. 0% and 100% void fraction were used. The cross sectional view of the control rod is shown in Fig. 15. The maximum number of control rod inserted in the core is eight as shown in Fig.16. Measured reactivities are compared in Table 1 with calculational results evaluated by logarithmic

boundary condition method and absorption area method. By using CITATION code in X-Y geometry, reactivity worth was calculated from three energy group constants obtained from the cell calculation by METHUSELAH code. As shown in Table 1, the two calculational methods give the same results to the reactivity worth evaluation of control rods. These calculations generally tend to underestimate reactivity worth in a fully voided core by about 15%.

7. Concluding remarks

It is concluded from these studies that the cell calculation METHUSELAH code will give the cell parameters of plutonium uranium mixed oxide fuel lattice with acceptable accuracy. Some more theoretical study will be necessary to understand the discrepancy of control rod worths in a fully voided core.

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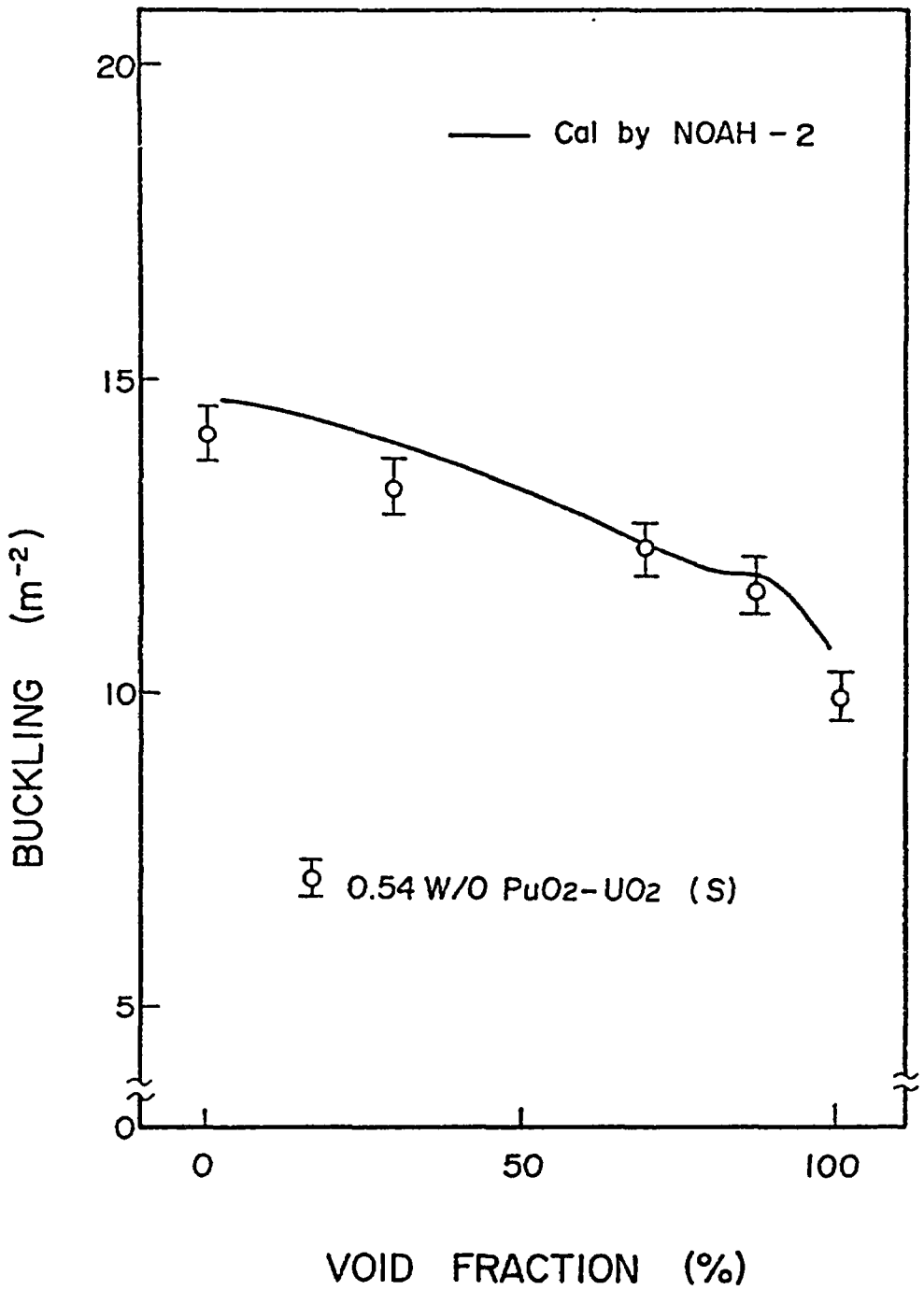


Fig.1. MATERIAL BUCKLING OF MIXED OXIDE FUELED LATTICES. LATTICE PITCH : 22.5cm.

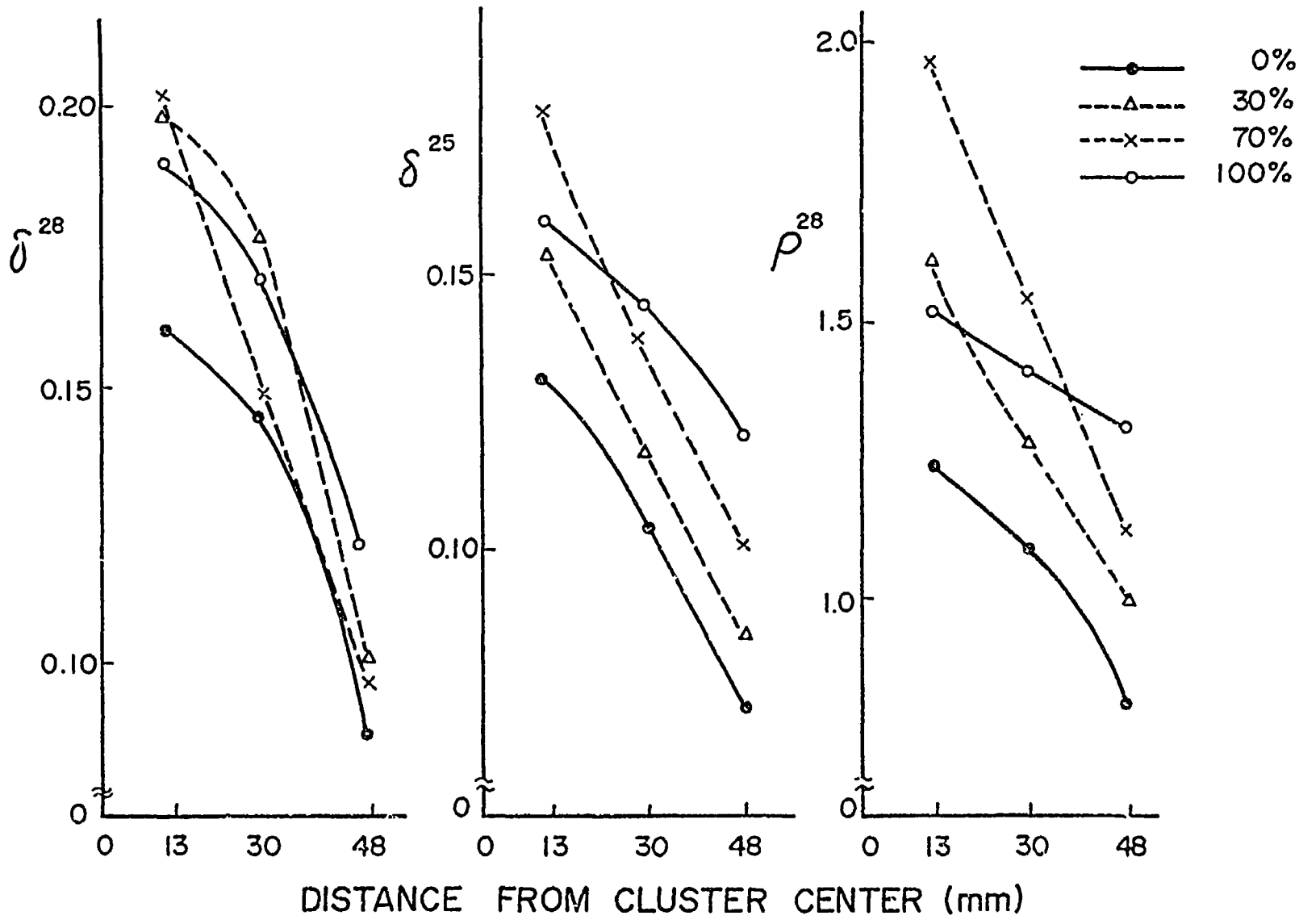


Fig.2. MICRO PARAMETERS OF 0.54W/O ENRICHED MIXED OXIDE FUEL CLUSTER AS A FUNCTION OF ROD POSITION. LATTICE PITCH : 22.5 cm.

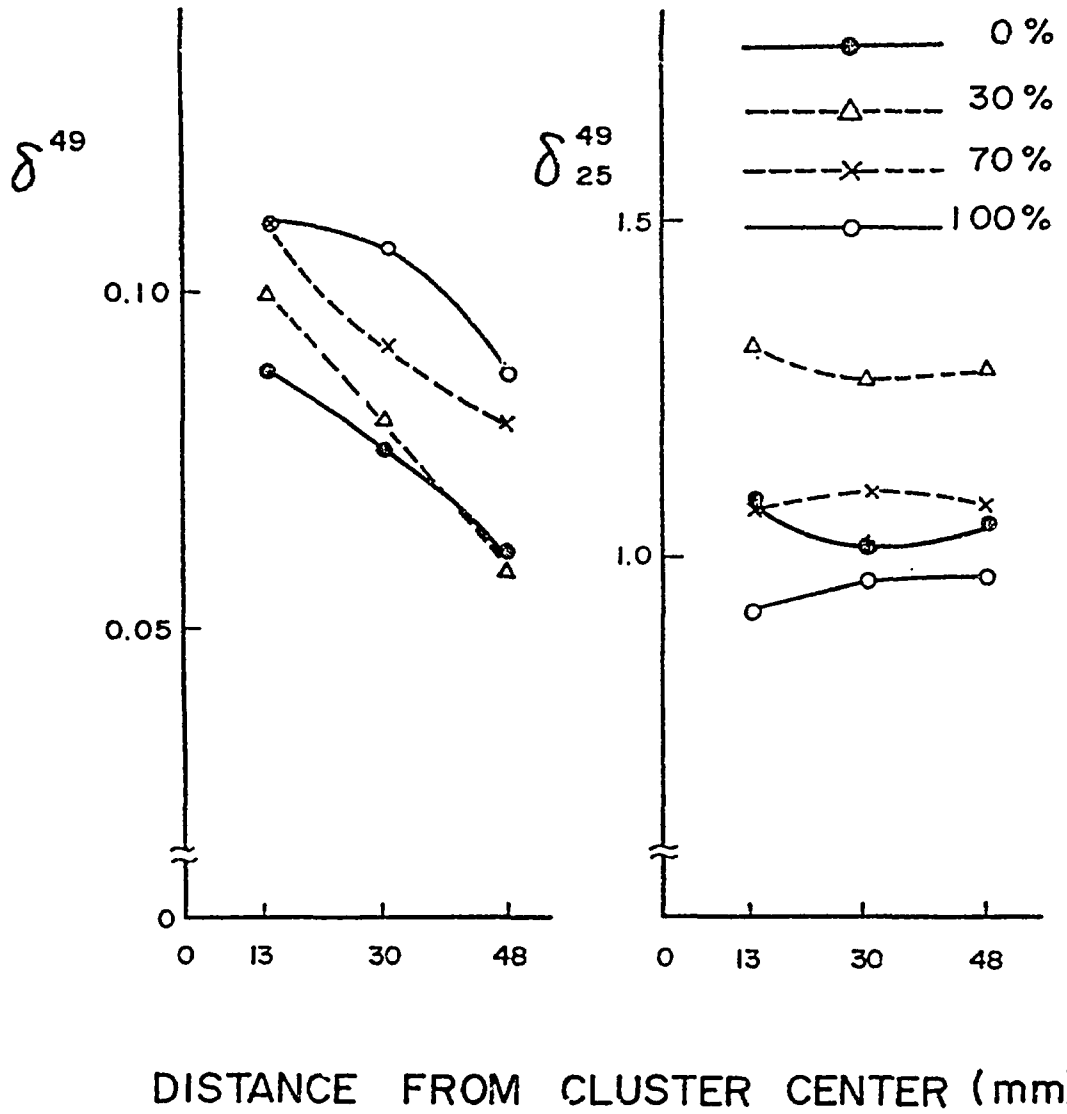


Fig.3. MICRO PARAMETERS OF 0.54W/O ENRICHED MIXED OXIDE FUEL CLUSTER AS A FUNCTION OF ROD POSITION. LATTICE PITCH : 22.5 cm.

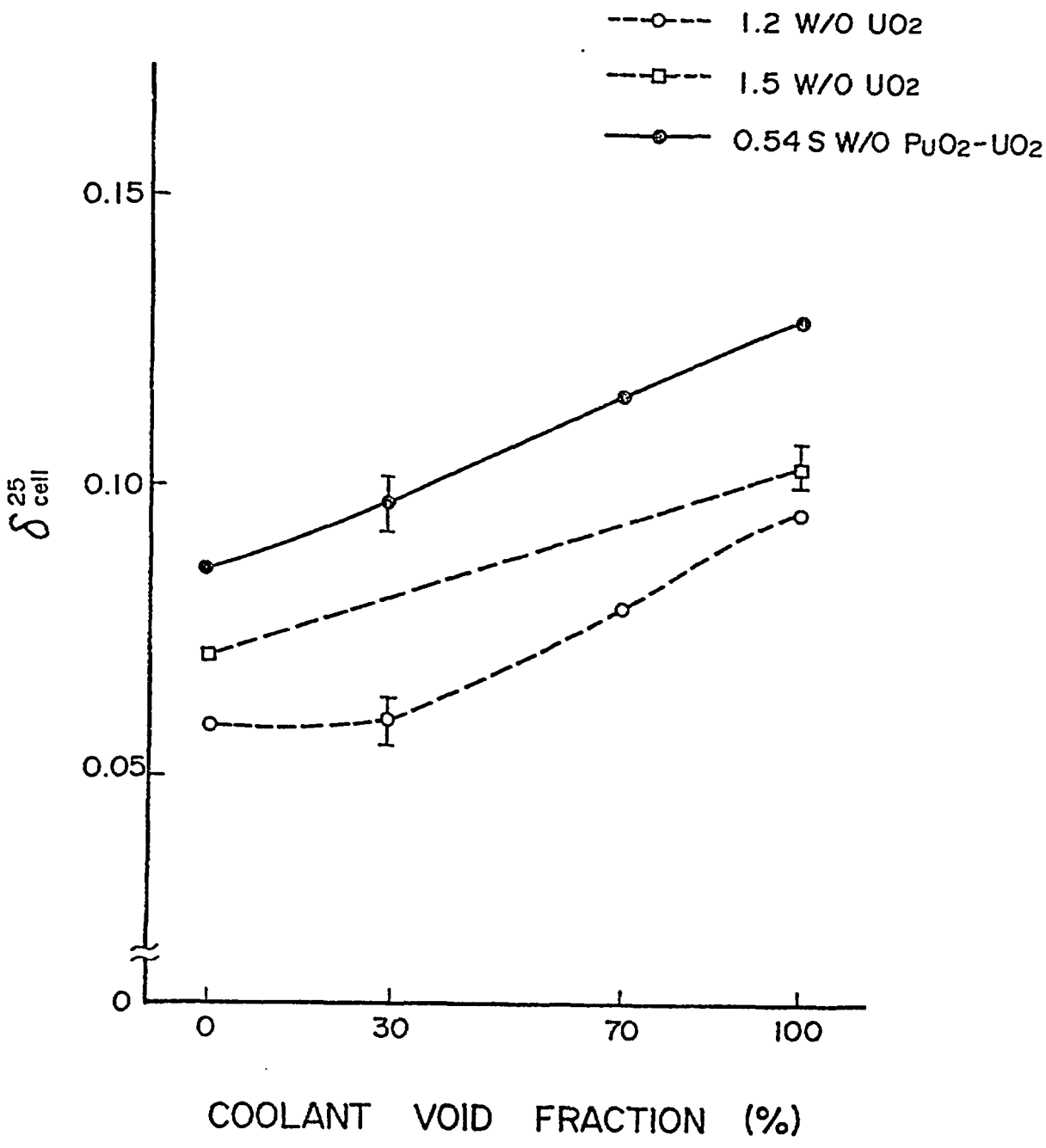


Fig. 4. δ^{25}_{cell} OF 0.54W/o ENRICHED MIXED OXIDE FUEL LATTICE AS A FUNCTION OF COOLANT VOID FRACTION.
LATTICE PITCH : 22.5 cm.

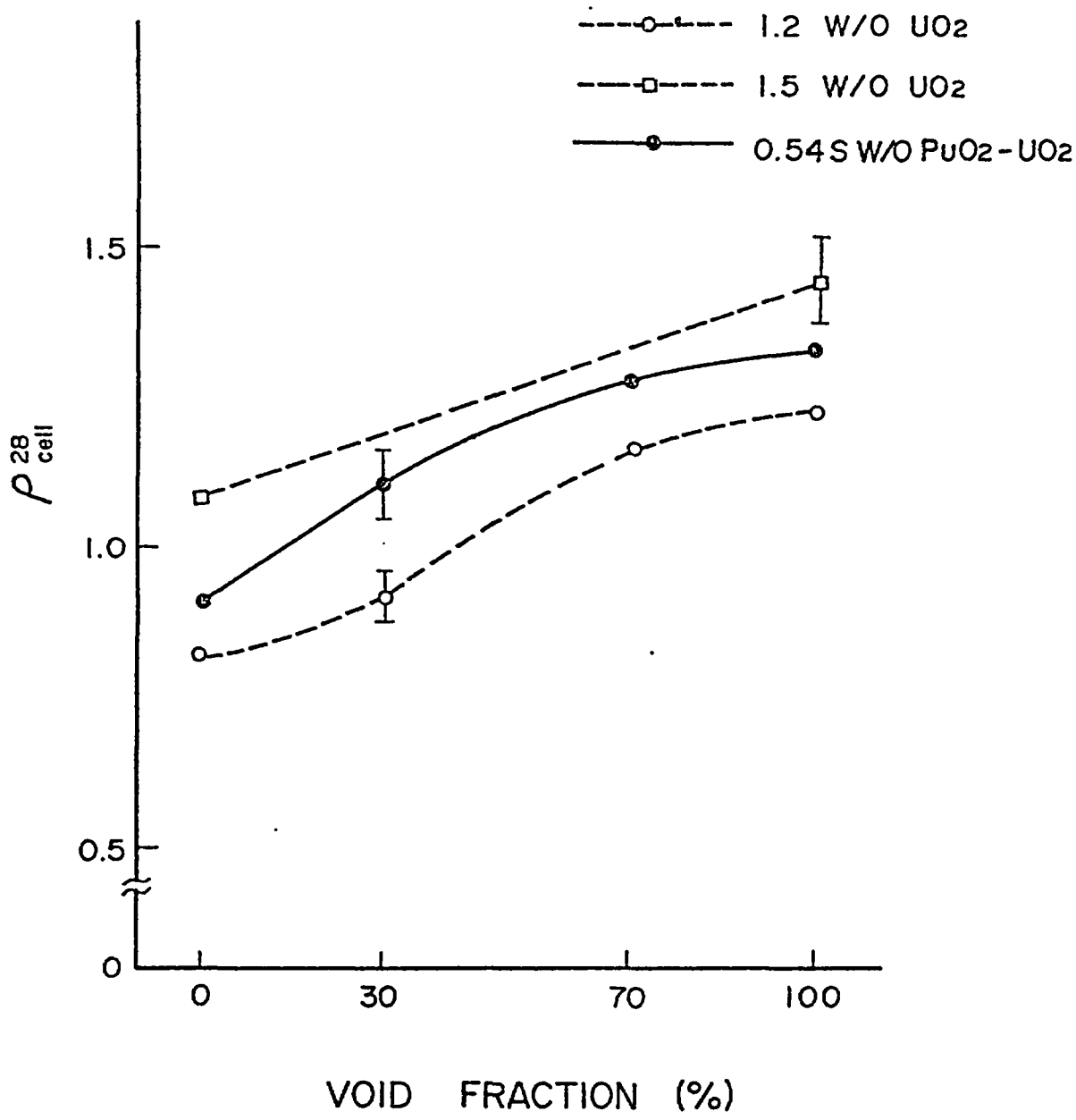


Fig.5. ρ^{28}_{cell} OF 0.54W/o ENRICHED MIXED OXIDE FUEL LATTICE AS A FUNCTION OF COOLANT VOID FRACTION. LATTICE PITCH: 22.5 cm.

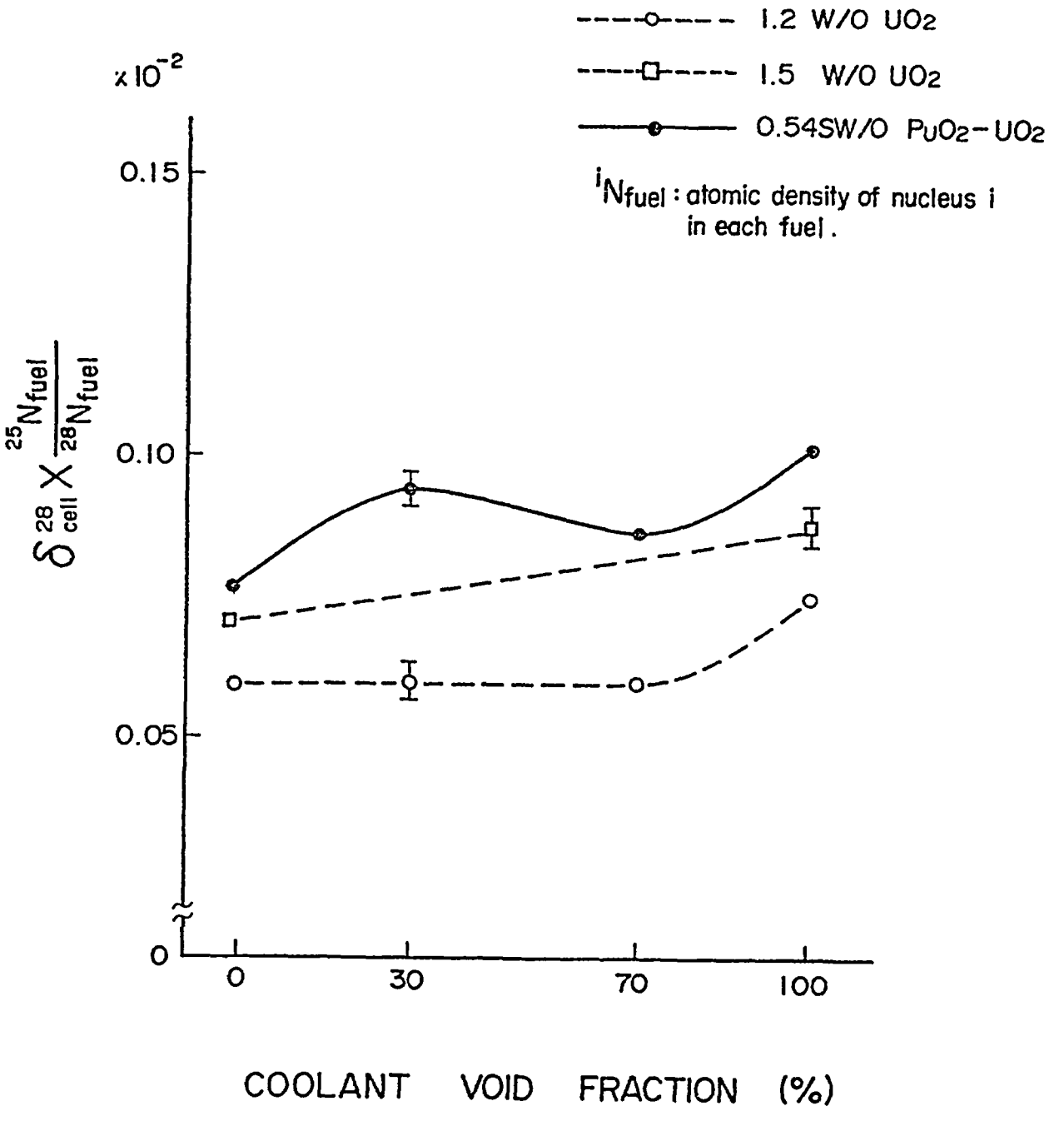


Fig.6. δ^{28}_{cell} ($^{25}N_{fuel}$ / $^{28}N_{fuel}$) OF 0.54 W/O ENRICHED MIXED OXIDE FUEL LATTICE AS A FUNCTION OF COOLANT VOID FRACTION. LATTICE PITCH : 22.5 cm.

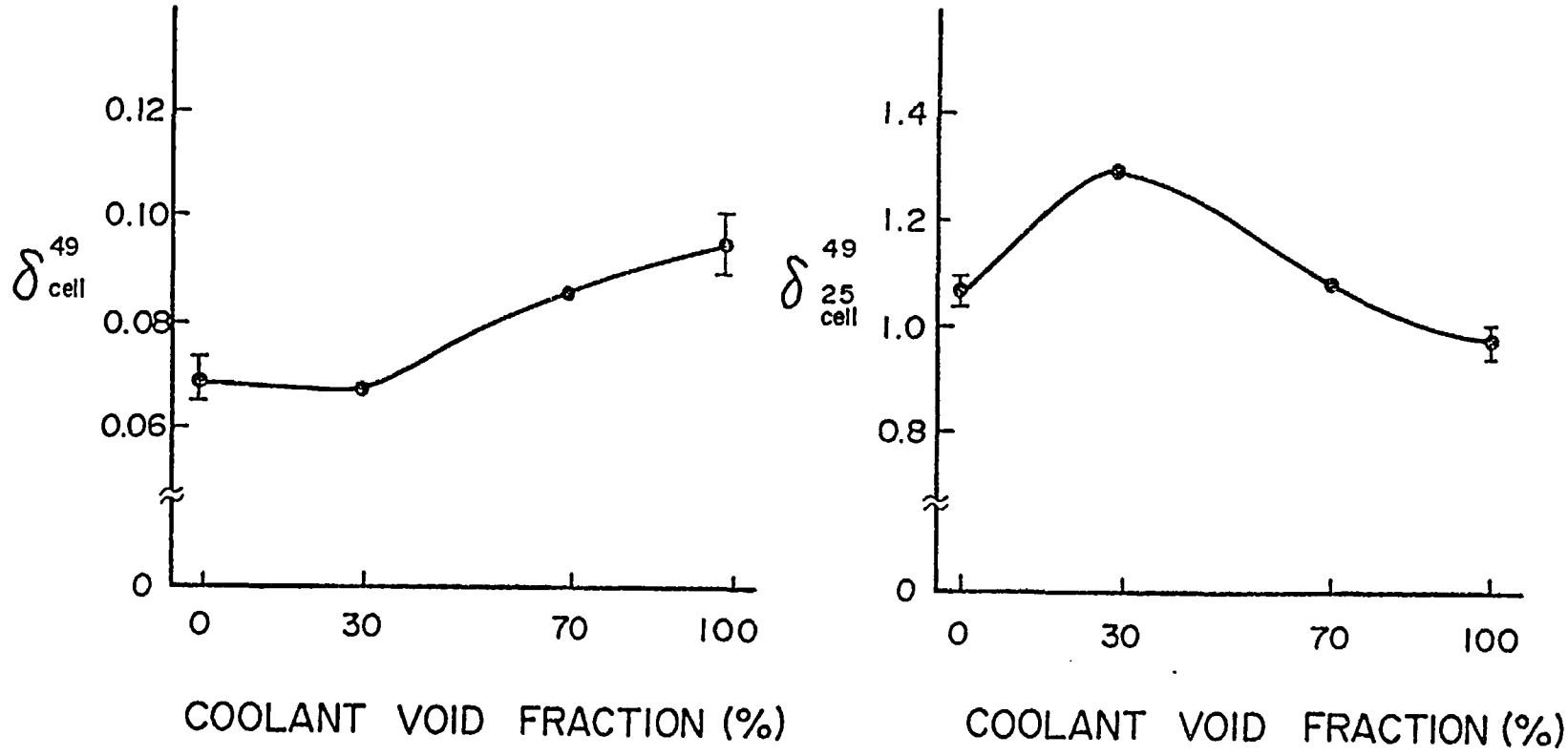


Fig. 7. δ^{49}_{cell} AND $\delta^{49}_{25\,cell}$ OF 0.54W/O ENRICHED MIXED FUEL LATTICE AS A FUNCTION OF COOLANT VOID FRACTION.
LATTICE PITCH : 22.5 cm.

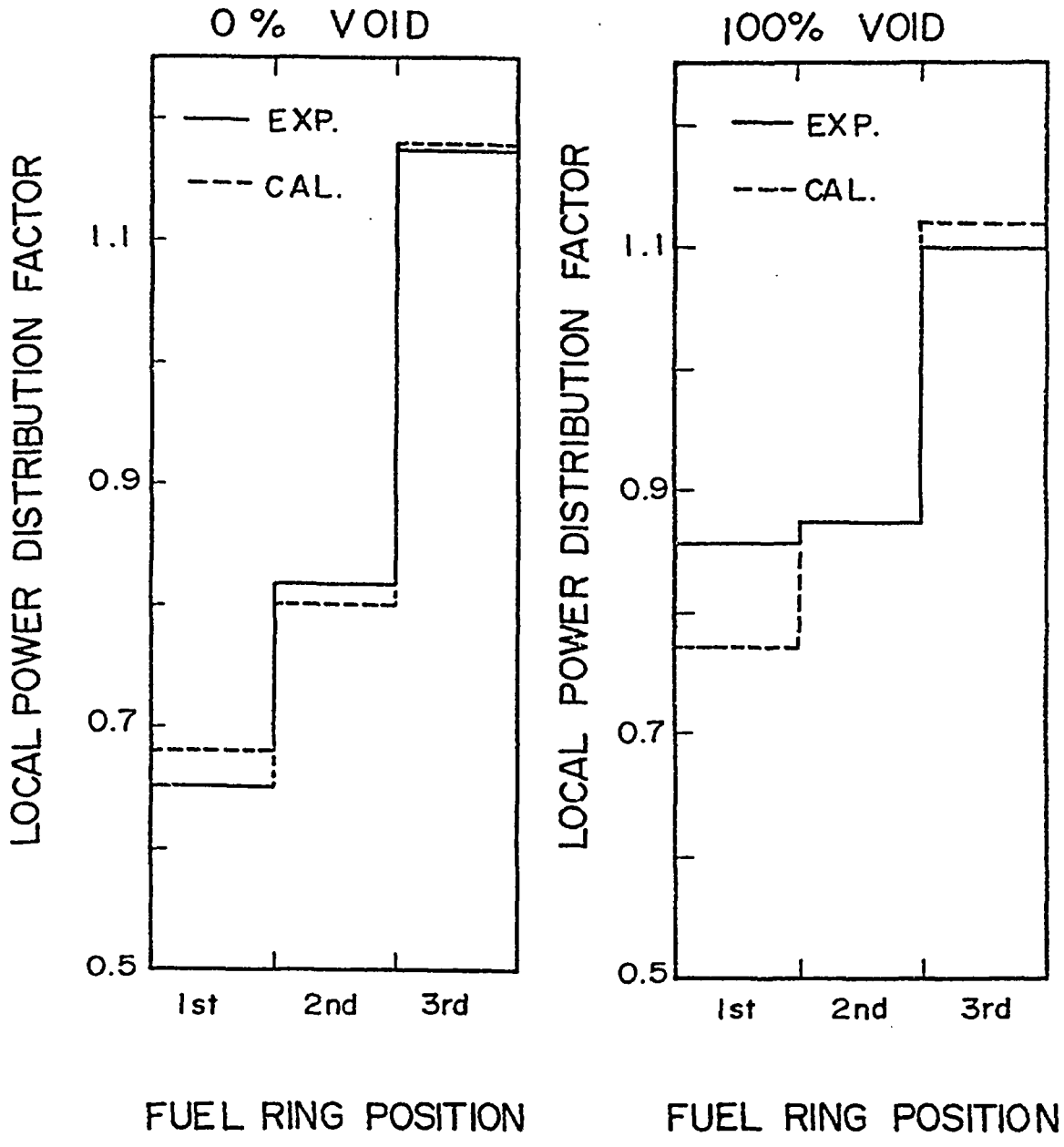


Fig.8. LOCAL POWER DISTRIBUTION FACTOR IN 1.2 W/O ENRICHED URANIUM FUEL LATTICE PITCH : 22.5cm.

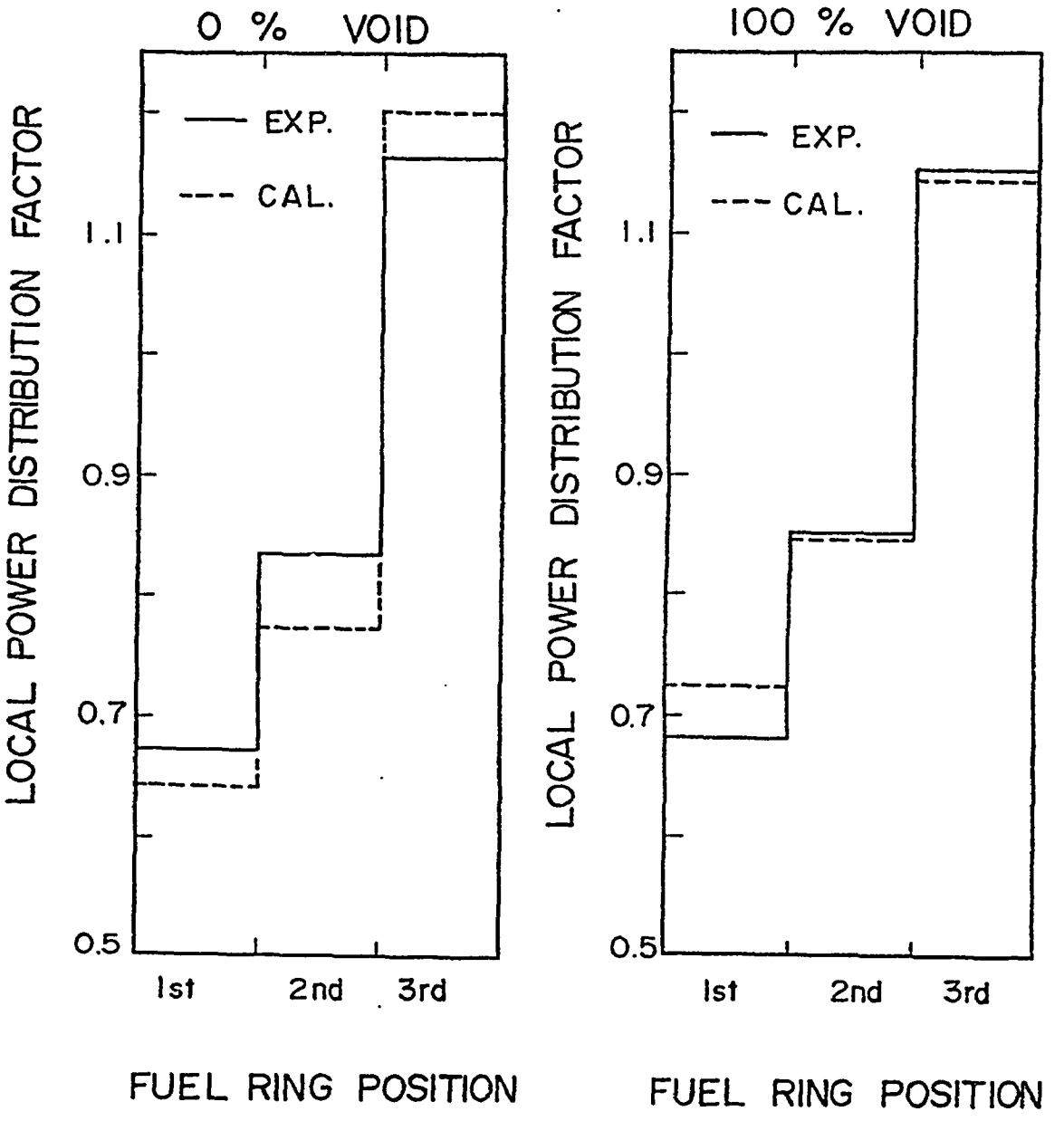
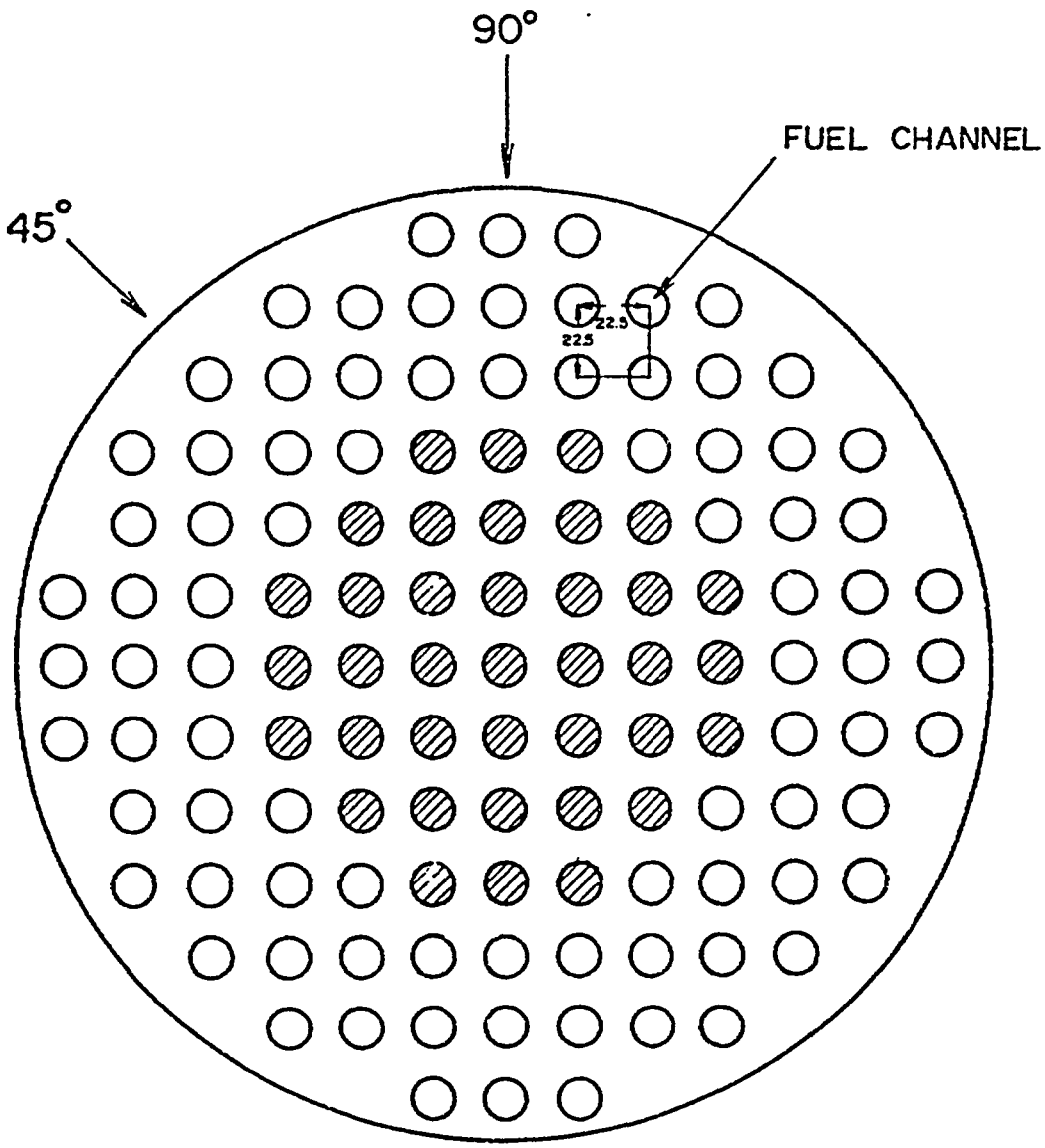


Fig.9. LOCAL POWER DISTRIBUTION FACTOR IN 0.54 W/O ENRICHED MIXED OXIDE FUEL LATTICE PITCH : 22.5cm.



URANIUM OXIDE FUEL

MIXED OXIDE FUEL

Fig.10. CONFIGURATION OF CORE LOADED WITH 37 MIXED OXIDE FUEL ASSEMBLIES

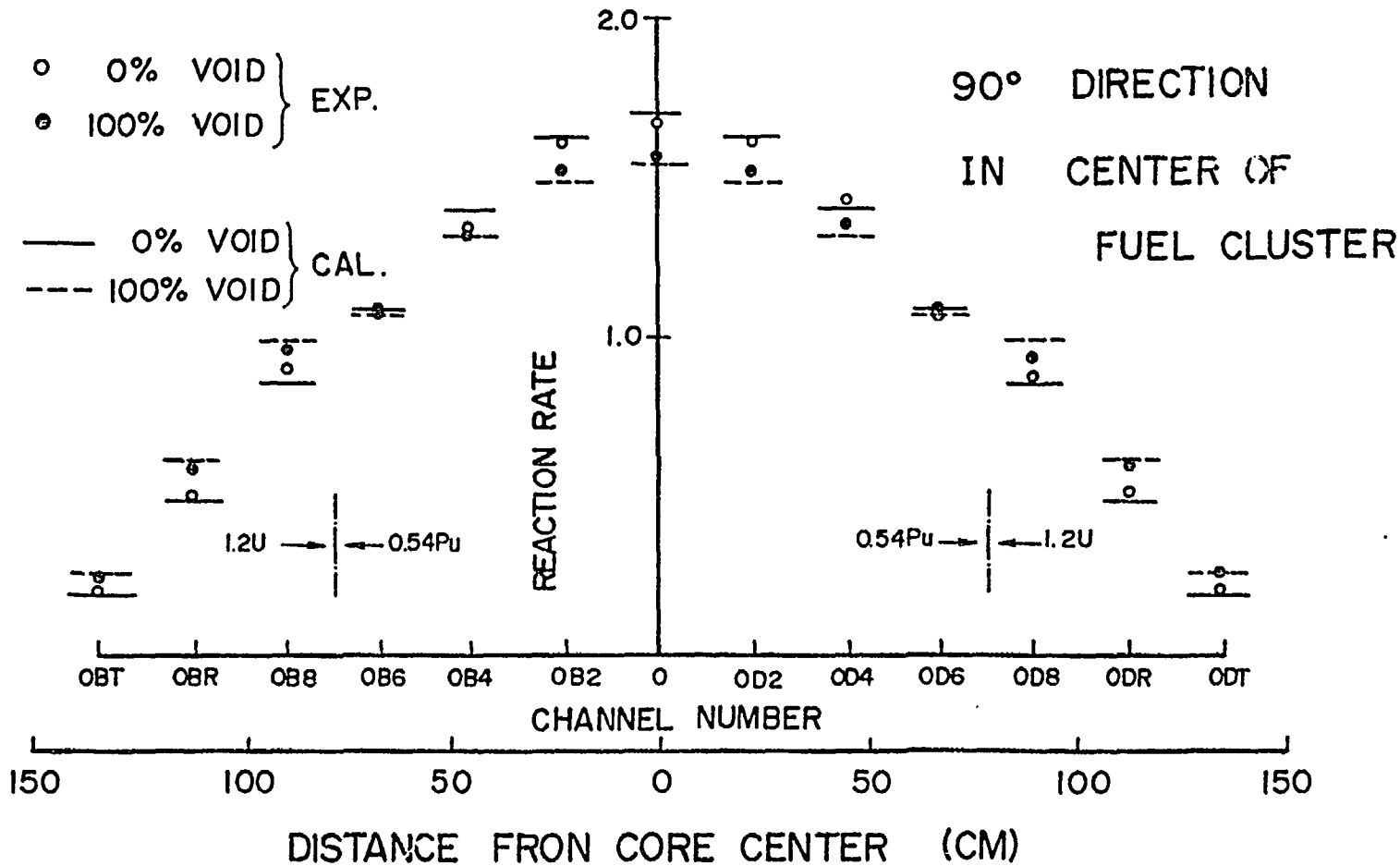


Fig.11. RADIAL Cu REACTION RATE DISTRIBUTION

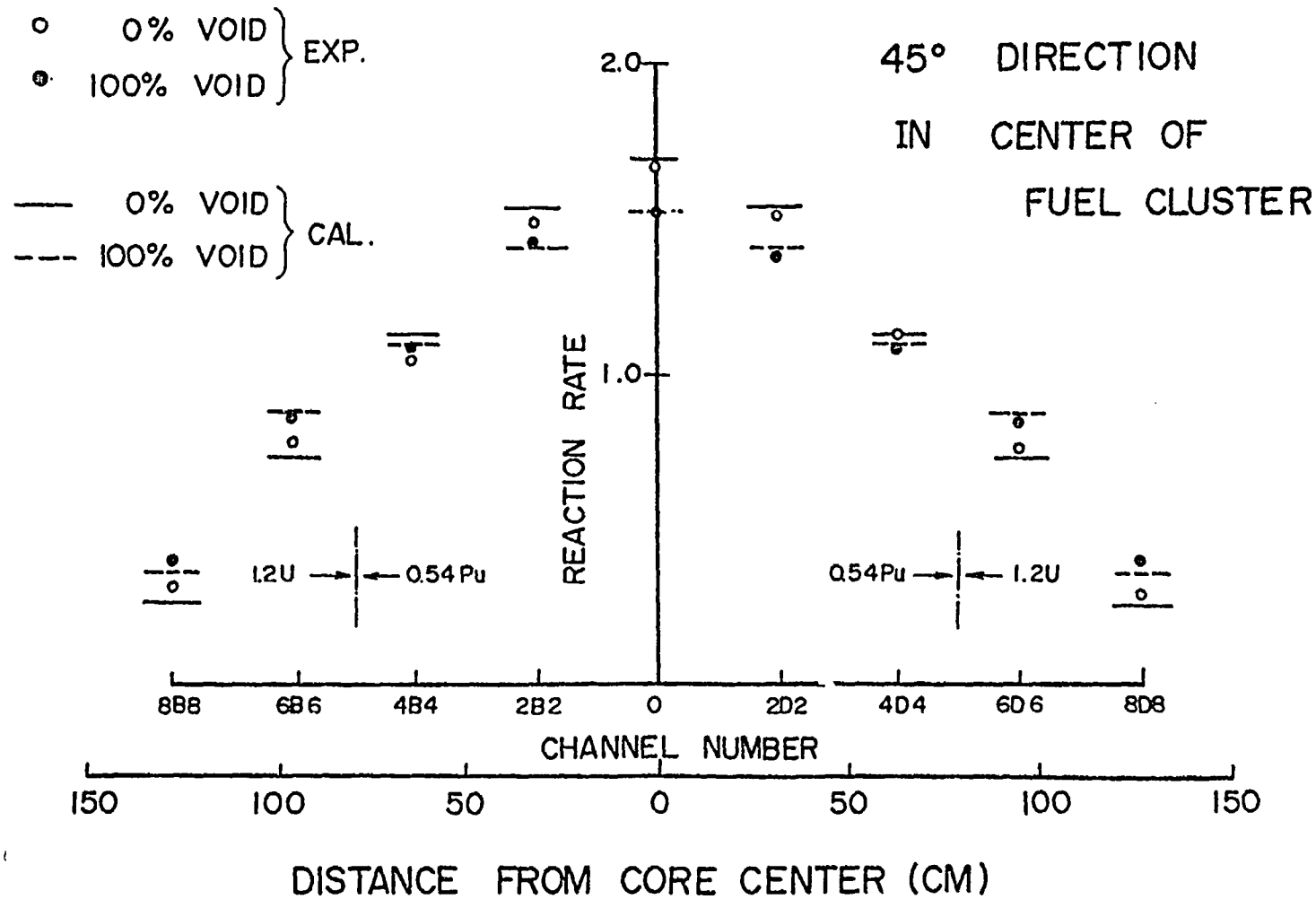


Fig.12. RADIAL Cu REACTION RATE DISTRIBUTION

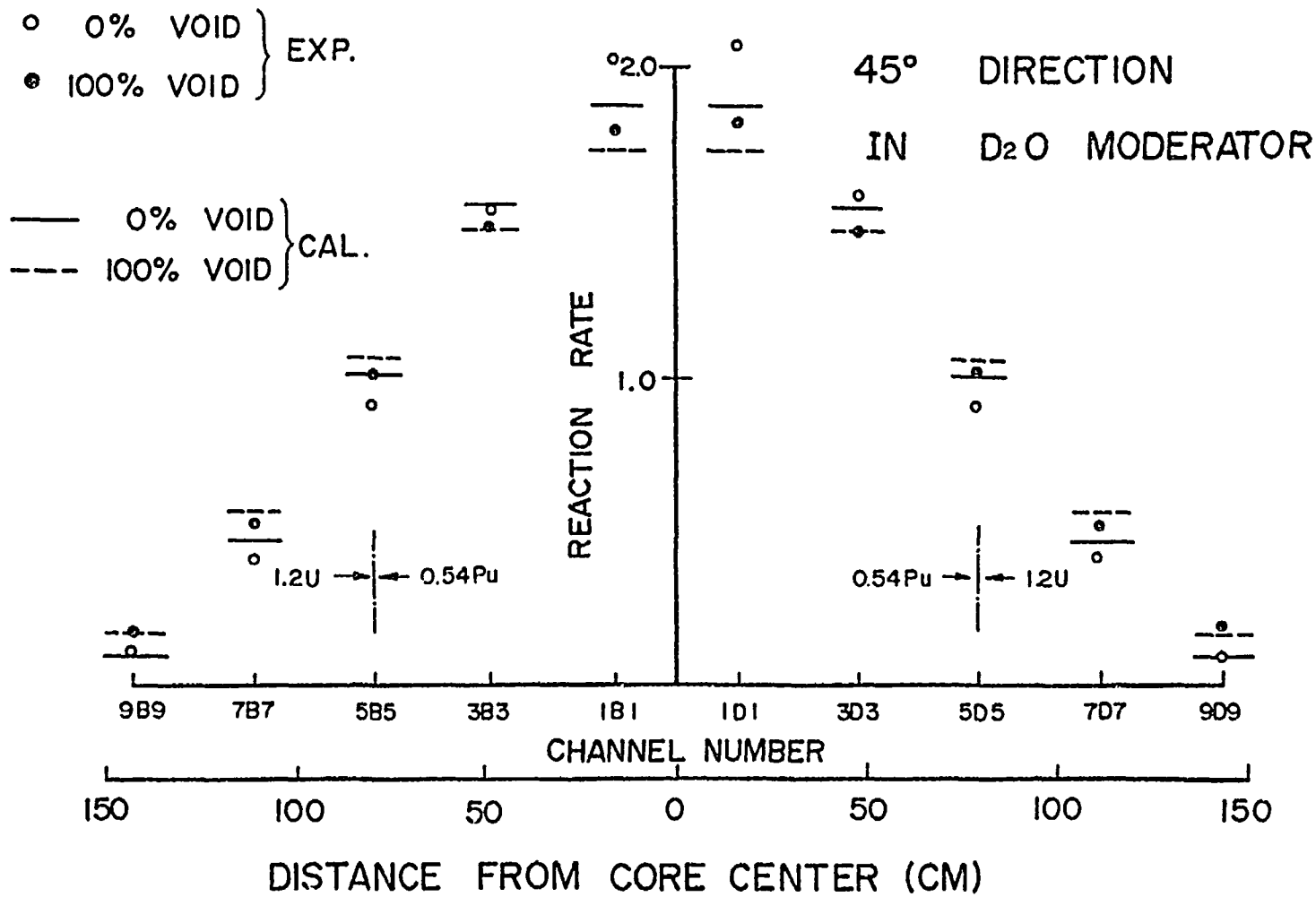


Fig.13. RADIAL Cu REACTION RATE DISTRIBUTION

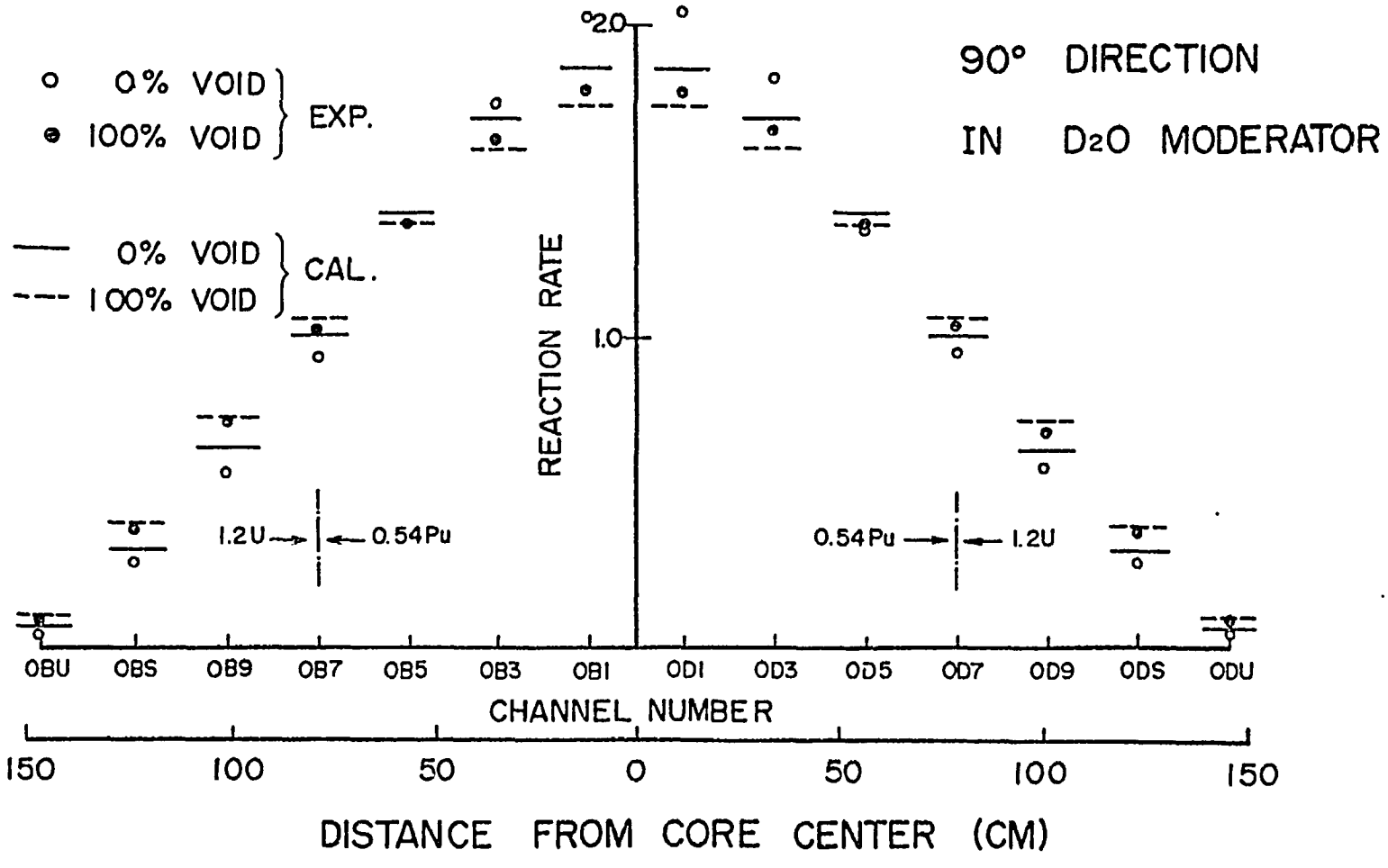
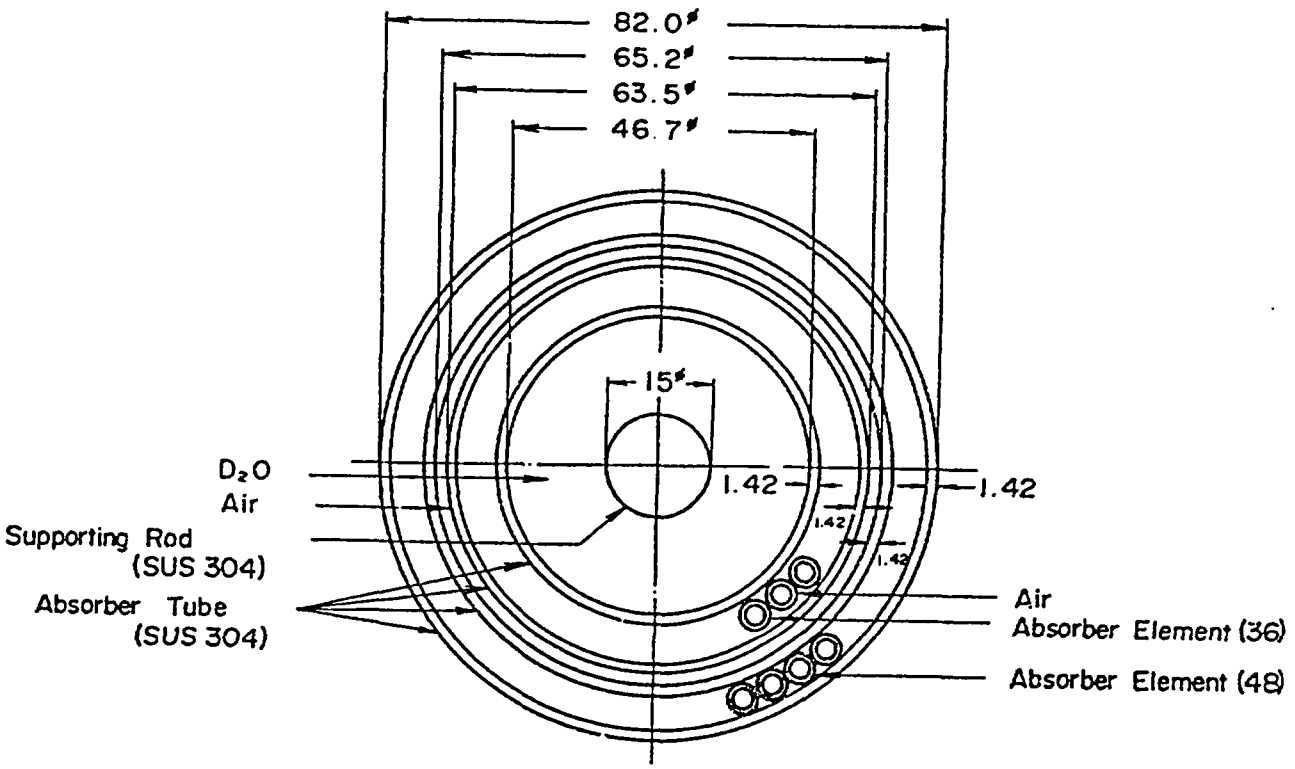


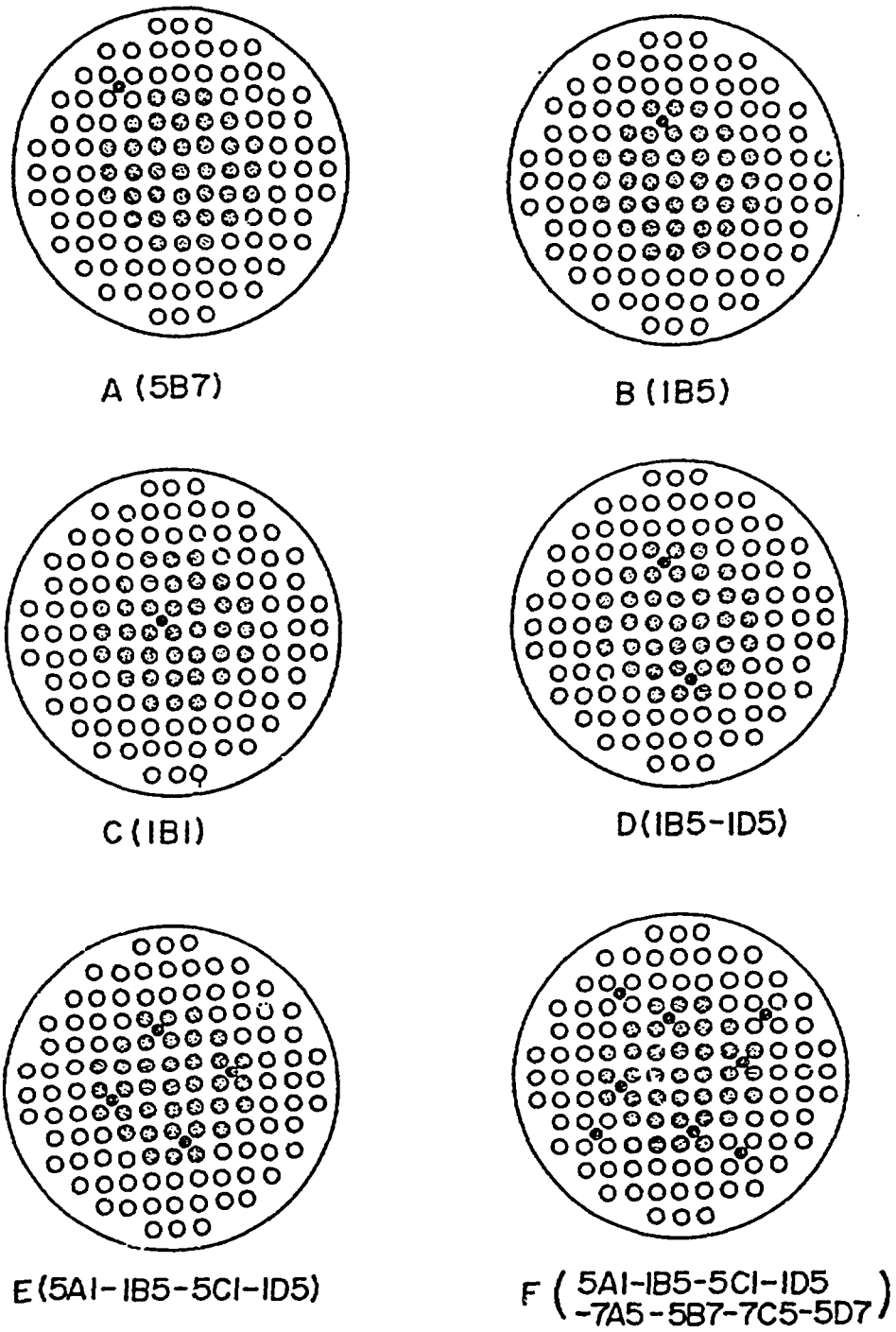
Fig. 14. RADIAL Cu REACTION RATE DISTRIBUTION



Absorber Element

Absorber		B_4C 34.8 ± 0.5g
Effective	Length	1975 mm
Density		70 % TD
Clad (SUS 304)		
Diameter		3.58mmID
Thickness		0.59mm
Length		1983mm

Fig.15. CROSS SECTIONAL VIEW OF CONTROL ROD



○ URANIUM OXIDE FUEL (84)

⊗ MIXED OXIDE FUEL (37)

● CONTROL ROD

Fig.16. INSERTING PATTERNS OF CONTROL RODS

Table 1 COMPARISON OF EXPERIMENTAL AND CALCULATED CONTROL-ROD REACTIVITY WORTH

VOID FRACTION	CONTROL ROD		EXPERIMENTAL VALUE	LOGARITHMIC BOUUDARY		ABSORPTION AREA	
	PATTERN	NUMBER	ρ_{ex} (\$)	ρ_{CAL} (\$)	Δ (%)	ρ_{CAL} (\$)	Δ (%)
0 %	A	1	-0.73± 0.03	-0.33	-10.8	-0.36	-2.7
	B	1	-1.32±0.08	-1.23	-6.8	-1.27	-3.8
	C	1	-2.61±0.16	-2.46	-5.7	-2.46	-5.7
	D	2	-2.90±0.18	-2.91	+0.3	-2.97	+2.4
	E	4	-7.01± 0.43	-6.67	-4.9	-6.67	-4.9
	F	8	-8.73±0.54	-8.42	-3.6	-8.57	-1.8
100 %	A	1	-0.57± 0.03	-0.50	-12.3	-0.56	-1.8
	B	1	-1.77±0.07	-1.42	-19.8	-1.50	-15.3
	C	1	-3.23± 0.12	-2.49	-22.9	-2.59	-19.8
	D	2	-4.16± 0.16	-3.30	-20.7	-3.47	-16.6
	E	4	-9.15± 0.35	-7.35	-19.7	-7.63	-16.6
	F	8	-12.24± 0.48	-10.12	-17.3	-10.70	-12.6

$$\Delta = \frac{|\rho_{cal}| - |\rho_{exp}|}{|\rho_{cal}|} \times 100$$

Appendix Core Parameter of DCA

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) 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
Gap	1.480	1.503	Helium	-
Fuel sheath	1.503	1.673	Aluminum alloy	2.674

Composition		w/o in fuel pellet	w/o in sheath	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
Sheath	Al		96.98	0.05788
	Mg		2.60	0.00172

(2) 0.54 w/o Enriched PuO_2 - UO_2 Fuel (Standard Grade)

	Inner dia (cm)	Outer dia (cm)	Material	Density (g/cm^3)
Fuel pellet	-	1.469	0.542 w/o enriched PuO_2-UO_2	10.17
Gap	1.469	1.506	Helium	-
Fuel sheath	1.506	1.668	Zry-2	6.523

Composition		w/o in Pu	w/o in fuel pellet	w/o in sheath	Atomic No. density ($10^{24}/cm^3$)
Pellet	^{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
Sheath	Zr			98.22	0.04218
	Sn			1.48	0.0004897
	Fe			0.14	0.0000985
	Cr			0.10	0.0000756
	Ni			0.06	0.0000401

Date of Analysis : 23 August 1971

(iii) Hanger Wire

No. in assembly	Pitch circle dia of hanger wire center (cm)	Outer dia (cm)	Material	Density (g/cm^3)
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	Outer dia (cm)	Thickness (cm)	Material	Density (g/cm^3)
2*	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

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

2. Fuel Channel

	Inner Dia (cm)	Outer Dia (cm)	Material	Density (g/cm3)
Pressure tube	11.68	12.08	Aluminum alloy	2.674
Air gap	12.08	15.25	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
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) 1.1078 g/cm^3

Material	w/o in Moderator	Density (g/cm^3)
D_2O	99.55	1.10834
H_2O	0.45	0.99777

Composition	w/o in D_2O	Atomic No. density ($g/cm^3 \times 10^{24}$)
H	0.05036	0.0003333
D	20.0223	0.06632
O	79.9283	0.03333

4. Coolant

Simulated void fraction (%)	w/o in Coolant				Density (g/cm^3)
	H_2O	D_2O	H_3BO_3	Air	
0	100				0.99777
30	63.17	36.82	0.00921	-	1.0359
70	18.07	81.91	0.0215		1.0866
86.7	0.45	99.55			1.1078
100				100	0.000001
Density (g/cm^3)	0.99777	1.10834	1.435	0.001205	

Composition	w/o in Coolant				
	0% void	30% void	70% void	86.7% void	100% void
H	11.1901	7.0693	2.0231	0.05036	
D		7.4055	16.4744	20.0223	
O	88.8099	85.5231	81.5001	79.9283	23.5204
^{10}B		0.0003158	0.000737		
B(Natural)		0.001611	0.003760		
N					76.4796

Composition	Atomic No. density ($10^{24}/cm^3$)				
	0% void	30% void	70% void	86.7% void	100% void
H	0.06671	0.04375	0.01313	0.0003333	
D		0.02294	0.05353	0.06632	
O	0.03335	0.03335	0.03334	0.03333	0.00001067
B (Natural)		0.0000009	0.0000023		
N					0.00003962

5. Others

(I) Temperature : $22^oC \approx 295^ok$
(II) Square lattice pitch : 22.5cm or 25.0cm
(III) Diameter of core tank : 300.5cm
(IV) No. of fuel channel (Standard core) : 121 for 22.5cm lattice pitch