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Heavy Water Critical Experiments on Plutonium Lattices (III)

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POWER REACTOR AND NUCLEAR FUEL DEVELOPMENT CORPORATION

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Heavy Water Critical Experiments on Plutonium Lattices (III)

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Abstract

Reactor physics studies on plutonium mixed oxide fuel lattices at 22.5- and 25.0-cm pitches have been made by use of the critical facility DCA in the Heavy Water Critical Experiment Section of PNC.

The following parameters are selected to study the dependence of nuclear characteristics on lattice pitch.

(i) Material Buckling

(ii) Coolant void reactivity

(iii) Local power distribution

(iv) Thermal-neutron flux distribution

The dependence of nuclear characteristics on the volume ratio between fuel and moiderator (Vm/Vf) in a highly heterogeneous cluster-type plutonium fuel lattice was made clear by a series of critical experiments.

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I. Introduction

A heavy-water moderated, light-water cooled, pressure tube FUGEN reactor[1] attained its initial critically in March, 1978. After many start-up tests, the FUGEN is in operation at rated power (165 MWe) from April, 1979.

The physics of the FUGEN reactor design is based on a large amount of accurate experiment of detailed physics parameters in the plutonium fuel lattices, because little was known about nuclear characteristics of the plutonium fuel assembly loaded in the core. The reactor design is also based on nuclear design code which was evaluated using these experiments.

Thus, a series of critical experiments on plutonium lattices have been carried out in Deuterium Critical Assembly. Since nuclear characterisitcs is sensitive to lattice pitch, various reactor physics parameters were measured in plutonium lattices ranging in pitch from 22.5 cm to 25.0 cm, with regard to the FUGEN's pitch i.e. 24.0 cm.

The experimental results of 0.54 wt% PuO_2-UO_2 and 0.87 wt% PuO_2-UO_2 fuel lattices at 22.5-cm pitch was already given in the previous paper[2].

The purpose of this paper is to describe the reactor physics on 25.0 cm-pitch lattice and to made the dependence of nuclear characteristics on lattice pitch clear in comparison with the results of 22.5 cm-pitch lattice. The following parameters are selected to investigate the dependence of nuclear characteristics on lattice pitch.

(i) Material buckling

(ii) Coolant void reactivity

(iii) Local power distribution

(iv) Thermal neutron flux distribution

II. Experimental Procedure

The dependence of the nuclear characteristics on lattice pitch was investigated in the lattices having 22.5- (Vm/Vf=7.57) and 25.0-cm (Vm/Vf=10.07) pitches in Deuterium Critical Assembly. The core configurations of 22.5- and 25.0-cm pitch lattices are shown Fig. 1 and 2. The dimensions and compositions of the present experimental lattices are listed in Table I. Fugre 3 shows the 28-pin fuel assembly.

(1) Material buckling[3),4),5)]

Material bucklings of 0.54 wt% and 0.87 wt% PuO_2-UO_2 fueled lattices were measured by the substitution method. The specifications of each fuel are listed in Table II. In the substitution measurements, the central part of the one-region reference loading was progressively replaced by test clusters of plutonium fuel, and the resultant critical D_2O heights were measured as a function of the number of substituted fuel clusters. The various test regions that were used comprosed 1, 4, 5, 9, 13, 21 and 25 fuel clusters. Axial bucklings were determined from critical D_2O heights and axial extrapolation distances were measured by the copper activation method in one-region reference core loaded with 1.2 wt% UO_2. The change of axial buckling caused by substitution was analyzed by the formula derived from the second order perturbation theory.

(2) Coolant void reactivity[4),6),7),8)]

Reactivity caused by loss-of-coolant was measured in various two-region cores loaded with 1.2 wt% UO_2 and 0.87

wt% PuO_2-UO_2 clusters. In the two-regions cores, 0.87 wt% PuO_2-UO_2 clusters loaded were progressively increased up to 25 clusters, as shown in Fig.4. The plutonium fuel clusters were symmetrically loaded with respect to the core axis. For measurements of the reactivity, a Cockcroft-Walton type neutron generator was used to carry out pulsed-neutron experiments. The decay constants of neutron density were converted to reactivity in dollars by the Simmons and King method. When evaluating void reactivities from measured prompt decay constants, corrections were made to the neutron generation time of a large subcritical system, and they accounted for up to 5 % maximum.

(3) Local power distribution[9)]

Dependence of local power distribution on lattice pitch was investigated by using the differently enriched fuel cluster. The cluster consists of 0.87 wt% PuO_2-UO_2 fuel pins for the inner and intermediate fuel layers, and 0.54 wt% PuO_2-UO_2 fuel pins for the outer layer, as shown in Fig. 5. The local power distributions were determined from the γ-ray activities of ^{140}La which were counted by a 2-in-diam x 2-in-thick NaI(Tl) scintillator.

(4) Thermal neutron flux distirbution[10),11)]

Thermal-neutron flux distributions in 0.54 wt% PuO_2-UO_2 fuel lattices were measured by a 0.1-mm-thick dysprosium-aluminum alloy(4.0 wt% dysprosium) foils set in the central unit cell as shown in Fig. 1 and 2. Measurement positions of foils are shown in Fig. 6. They are within the plutonium fuel pins, in the coolant, on both inside and

outside surfaces of the pressure tube and the calandria tube, and in the D_2O-moderator. For measurements within the plutonium fuel pins, four 14.8-mm-diam foils were set in positions of F-1, F-2, F-3 and F-3' shown in Fig. 6. The foil arrangement within the plutonium fuel pin is shown in Fig. 7. The dysprosium reaction rates at the surface of the pressure and calandria tubes, and in the D_2O-moderator region were measured with 7-mm-diam foils. For measurements in coolant region, a 0.1-mm-thick sector foil was used as shown in hatched section in Fig. 6.
The dysprosium activities were counted by a 2-in.-diam x 1/8-in.-thick CaF(Eu) scintillator.

III. Results and Discussion

(1) Material buckling

Experimental results of material buckling are listed in Table III. Also, these results are illustrated in Fig. 8 as a function of lattice pitch.

The material bucklings for zero coolant void fraction are larger in both 0.54 wt% and 0.87 wt% PuO_2-UO_2 fuel lattices at 22.5 cm pitch than in those at 25.0 cm pitch. The material bucklings increase at 0 % void fraction with the expansion of lattice pitch but decrease at 100 % void fracions.

This tendency can be explained as follow. In the air-filled lattices, the expansion of lattice pitch increases thermal neutrons because moderator material increases, and it decreases neutron leakage because fraction of volume occupied by voided coolant decreases with increase in moderator region.

In the H_2O-filled lattices, increase in D_2O moderator region intensifies absorption effect of H_2O coolant compared with slowing down effect, because neutrons are sufficiently thermalised by enough D_2O moderator in the lattice of the larger pitch.

(2) Coolant void reactivity

The dependence of coolant void reactivity on lattice pitch are shown in Table IV, and Fig. 9 as a function of statistical weight of the plutonium fueled region. Figure 10 shows the relation between number of substituted plutonium fueled clusters and statistical weight of the region occupied by them.

When the lattice pitch extends from 22.5 cm to 25.0 cm, coolant void reactivity markedly shiftes to the positive side. Furthermore, this shift of coolant void reacitivity to the positive side is gradually enhanced by increase of statistical weight (i.e., increase of the number of plutonium fuel assemblies.)

(3) Local power distribution

Measured local power distributions are shown in Table V and Fig. 8.

As seen in Fig. 8, the local power peaking factor of 25.0 cm pitch lattice is at 0% void fraction larger than that of 22.5 cm pitch lattice. However, the tendency of local power peaking is contrary at 100% void fraction.

The tendency at 0% void fraction can be explained as the depression of thermal-neutron flux in the fuel cluster increases by softening of thermal-neutron spectrum due to an increase in the region of D_2O moderator, which results in decreasing the fission rate in the inner fuel pins (i.e, increasing the local power peaking factor). On the other hand, the tendency at 100% void fraction can be explained as follows. Since absorption cross section of ^{239}Pu has a large resonance at 0.3 eV, neutrons with energy of around 0.3 eV which come from moderator region are strongly and selectively absorbed at the outermost fuel ring. Then, neutrons having passed though the outermost fuel ring have energy spectrum with a dip around 0.3 eV. Consequently, neutron absorption in the inner fuel rings occurs predominantly

in the low thermal energy region where the absorption cross section of ^{239}Pu essentially obeys 1/v -low. As a result, fission reaction rate in the inner rings increases with softening of thermal-neutron energy spectrum due to expansion of lattice pitch.

For the above case of 0% void fraction, this dip around 0.3 eV in the thermal energy spectrum is considered to be easily recovered by the rather large up and down scattering power of the H_2O coolant.

(4) Thermal flux distribution

Figure 12 and 13 show the dysprosium reaction rate distribution in the unit cells of 0.54-wt% PuO_2-UO_2 fuel lattices at 22.5- and 25.0-cm pitch, and 0 % void fraction. Also, the dependence of the thermal neutron flux on lattice pitch is shown in Fig. 14. The depression of the thermal-neutron flux is appreciably larger in the fuel region of the 25.0-cm-pitch lattice than in that of the 22.5-cm pitch (lattice. It is considered that this tendency originates in the increase in neutron absorption in the fuel by softening of the thermal neutron spectum due to an increase in the region of the D_2O moderator. The thermal neutron spectrum calculated the by code LAMP-DCA, as seen in Fig. 15 indicates a softer neutron spectrum in the larger 25.0-cm pitch lattice.

In the D_2O moderator, when the lattice pitch is extended from 22.5 to 25.0 cm, the thermal neutron flux distributions apparantly become higher at the cell boundary, as seen in Fig. 16. This tendency is accounted for by the increase of the slowing down effect in the D_2O moderator region.

The same tendencies were also observed in the experiment with UO_2 lattice[12].

IV. General Conclusion

The dependence of nuclear characteristics on lattice pitch in a highly heterogeneous cluster-type plutonium fuel lattice was made clear by a series of critical experiments on plutonium fuel at 22.5- and 25.0-cm.

In addition to the present studies for material buckling, coolant void reactivity, local power peaking and thermal neutron flux distribution, studies of lattice parameters and moderator temperature coefficient have been performed at these lattice pitches. Also, analysis of the experimental data have been made by the use of WIMS, METHUSELAH-II and MESSIAH code.

The results are used to continually modify and improve the design code of FUGEN, and to reduce in design margins for design of the FUGEN-HWR.

Acnowledgements

The authors are indebted to the operating staff of DCA for teir help in the experiments. We would like to thank Mr.Miyawaki for his support in this series of experiments.

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Table I

Lattice Dimensions and Compositions

Cluster			
	Radius of Each Layer	1 st	13.13 mm
		2 nd	30.00 mm
		3 rd	47.58 mm
	Hanger Wire	Diameter	2.0 mm
		Material	AL
	Spacer	Diameter	114.4 mm
		Material	AL
	Cluster Length		2223 mm
	Standard Fuel Meat Length		2000 mm
Pressure Tube			
	Outer Diameter		121.0 mm
	Inner Diameter		116.8 mm
	Material		AL
Calandria Tube			
	Outer Diameter		136.5 mm
	Inner Diameter		132.5 mm
	Material		AL
Moderator			
	Material		D_2O
	Purity		99.5 mol%
Core Tank			
	Outer Diameter		3025 mm
	Inner Diameter		3005 mm
	Height		3500 mm
	Material		AL
Lattice Pitch			22.5cm or 25.0cm (Square Lattice)
Upper and Lower Grid Plate			
	Material		AL
Temperature			20°C

Table II Dimensions and Compositions of Fuel Pellet

Fuel	0.54 w/o PuO_2 - UO_2	0.87 w/o PuO_2 - UO_2
Fuel Pellet		
Outer Dia.(cm)	1.47	1.47
Density (g/cc)	10.17	10.17
Isotope (w/o)		
U-235	0.6214	0.6194
U-238	86.782	86.503
Pu-238	0.000102	0.000145
Pu-239	0.4304	0.6849
Pu-240	0.04115	0.06584
Pu-241	0.004359	0.006960
Pu-242	0.000303	0.000510
O-16	12.12	12.12

Table III Dependence of Material Buckling on Lattice Pitch

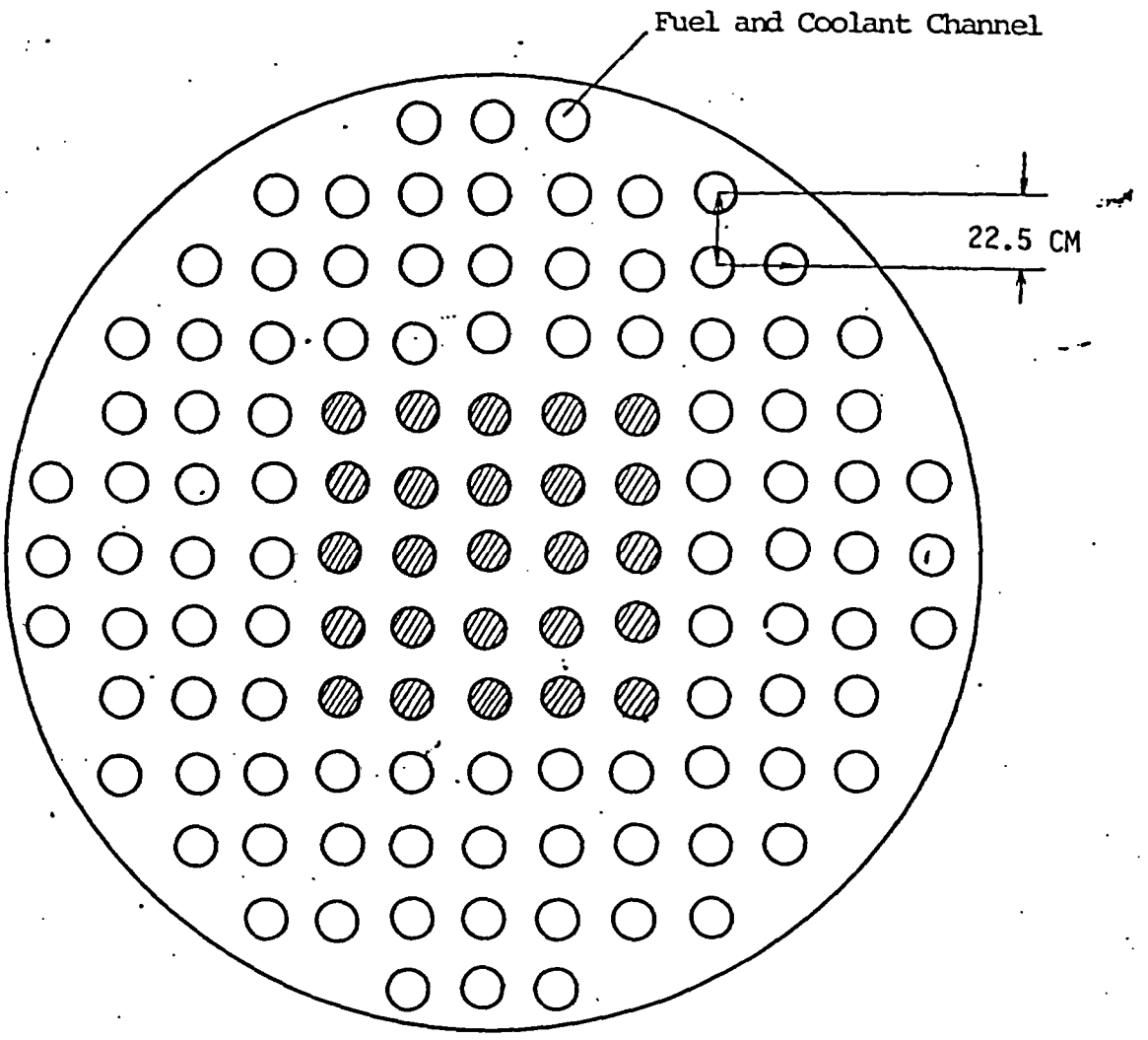
Test Fuel	Coolant Void Fraction (%)	Material Buckling (m^{-2})	
		Lattice Pitch 22.5 cm	Lattice Pitch 25.0 cm
0.54 wt% (s)	0	14.89 ± 0.15	13.03 ± 0.12
PuO_2-UO_2	100	10.52 ± 0.09	11.80 ± 0.10
0.87 wt% (s)	0	19.78 ± 0.11	17.51 ± 0.17
PuO_2-UO_2	100	13.56 ± 0.09	14.65 ± 0.09

Table IV Void Reactivity in Loss of Coolant

Loaded Fuel	Lattice Pitch (cm)	Number of Substituted Fuel	Statistical Weight of PuO_2-UO_2 Fueled Region	Loss-of-Coolant Reactivity ($)
0.87 wt% (s) PuO_2-UO_2 & 1.2 wt% UO_2	22.5	1	0.03	-7.82 ± 0.44
		5	0.12	-10.52 ± 0.57
		9	0.20	-13.75 ± 0.70
		13	0.28	-16.09 ± 1.00
		21	0.43	-19.79 ± 1.40
		25	0.48	-21.54 ± 1.13
	25.0	1	0.03	-0.98 ± 0.20
		5	0.15	-3.22 ± 0.42
		9	0.26	-5.65 ± 0.62
		13	0.36	-7.28 ± 0.73
		21	0.53	-10.28 ± 0.99
		25	0.59	-10.96 ± 1.05

Table V Dependence of Local Power Distribution on Lattice Pitch

Fuel	Lattice Pitch	Void Fraction	1st Ring	2nd Ring	3rd Ring (Local Peaking Factor)
Different Enriched Fuel	22.5 cm	0 %	0.707 ± 0.004	0.931 ± 0.005	1.108 ± 0.003
		100 %	0.827 ± 0.004	0.948 ± 0.005	1.070 ± 0.003
Different Enriched Fuel	25.0 cm	0 %	0.672 ± 0.008	0.906 ± 0.005	1.129 ± 0.003
		100 %	0.859 ± 0.013	0.991 ± 0.010	1.039 ± 0.007

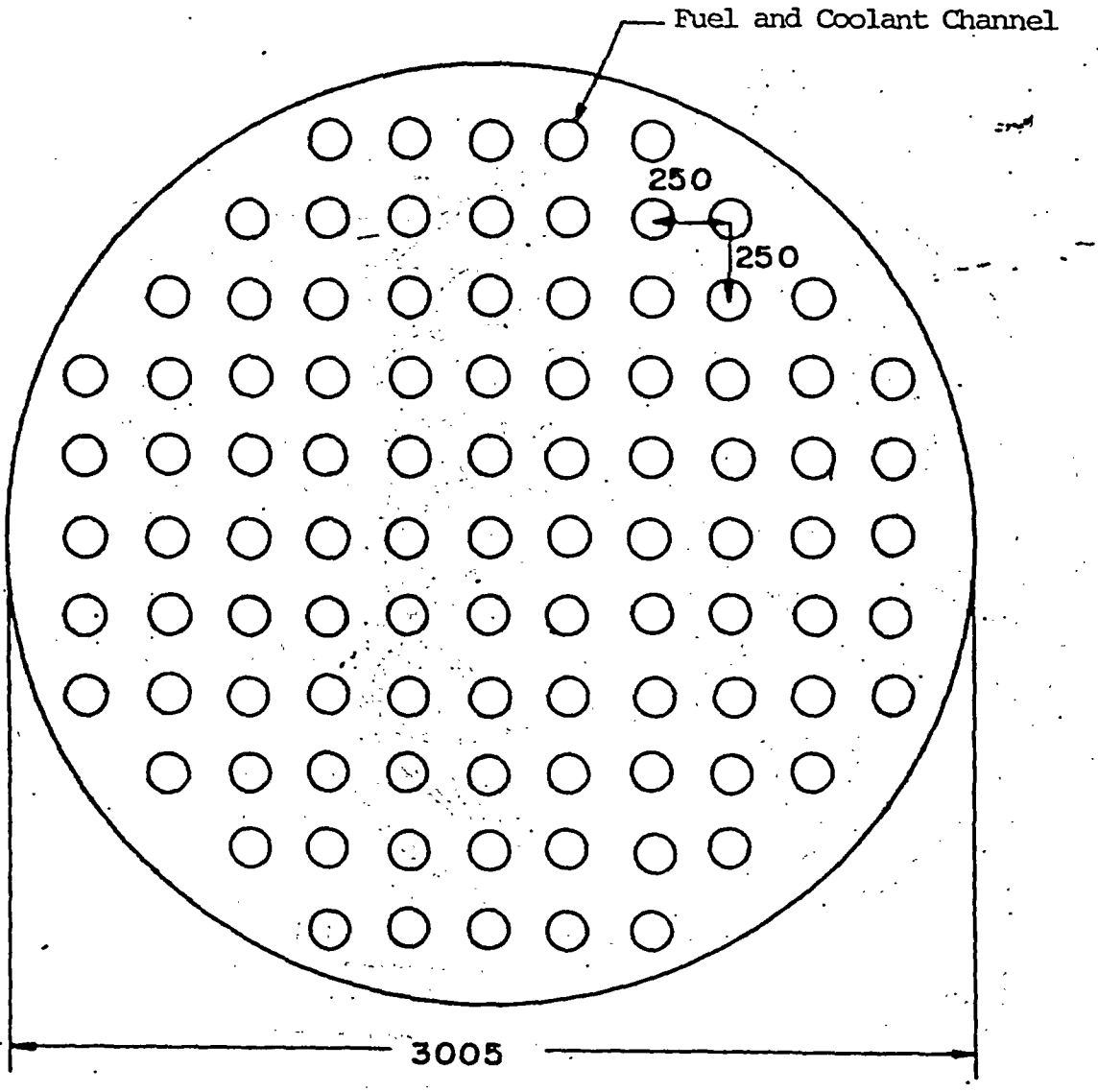


Total Number of Fuel Cluster: 121

Plutonium Fuel Assembly

Uranium Fuel Assembly

Fig. 1 Configuration of DCA Lattice having 22.5-cm Pitch



Total Number of Fuel Clusters: 97

Fig. 2 Configuration of DCA Lattice having 25-cm Pitch

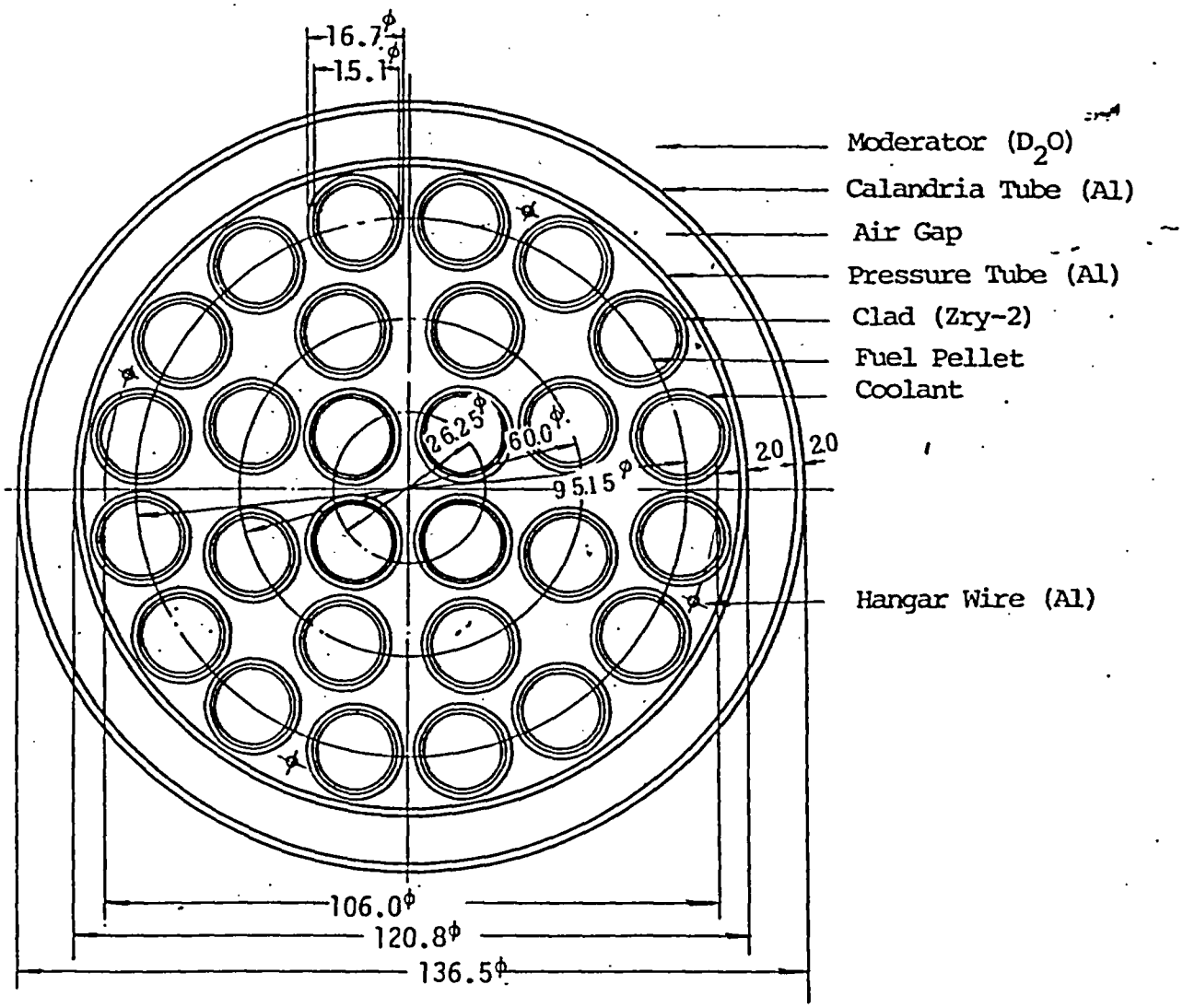


Fig. 3 Configuration of Fuel Assembly

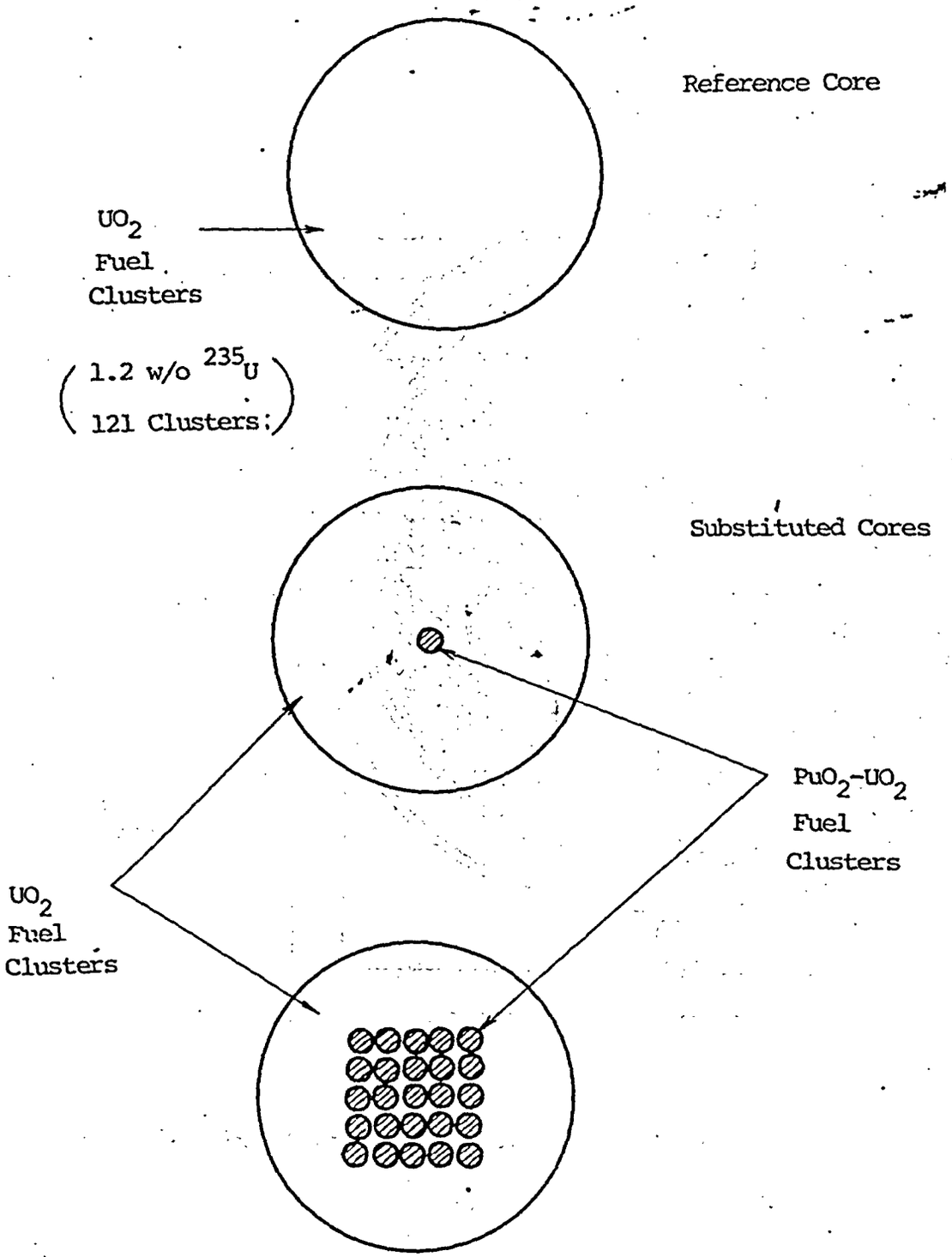


Fig. 4 Progressive Substitution Experiment

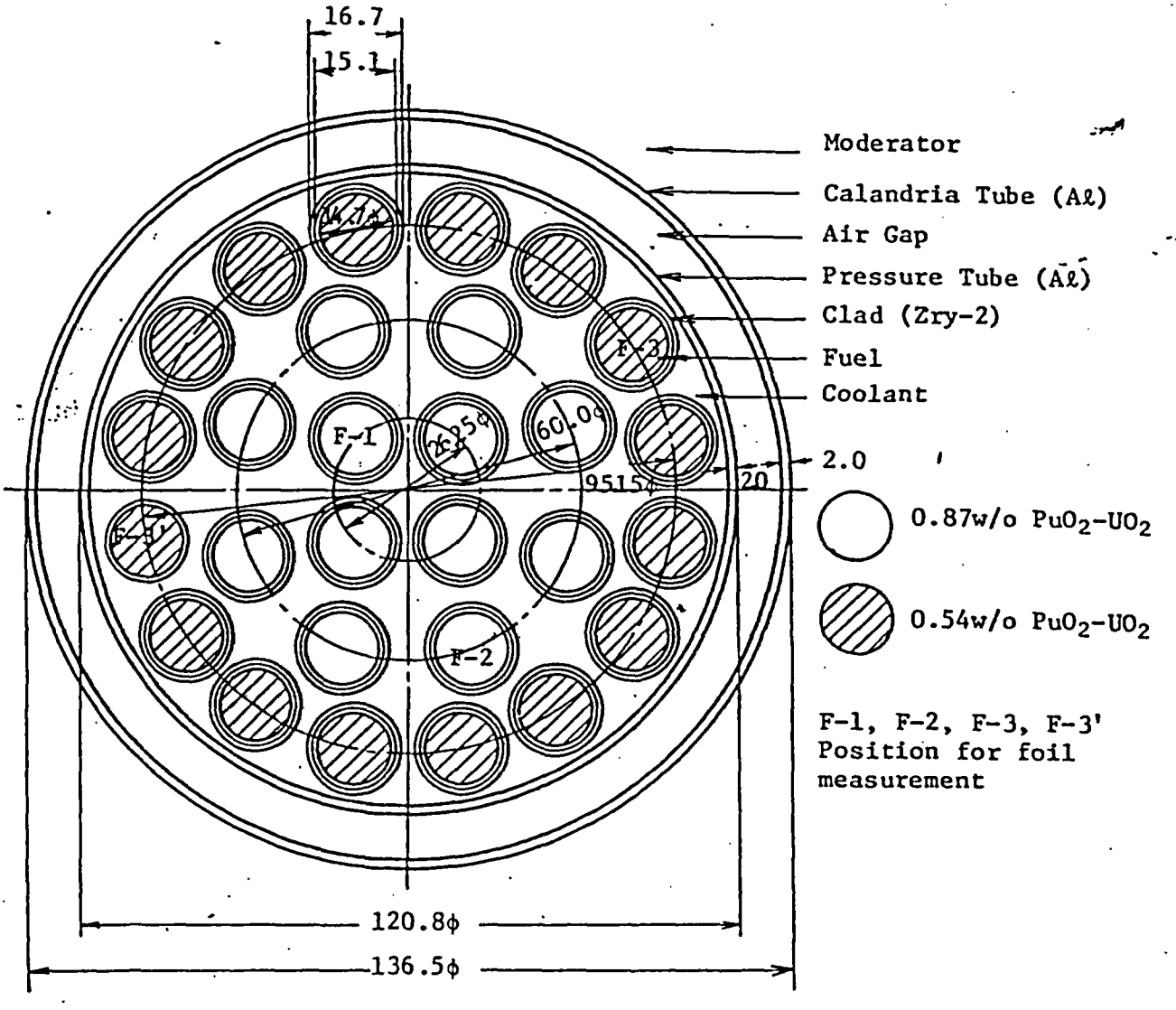


Fig. 5 Cross Sectional View of 0.54 & 0.87 wt% PuO_2-UO_2 Mixed Fuel Cluster

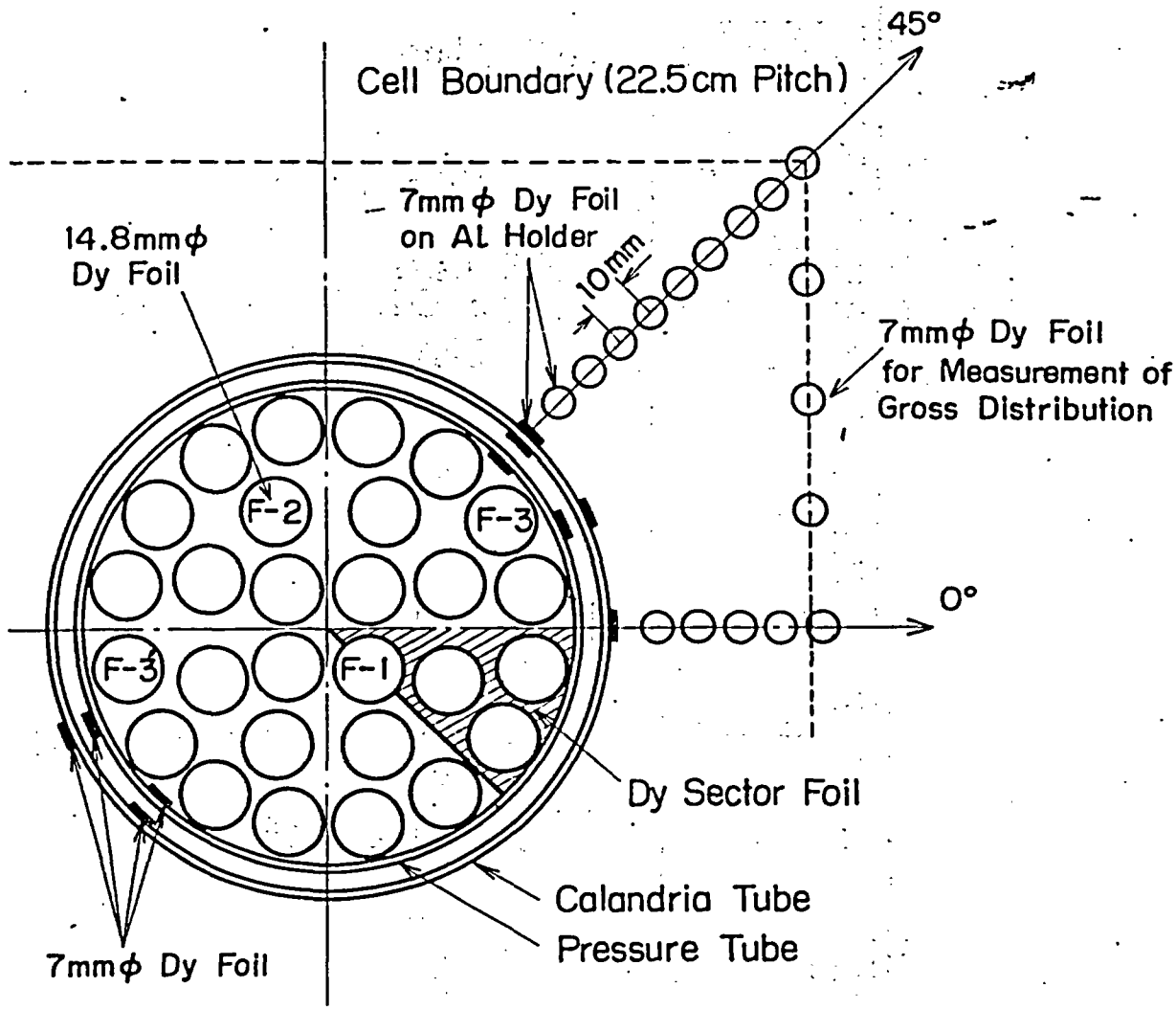


Fig. 6 Arrangement of Dysprosium Foils in Central Unit Cell

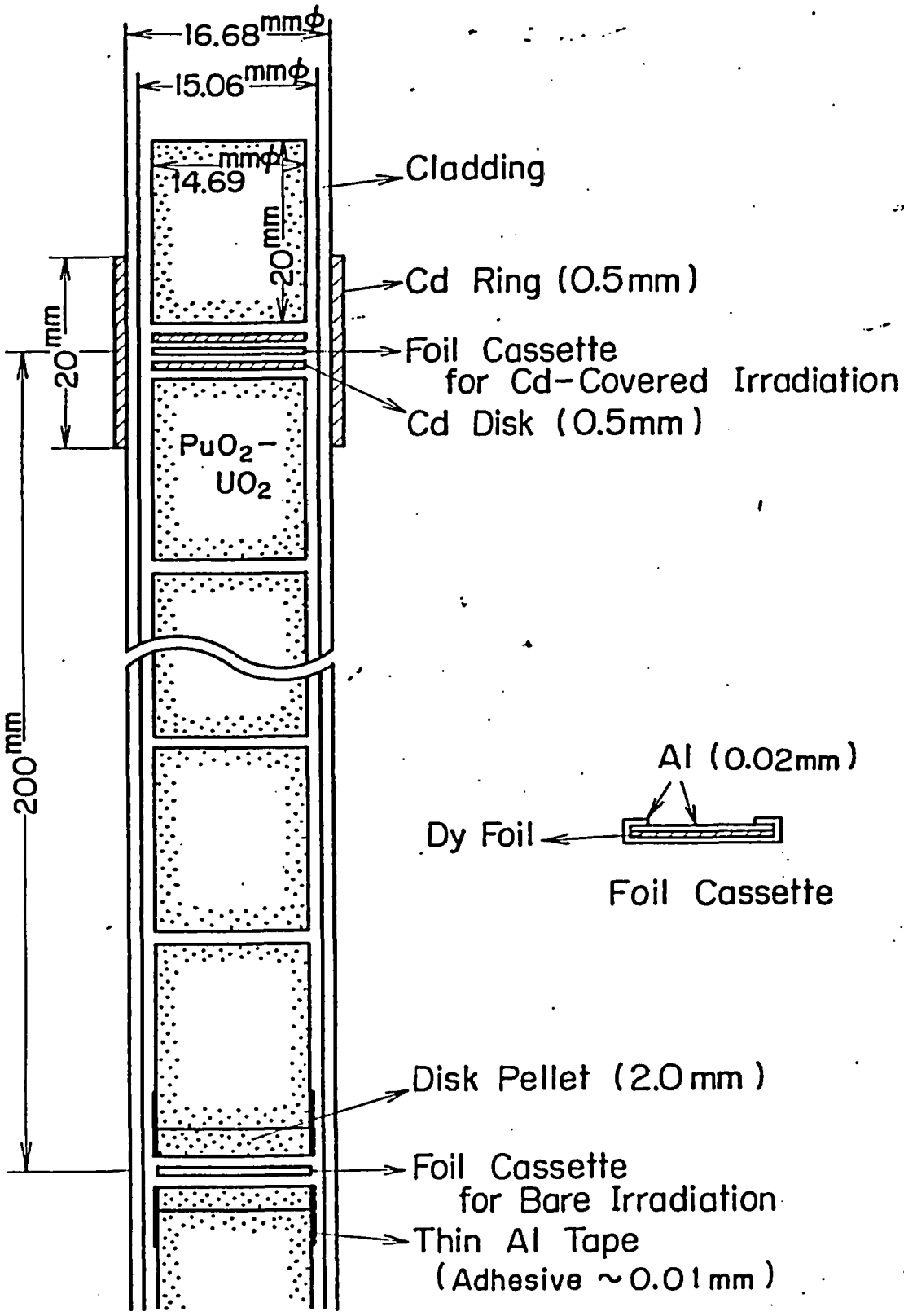


Fig. 7 Foil Arrangement in PuO_2-UO_2 Fuel Pin

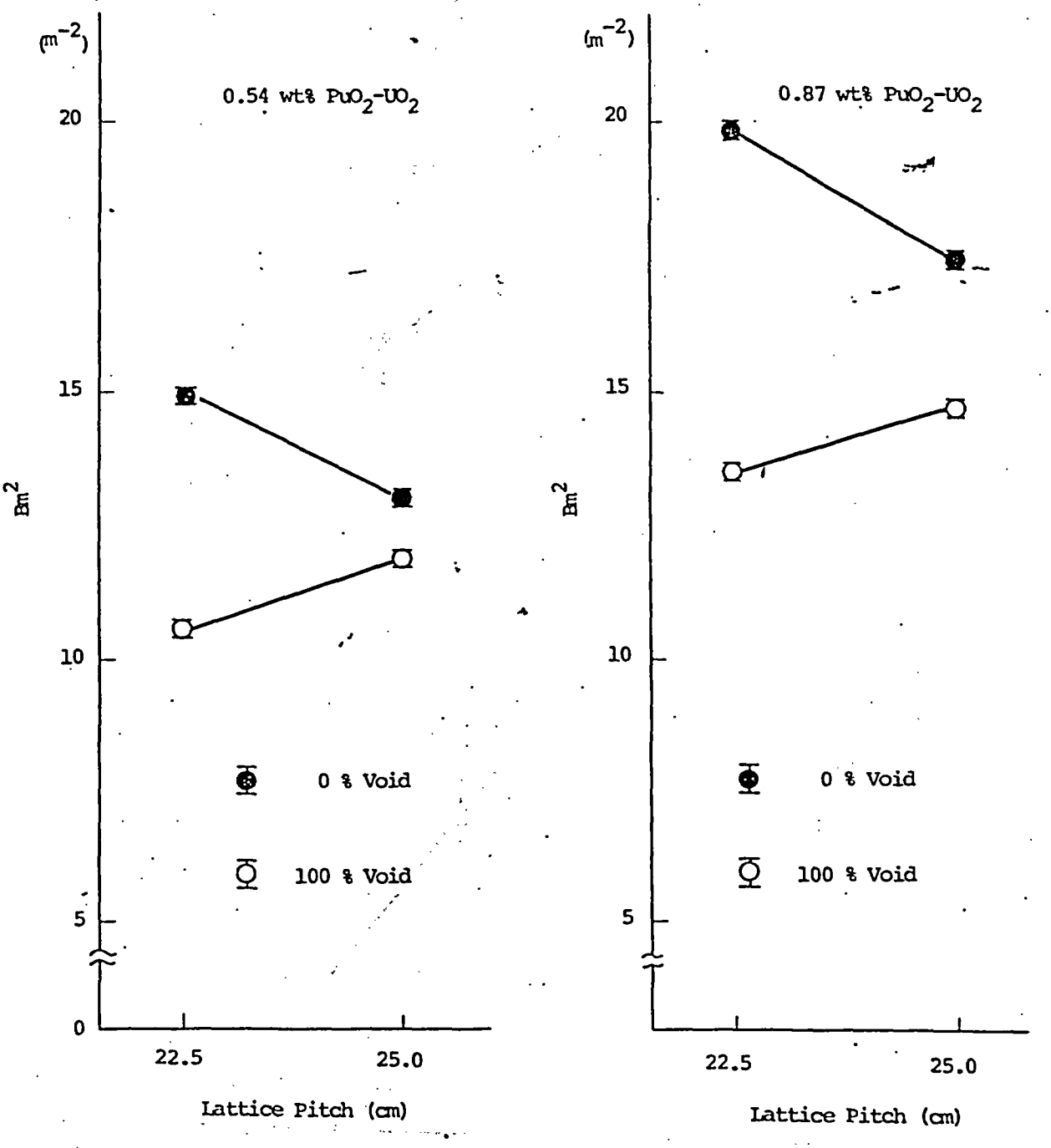


Fig. 8 Dependence of Bm^2 on Lattice Pitch

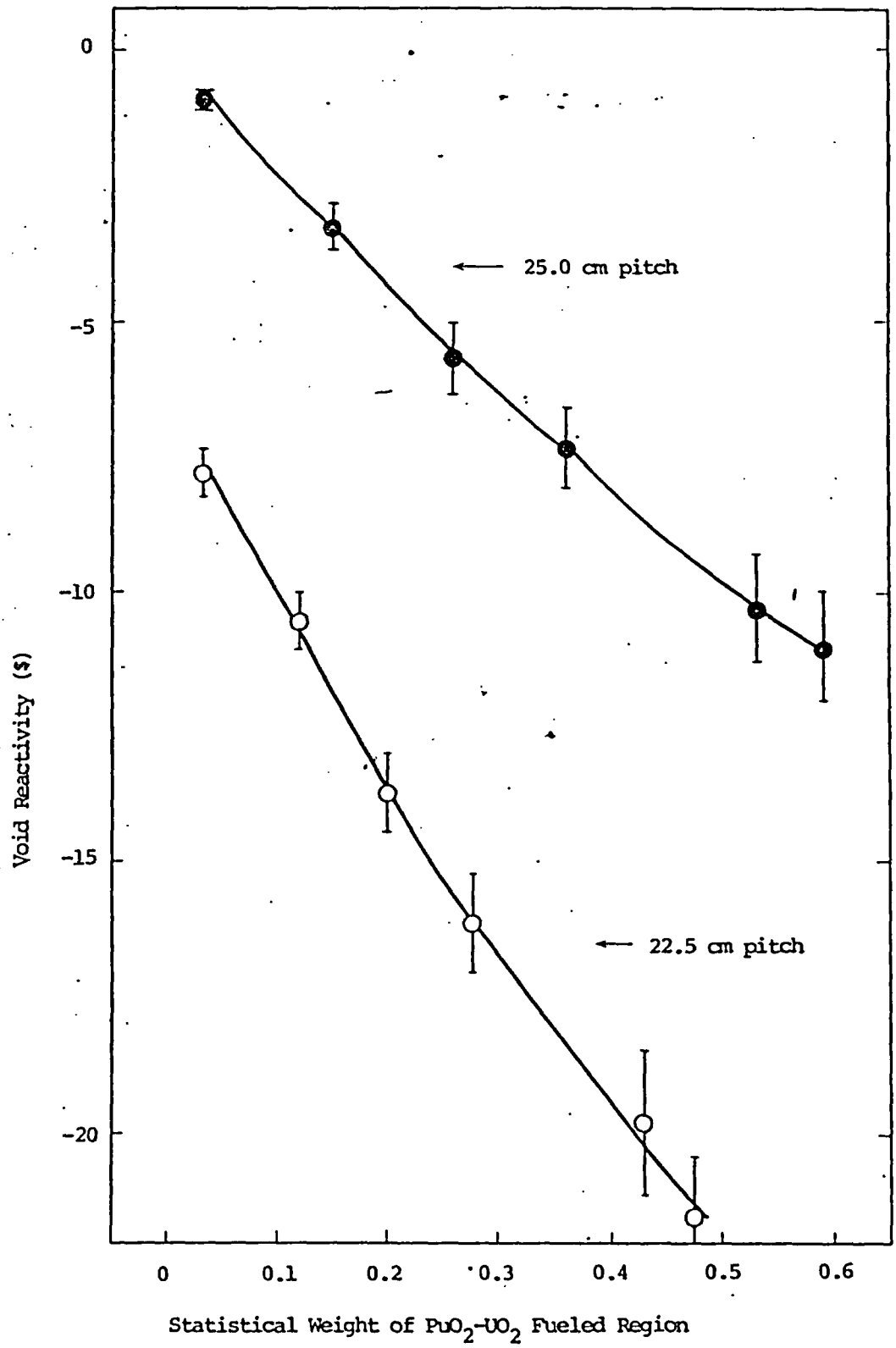


Fig. 9 Change in Loss-of-coolant as a Function of Statistical Weight of PuO_2-UO_2 Fueled Region

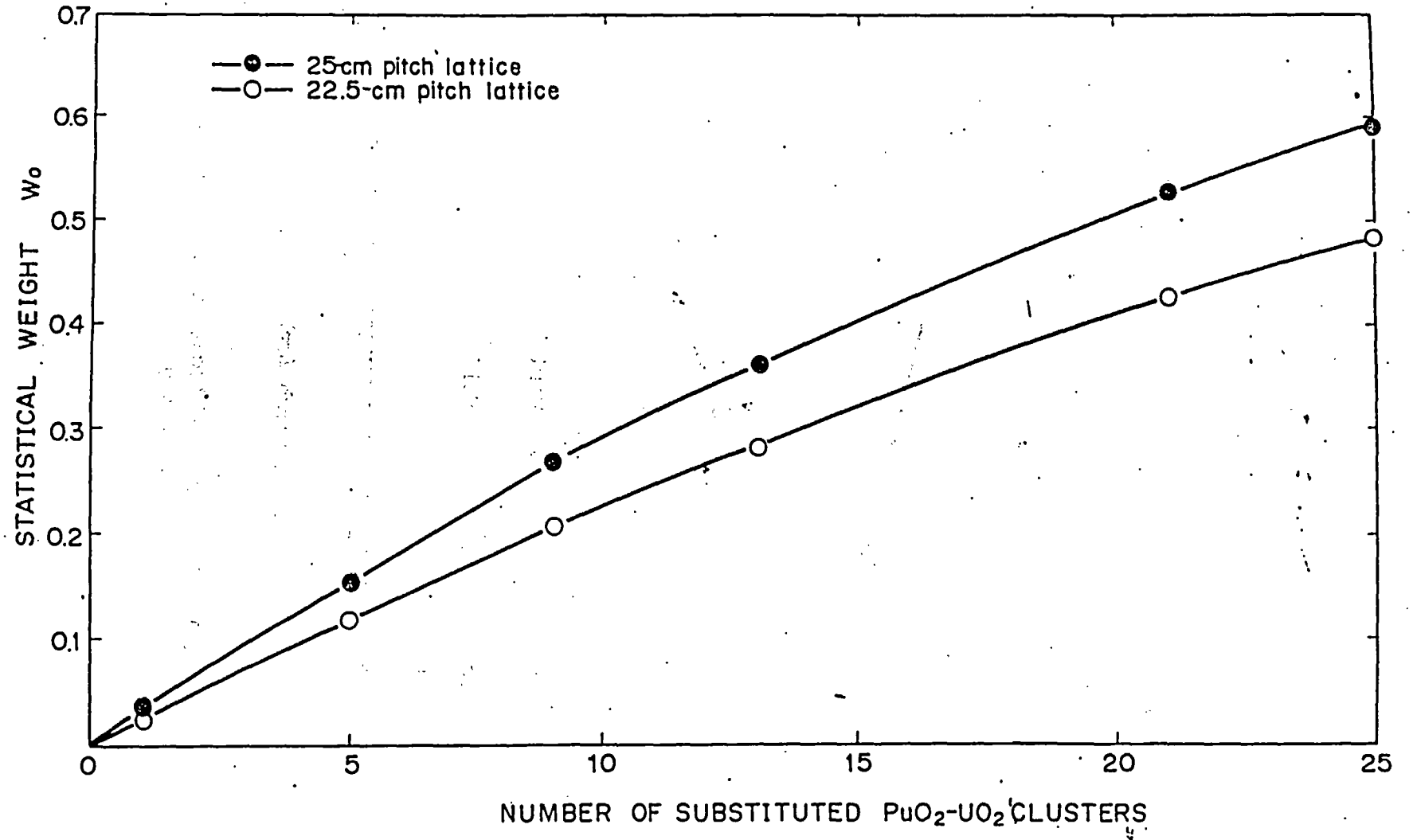


Fig. 10 Relation Between Number of Substituted PuO_2-UO_2 Clusters and Statistical Weight of PuO_2-UO_2 Fueled Region

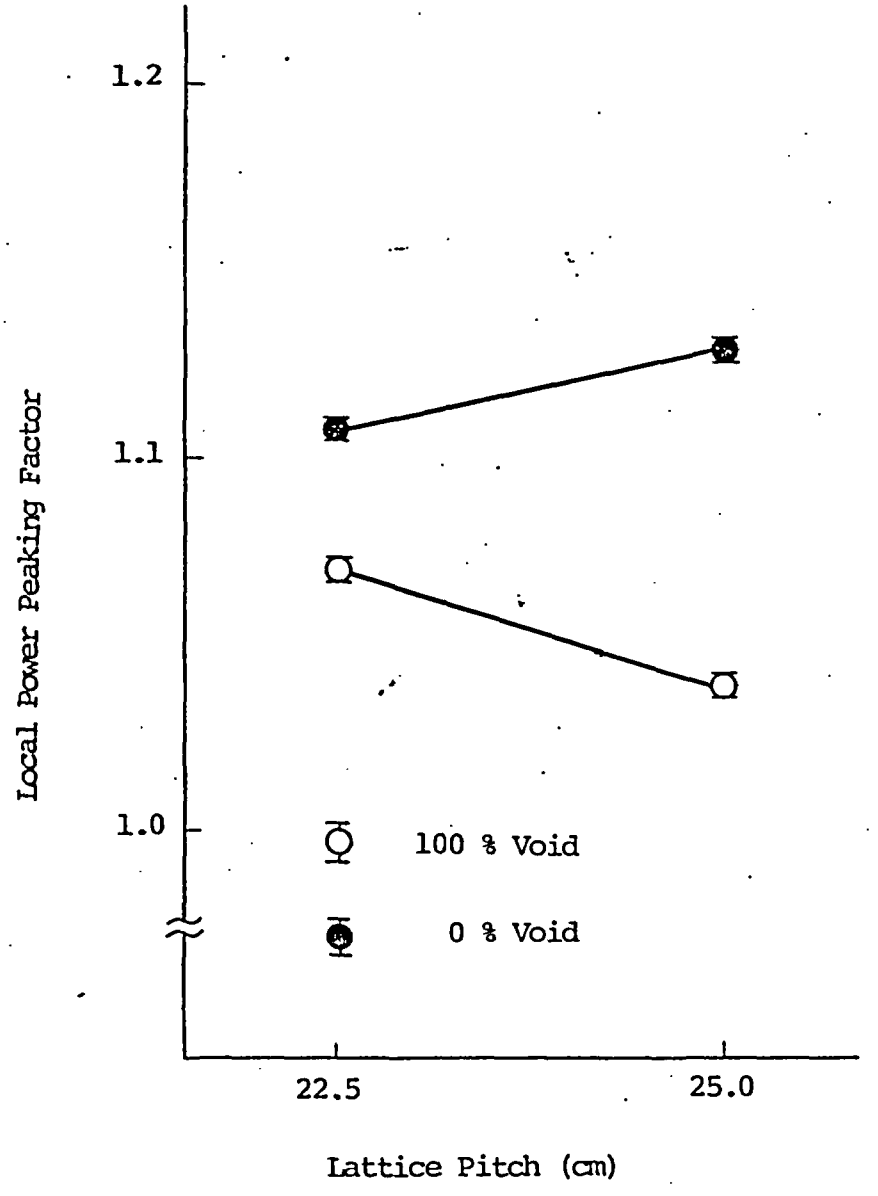


Fig. 11 Dependence of Local Power Peaking Factor on Lattice Pitch

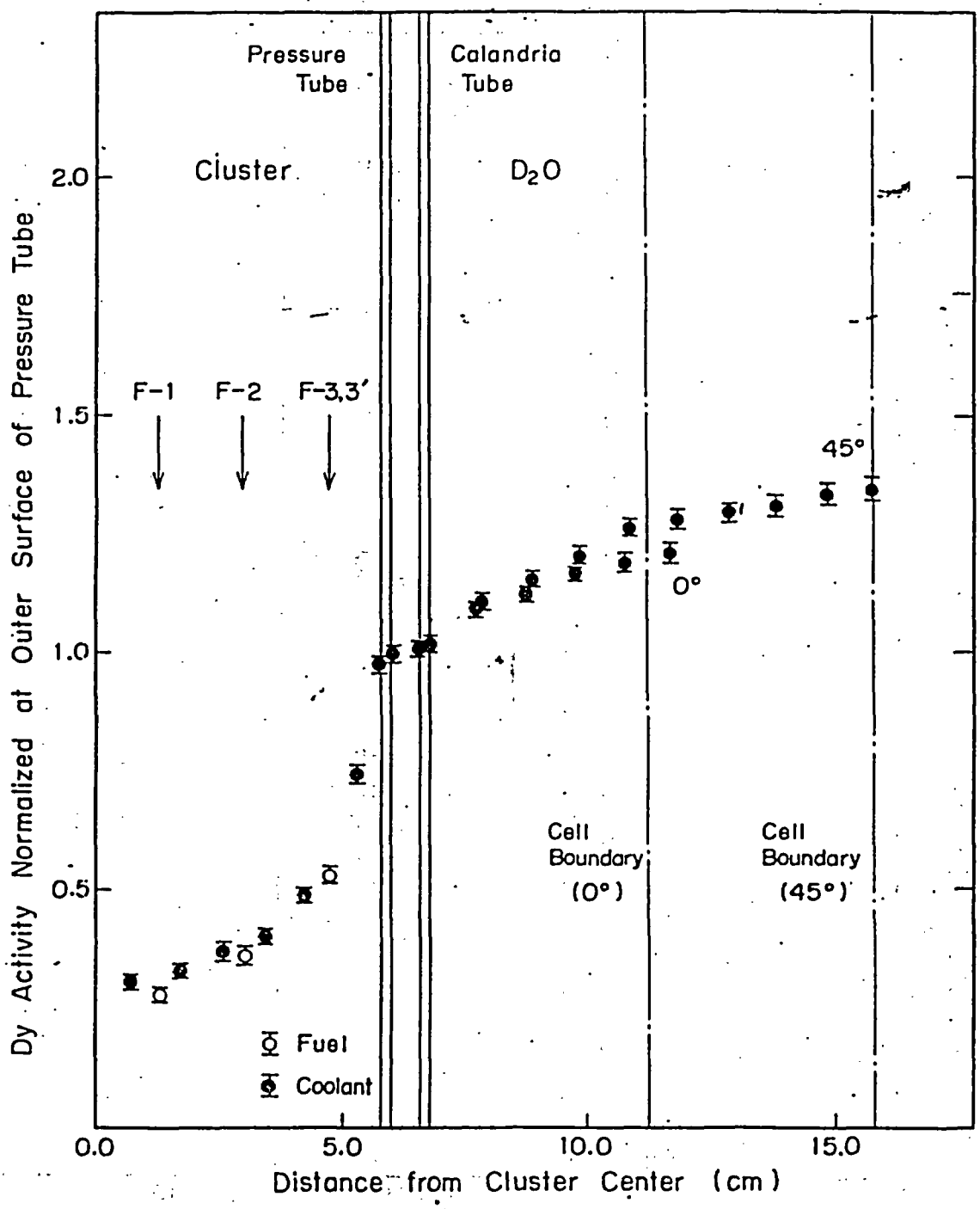


Fig. 12 Dysprosium Reaction Rate Distribution for Coolant Void Fraction of 0 % in 0.54 wt% (s) PuO_2-UO_2 Fuel at 22.5-cm Pitch Lattice

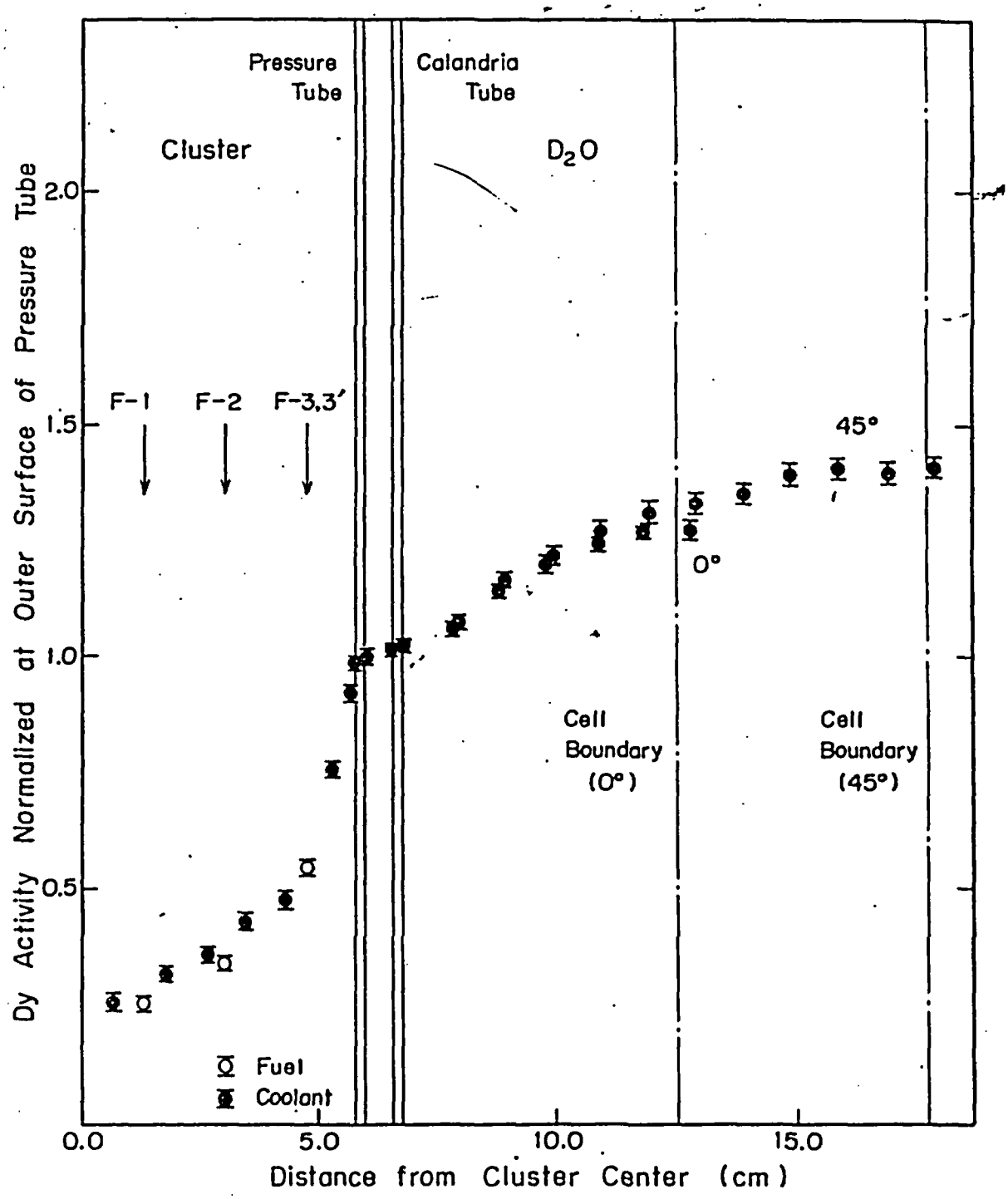


Fig. 13 Dysprosium Reaction Rate Distribution for Coolant Void Fraction of 0 % in 0.54 wt% (s) PuO_2-UO_2 Fuel at 25.0-cm Pitch Lattice

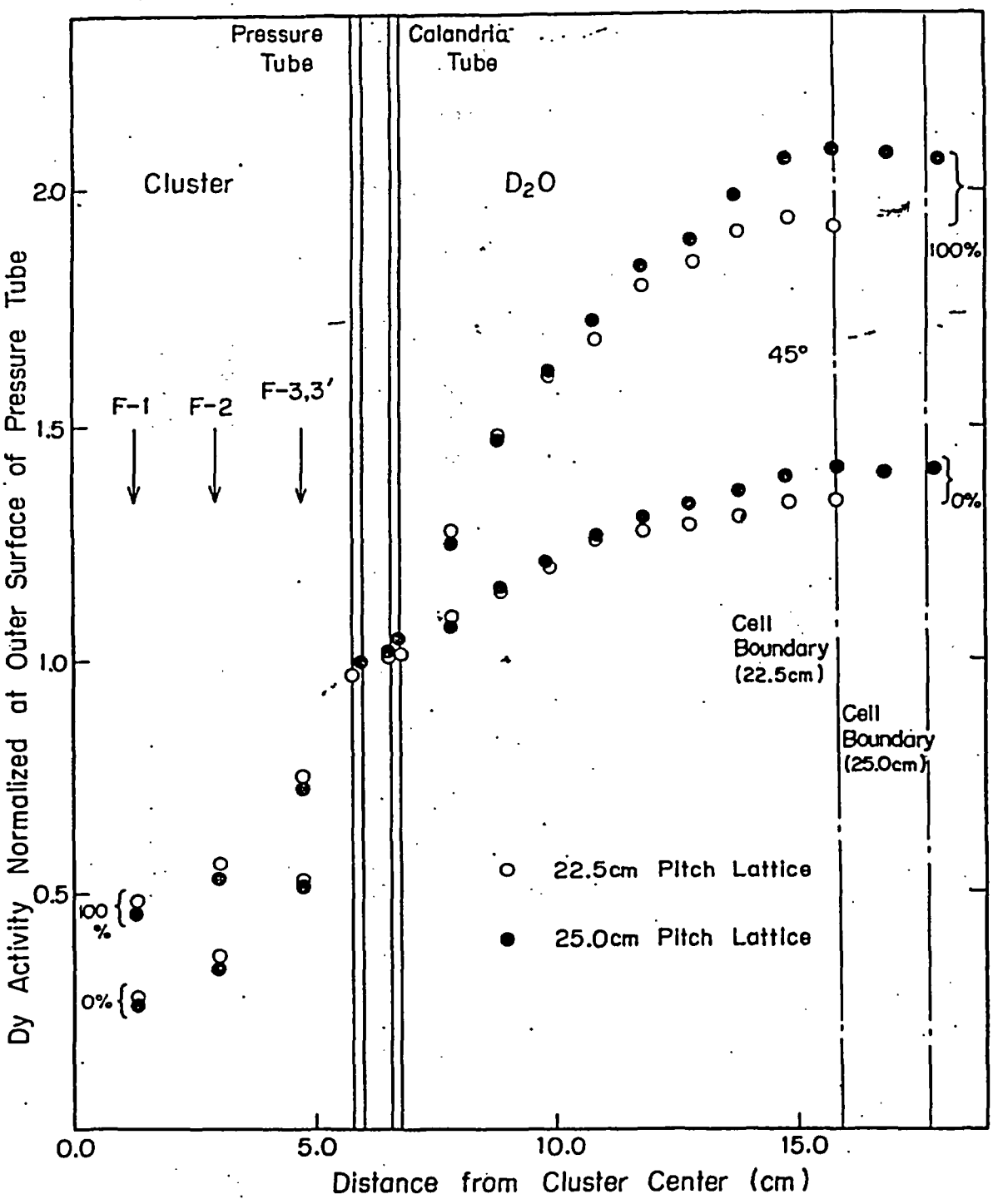


Fig. 14 Dependence of Thermal Neutron Flux Distributions on Lattice Pitch Measured with 0.54 wt% (s) PuO_2-UO_2 Fuel

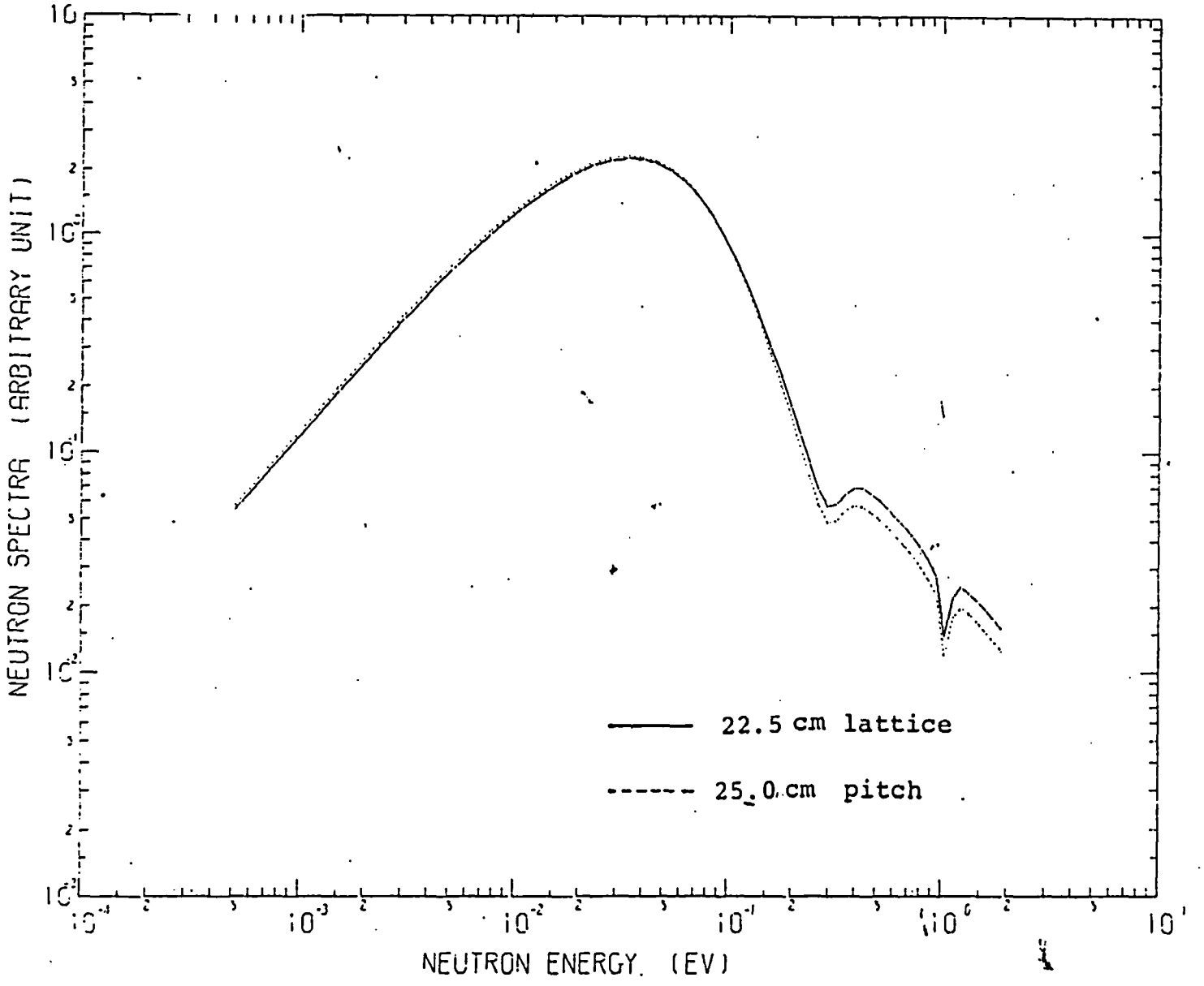


Fig. 15 Neutron Spectra Calculated by LAMP (0.54 wt% PuO_2-UO_2, 0 % Void, in Fuel)