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Atomic Energy of Canada Limited

BUCKLING MEASUREMENTS FOR 7-ELEMENT UO₂ CLUSTERS IN ZEEP

RPI-76

by

G.A. BEER and R.E. GREEN

Chalk River, Ontario

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AECL-1191

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ABSTRACT

Buckling measurements have been made in ZEEP for a hexagonal lattice of 55 7-element UO_2 clusters spaced at 24.56 cm. Measurements were made with different moderator purities and the effect of removing the coolant from the clusters was also measured. The results are in good agreement with lattice calculations.

INTRODUCTION

The proposed NPD-2 initial fuel charge will contain 7-element clusters of sintered UO_2 pellets clad in Zircaloy-2. It is intended to determine lattice parameters for similar 7-element UO_2 fuel clusters clad in aluminum, at a number of spacings, in ZED-2. At the time these rods became available, however, ZED-2 was not ready to operate and it was decided to assemble one lattice in ZEEP to do some preliminary measurements.

This report describes buckling and Cd ratio measurements made in ZEEP in a hexagonal array of 55 of these 7-element UO_2 clusters spaced at 24.56 cm. (Fine structure flux measurements throughout the central cell will be reported later.) The measurements were made for two moderators having different D_2O concentrations; the normal ZEEP moderator, 99.526 atom %, and the ZED-2 moderator, 99.745 atom %. In the case of the ZED-2 D_2O measurements were also made with the coolant excluded^{*}. The measurements using the ZED-2 D_2O were to serve as a cross check between bucklings measured in ZEEP and ZED-2. While the experiments with ZED-2 moderator were proceeding, the ZEEP D_2O was purified by distillation. When this was completed and the D_2O returned to the reactor, another buckling measurement was made to determine the effect, if any, of the purification. (As a result of the extra handling in the transfer, the D_2O content had dropped to 99.511 atom %.)

^{*}Reactivity effects due to coolant removal from various combinations of rods were also studied for both moderator purities and have been published in reference (1).

EXPERIMENTAL

1. Description of Lattice and Fuel

A cross sectional view of the 7-element UO_2 fuel cluster is given in Fig. 1. The UO_2 was in the form of cylindrical pellets 2.54 cm long, 2.40 cm in diameter having an average density of 10.2 gm/cm^3 . 18 pellets were stacked in a 1S aluminum tube with an inside diameter of 2.44 cm, a wall thickness of 0.051 cm and a length of 46.5 cm to form a cluster 'element'. Seven such elements were 'bundled' together in a hexagonal pattern with a centre-to-centre spacing of 2.67 cm. Five bundles loaded into a 1S aluminum tube with an inside diameter of 8.26 cm and a wall thickness of 0.089 cm formed one fuel assembly; no attempt was made to align the elements in adjacent bundles. Fig. 2 shows the details of the bundle construction and Fig. 3 is a sketch of the complete assembly. It was found necessary to notch the edges of the end plates of the bundles and to put short lengths of 0.31 cm diameter Al wire below the bottom bundle to allow the D_2O to flow freely in and out of the assembly.

The lattice studied was a hexagonal array of 55 7-element UO_2 clusters spaced at 24.56 cm. The lattice arrangement is shown in Fig. 4. The fuel assemblies were hung from beams within the reactor by a gimbal suspension which allowed the rods to swing freely in two orthogonal vertical planes. (See Fig. 5.) The cluster spacing was set by measurements made from a punch mark on top of the rod suspension. This mark was assumed to be coaxial with the fuel rod centre line; however, subsequent measurements of the 55 rods revealed that the average deviation of the bottom of the rods from a true vertical axis through the punch mark was 0.23 cm.

2. Buckling Measurements

The total buckling was determined by measuring neutron flux distributions throughout the pile. For a critical, homogeneous, cylindrical reactor, the one-group diffusion equation can be written as;

$$\nabla^2 \phi(r, z) + B^2 \phi(r, z) = 0 \quad (1)$$

where $\phi(r, z)$ is the neutron flux at r, z and B^2 is the buckling.

For a cylindrical reactor with the origin located a distance z_0 below the centre of the pile the fundamental solution of (1) is

$$\phi(r, z) = \phi(0, 0) J_0(\lambda r) \cos \alpha(z - z_0) \quad (2)$$

where $\phi(0, 0)$ is the flux at the centre of the pile
 $\alpha = \pi/h$, h being the extrapolated height of the pile, and
 $\lambda = 2.405/R$, R being the extrapolated radius.

From (1) and (2) the buckling is given by

$$\begin{aligned} B^2 &= \alpha^2 + \lambda^2 \\ &= (\pi/h)^2 + (2.405/R)^2 \end{aligned}$$

where α^2 and λ^2 are the axial and radial bucklings respectively.

The above treatment is also applicable to a bare, heterogeneous reactor if the neutron flux is measured at identical positions in each cell so that fine structure effects do not enter. For a reflected pile such as ZEEP the one-group theory holds only in a region $\geq 1\frac{1}{2}$ migration lengths inside the UO_2 core boundary. This region can be determined experimentally by measuring the Cd ratio for a given detector throughout the lattice; in the region where the Cd ratio is constant, one-group theory is applicable.

For the buckling measurements reported here, the relative neutron flux is measured at mid-rod positions. These are shown as thimble locations in Fig. 4. The usual procedure was to place foils at 10 cm intervals along the vertical axis of the pile in thimbles E and F and at several levels near the midplane in the other thimbles.

As neutron detectors, copper and manganese foils were used. The Mn(10% Ni) foils were 1 cm square, weighed ~ 108 mgm and were spot-welded to 25 x 21 x 0.5 mm Al rectangles. The Cu foils were circular, 2.38 cm in diameter and weighed ~ 275 mgm. Both types of foil were placed in thin Al channels which were then inserted into re-entrant Al thimbles containing lower grade D_2O ($\sim 99\%$) than the moderator. After irradiation the Mn foil activities were measured with a TQQB electroscope while the Cu foils were counted with NaI(Tl) scintillation counters. The corrected activities were then fitted by the method of least squares to expression (2) to obtain values of α, λ and hence B^2 .

3. Cd Ratio Measurements

To determine the region of the lattice in which the one-group treatment could be applied, Cd ratio measurements were made, also at mid-rod positions, using 0.051 cm diameter 0.50 cm long Mn-Ni wires. These wires were contained in Al or Cd capsules 0.794 cm long having 0.076 cm walls. The activated wires were counted with scintillation counters.

4. Critical Height Measurements

In order to obtain the axial extrapolation lengths and the correction for foil loading, critical moderator heights were determined for the various lattices. For most of the flux distribution experiments the critical height was obtained from the D_2O manometer from which the D_2O level in the calandria can be read directly. To obtain the loading correction critical heights with and without thimbles and foils were determined with a selsyn-driven probe which closed an electrical circuit when its tip made contact with the D_2O . (See Fig. 5.) The probe is marked at known distances from its tip and is calibrated by observing the reading when one of these marks is sighted with a surveyor's level (mounted permanently on the railing around the top of the pile). The height of the level above the pile zero plane^{*} is determined from a bench mark reading taken on a fixed part of the reactor structure. With this instrument height changes can be measured to ± 0.007 cm. However, uncertainties in the height of the level and positions of the probe marks are such that the critical moderator height is known only to ± 0.20 cm. The D_2O manometer was calibrated against the height probe by measuring the elevation of the manometer zero with the surveyor's level. Adding 0.5 ± 0.2 cm to the manometer reading yields h_m , the distance from the zero plane to the moderator level.

5. Coolant Exclusion Technique

Buckling and Cd ratio measurements were made with the D_2O excluded from the coolant space in all 55 rods. The coolant tubes

^{*}The zero plane is defined as the plane through the bottom of the uranium in a ZEEP rod; the bottom of the UO_2 was 4.76 cm above this.

which contained the fuel bundles were made airtight at the top (see Fig. 3) and each was fitted with 1/4" Poly-Flo tubing. These tubes were taken out through seals in the reactor lid to brass manifolds. The inputs to these manifolds were in turn connected to another manifold which was attached to the regulator on a helium cylinder as shown in Fig. 6. The helium pressure was measured with an oil manometer connected to the manifold at the He cylinder, as shown in the figure. As the helium pressure was increased, the D₂O coolant was expelled into the moderator region of the lattice through a hole in the bottom of the coolant tube. By varying the He pressure, the D₂O level in the coolant tubes could be made to assume any desired level. The relationship between He pressure and D₂O level was determined by observing, on the oil manometer, the He pressure required to completely exclude the coolant from the rods for various moderator levels. The point of complete exclusion was determined by observing the onset of bubbling in the moderator. During a foil irradiation a slightly lower pressure (~1 cm of D₂O) was maintained.

EXPERIMENTAL RESULTS AND DISCUSSION

I. Cd Ratios

The results of the Cd ratio measurements are summarized in Tables 1 - 4. The values shown are the ratios of aluminum-covered to Cd-covered activities for Mn wires irradiated at the same elevation and radial position in two thimbles, i.e., data from thimbles E and F, D and G, C and H etc. were combined. The values are listed in the tables at the positions of the Al-covered wires. Tables 1 and 2 list the results for the experiments with ZEEP D₂O as coolant and moderator, Table 1 before purification and Table 2 after purification. Tables 3 and 4 list the results for the experiments with ZED-2 D₂O; Table 3 with coolant in and Table 4 with the coolant excluded.

These results are also plotted in Figs. 7 - 10. Figs. 7 and 8 show the axial and radial variations respectively of the Cd ratio for the ZEEP D₂O case and Figs. 9 and 10 the same results for the ZED-2 D₂O experiments. The axial plots include the data of thimbles E and F while the radial plots are averages of the data from the two elevations used. From these results the region of constant Cd ratio was taken to be

$$25 \text{ cm} < z < 155 \text{ cm}$$

axially and

$$0 < r < 65 \text{ cm}$$

radially. In fitting the flux distributions to obtain the buckling, the regions used were always equal to or smaller than those given above.

Table 1. Mn Cadmium Ratio - ZEEP D₂O Moderator and Coolant

Critical Height = 194.13 cm			Nov. 5, 1959					Moderator Temperature 24.3°C				
Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J
Radius cm	85.97	63.81	61.41	36.84	21.27	12.28	12.28	21.27	36.84	61.41	63.81	85.97
Elevation cm												
185						33.36						
175							34.52					
165						34.76						
155							36.61					
145						36.25						
135							37.01					
125						36.35						
115							36.41					
105						37.30						
95	53.76			36.16	35.77		36.99			36.94	37.00	
85						36.95						
75		36.72	35.92				36.23	36.53	37.63			49.85
65						36.17						
55							36.29					
45						36.91						
35							35.83					
25						35.69						
15							40.77					
5						54.92						

Table 2. Mn Cadmium Ratio - Purified ZEEP D₂O Moderator and Coolant

Critical Height = 192.53 cm			Jan. 12, 1960					Moderator Temperature 21.6°C				
Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J
Radius cm	85.97	63.81	61.41	36.84	21.27	12.28	12.28	21.27	36.84	61.41	63.81	85.97
Elevation cm												
185						32.21						
175							33.52					
165						36.84						
155							36.19					
145						36.15						
135							36.69					
125						36.20						
115							35.90					
105						37.85						
95	52.59	37.16		35.84	36.95		36.23			37.72		
85						35.38						
75			35.88				35.58	36.11	35.55		36.68	49.15
65						36.33						
55							36.21					
45						36.93						
35							35.77					
25						36.26						
15							38.87					
5						53.03						

Table 3. Mn Cadmium Ratio - ZED-2 D₂O Moderator and Coolant

Critical Height = 181.1 cm		Dec. 11, 1959					Moderator Temperature 21.8°C					
Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J
Radius cm	85.97	63.81	61.41	36.84	21.27	12.28	12.28	21.27	36.84	61.41	63.81	85.97
Elevation cm												
175								26.94				
165							34.81					
155								36.64				
145							34.83					
135								35.85				
125							35.59					
115								35.62				
105							36.58					
95	51.65			35.55	36.32			36.16		37.23	35.99	
85							35.6					
75		34.98	34.86					35.41	36.29	35.26		52.97
65							35.19					
55								35.67				
45							36.17					
35								34.58				
25							34.76					
15								39.07				
5							52.32					

Table 4. Mn Cadmium Ratio - ZED-2 D₂O Moderator, Coolant Excluded

Critical Height = 178.00 cm			Dec. 17, 1959					Moderator Temperature 22.0°C				
Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J
Radius cm	85.97	63.81	61.41	36.84	21.27	12.28	12.28	21.27	36.84	61.41	63.81	85.97
Elevation cm												
175						23.21						
165							31.38					
155						33.56						
145							32.72					
135						31.90						
125							33.03					
115						32.90						
105							33.96					
95	46.96			32.97	-	33.56				33.04	34.32	
85							33.05					
75		33.03	33.64			32.97		-	32.11			47.40
65							33.05					
55						33.57						
45							33.39					
35						33.06						
25							32.79					
15						35.77						
5							47.97					

Where the Cd ratio was constant the average values for the four cases were found to be,

<u>Moderator</u>	<u>Purity (atom % D₂O)</u>	<u>Mean R_{Cd}</u>
(1) ZEEP D ₂ O (unpurified)	99.526	36.53 ± 0.11
(2) ZEEP D ₂ O (after purification)	99.511	36.31 ± 0.12
(3) ZED-2 D ₂ O (coolant in)	99.745	35.69 ± 0.14
(4) ZED-2 D ₂ O (coolant excluded)	99.745	33.13 ± 0.12

where the errors shown are the errors in the mean values. From these results it is clear that the purification of the ZEEP D₂O did not alter the Cd ratio. This is reasonable since the purification removed only some metal ions (mostly Al) and the D₂O concentration was reduced by only 0.01%. The difference between the cases with ZEEP D₂O and ZED-2 D₂O with coolant in is small but perhaps significant and can be explained by the fact that the ZEEP heavy water contains about twice as much hydrogen as the ZED-2 heavy water which would make the spectrum more thermal in the ZEEP D₂O case, as evidenced by the slightly higher Cd ratio. The difference between the Cd ratios for ZED-2 D₂O with coolant in and out is more striking and is explained by the fact that with the coolant excluded the volume of D₂O in the cell is reduced, hence the slowing-down power of the cell is lower. This results in a harder spectrum, as observed. Also the exclusion of scattering material from the vicinity of the fuel will flatten the flux distribution across the cluster. This will result in a shorter thermal neutron lifetime and hence a lower Cd ratio.

2. Buckling Results

The results of the full-scale flux distribution measurements are given in Tables 5 - 12 along with the values of α and λ obtained from the least squares fits. The bracketed activities were not used in the fitting. The foil elevations and the critical moderator height h_m were both measured with respect to the zero plane^{*}. The temperature listed is an average of readings taken at 20 cm intervals along a vertical axis ~ 50 cm from the centre of the core.

Two values of z_0 and α were obtained for each run from cosine fits of the data from thimbles E and F. Six values of λ were obtained by fitting the data from the combined North plus West (N+W) and South plus East (S+E) axes for the three elevations. The error quoted for the α and λ values is either,

- (1) the error calculated from the assumed counting statistics ($\pm 1/4\%$) and foil positioning errors (± 0.2 cm),
- (2) the error obtained from the "goodness-of-fit" of the data to the assumed distribution function, or
- (3) the standard deviation in the mean of the several values obtained for each parameter,

whichever is the greatest.

In order to compare the buckling results obtained from the various experiments, corrections must be made for the loading effect of the experimental thimbles and foils and for the differences in temperature of the various lattices.

^{*}Foil elevations were determined with the surveyor's level whereas the moderator level was obtained from the D_2O manometer reading.

Table 5. Buckling Data - ZEEP D₂O Moderator and Coolant

$h_m = 194.18$ cm		Copper Foils						Nov. 4, 1959		Moderator Temperature 24.3°C			
Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J	
Radius cm	85.97	63.81	61.41	36.84	21.27	12.28	12.28	21.27	36.84	61.41	63.81	85.97	
Elevation cm													
185						(0.402)	(0.409)						
175						(0.711)	(0.720)						
165						(0.990)	(1.011)						
155						1.252	1.280						
145						1.490	1.518						
135						1.684	1.713						
125						1.848	1.881						
115						1.981	2.012						
105	(1.056)	1.429	1.473	1.898	2.035	2.082	2.120	2.052	1.895	1.471	1.416	(1.060)	
95	(1.082)	1.467	1.515	1.945	2.086	2.140	2.175	2.103	1.944	1.489	1.450	(1.091)	
85	(1.085)	1.466	1.513	1.944	2.084	2.123	2.171	2.008	1.939	1.513	1.452	(1.094)	
75						2.088	2.135						
65						2.019	2.058						
55						1.914	1.950						
45						1.755	1.789						
35						1.560	1.583						
25						(1.342)	(1.357)						
15						(1.119)	(1.127)						
5						(0.922)	(0.932)						

35-155 cm	Thimble		Average
	E	F	
z ₀ (cm)	88.15	88.19	88.17 ±0.07
α(m ⁻¹)	1.411	1.411	1.411 ±0.002

Level	λ(m ⁻¹)	
	N & W	S & E
105 cm	1.873	1.912
95	1.870	1.929
85	1.863	1.906
Average	1.869	1.916

Average (N&W, S&E) = 1.892 ±0.011

Table 6. Buckling Data - ZEEP D₂O Moderator and Coolant

$h_m = 193.65$ cm		Manganese Foils						Nov. 17, 1959					Moderator Temperature 22.4°C		
Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J			
Radius cm	85.97	63.81	61.41	36.84	21.27	12.28	12.28	21.27	36.84	61.41	63.81	85.97			
Elevation cm															
185													(.1886)	(.1876)	
175													(.3329)	(.3333)	
165													(.4677)	(.4693)	
155													.5873	.5923	
145													.7057	.7022	
135													.7893	.7934	
125													.8697	.8713	
115													.9345	.9304	
105													.9756	.9738	
95	(.5125)	.6845	.7102	.9168	1.003	1.004	.9938	.9915	.9136	.7129	.6879	(.5158)			
85	(.5136)	.6854	.7185	.9122	.9913	1.000	1.000	.9919	.9180	.7143	.6860	(.5132)			
75	(.5045)	.6747	.7056	.9016	.9792	.9829	.9796	.9739	.9003	.7070	.6785	(.5106)			
65													.9457	.9427	
55													.9057	.8932	
45													.8203	.8168	
35													.7316	.7260	
25													(.6310)	(.6174)	
15													(.5290)	(.5154)	
5													(.4364)	(.4276)	

35-155 cm	Thimble		Average	
	E	F		
z ₀ (cm)	88.27	88.64	88.46	±0.19
α(m ⁻¹)	1.413	1.410	1.411	±0.004

Level	λ(m ⁻¹)	
	N & W	S & E
95 cm	1.903	1.869
85	1.871	1.880
75	1.877	1.858
Average	1.884	1.869

Average (N&W, S&E) = 1.876 ±0.012

Table 7. Buckling Data - ZED-2 D₂O Moderator and Coolant

$h_m = 181.1$ cm		Manganese Foils						Dec. 10, 1959		Moderator Temperature 21.8°C			
Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J	
Radius cm	85.97	63.81	61.41	36.84	21.27	12.28	12.28	21.27	36.84	61.41	63.81	85.97	
Elevation cm													
185													
175													
165													
155													
145													
135													
125													
115													
105													
95	(.9035)	1.222	1.243	1.561	1.702	1.720	1.732	1.684	1.557	1.252	1.195	(.9039)	
85	(.9139)	1.242	1.279	1.592	1.716	1.736	1.777	1.711	1.596	1.287	1.213	(.9216)	
75	(.9126)	1.240	1.282	1.603	1.725	1.739	1.765	1.701	1.591	1.283	1.216	(.9236)	
65													
55													
45													
35													
25													
15													
5													

25-155 cm	Thimble			Average	Level	$\lambda(m^{-1})$	
	E	F	Average			N & W	S & E
zo(cm)	80.40	80.11	80.26	± 0.15	95 cm	1.810	1.830
$\alpha(m^{-1})$	1.489	1.489	1.489	± 0.005	85	1.780	1.832
					75	1.791	1.831
					Average	1.794	1.831
					Average (N&W, S&E)	= 1.812 ± 0.009	

Table 8. Buckling Data - ZED-2 D₂O Moderator and Coolant

$h_m = 181.21$ cm	Manganese Foils				Dec. 14, 1959				Moderator Temperature 22.1°			
Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J
Radius cm	85.97	63.81	61.41	36.84	21.27	12.28	12.28	21.27	36.84	61.41	63.81	85.97
Elevation cm												
175						(.1514)	(.1514)					
165						(.3059)	(.3063)					
155						.4432	.4491					
145						.5817	.5814					
135						.6897	.6954					
125						.7865	.7926					
115						.8652	.8740					
105						.9249	.9342					
95	(.4930)	.6710	.6847	.8804	.9579	.9700	.9722	.9512	.8761	.6905	.6607	(.4962)
85	(.4988)	.6811	.7006	.8915	.9665	.9843	1.000	.9635	.8919	.7044	.6680	(.5033)
75	(.4974)	.6764	.6986	.8905	.9656	.9769	.9890	.9521	.8840	.7029	.6700	(.5023)
65						.9507	.9603					
55						.9184	.9220					
45						.8374	.8516					
35						.7571	.7634					
25						.6489	.6564					
15						(.5454)	(.5458)					
5						(.4471)	(.4481)					

25-155 cm	Thimble		Average
	E	F	
z_0 (cm)	81.74	81.63	81.68 ±0.10
α (m ⁻¹)	1.502	1.501	1.501 ±0.003

Level	λ (m ⁻¹)	
	N & W	S & E
95 cm	1.872	1.877
85	1.856	1.891
75	1.859	1.862
Average	1.862	1.877
Average (N&W, S&E) = 1.869		±0.007

Table 9. Buckling Data - ZED-2 D₂O Moderator, Coolant Excluded

$h_m = 177.9$ cm		Copper Foils					Dec. 16, 1959		Moderator Temperature 21.9°C				
Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J	
Radius cm	85.97	63.81	61.41	36.84	21.27	12.28	12.28	21.27	36.84	61.41	63.81	85.97	
Elevation cm													
175						(.1918)		(.1969)					
165						(.5140)		(.5182)					
155						.8056		.8076					
145						1.067		1.069					
135						1.273		1.296					
125						1.486		1.492					
115						1.652		1.660					
105						1.787		1.799					
95	(.9898)	1.299	1.347	1.712	1.840	1.872	1.897	1.837	1.700	1.350	1.275	(.9938)	
85	(1.011)	1.321	1.371	1.742	1.874	1.903	1.924	1.869	1.723	1.374	1.301	(1.011)	
75	(1.010)	1.325	1.372	1.743	1.873	1.899	1.925	1.870	1.724	1.379	1.303	(1.016)	
65						1.858		1.886					
55						1.790		1.818					
45						1.658		1.688					
35						1.485		1.511					
25						1.289		1.318					
15						(1.092)		(1.107)					
5						(.9172)		(.9268)					

25-155 cm	Thimble		Average
	E	F	
zo (cm)	79.95	79.47	79.71 ±0.24
α (m ⁻¹)	1.514	1.510	1.512 ±0.003

Level	λ (m ⁻¹)	
	N & W	S & E
95 cm	1.872	1.853
85	1.867	1.848
75	1.861	1.841
Average	1.867	1.847
Average (N&W, S&E) = 1.857		±0.009

Table 10. Buckling Data - ZED-2 D₂O Moderator, Coolant Excluded

$h_m = 177.98$ cm		Manganese Foils				Dec. 17, 1959			Moderator Temperature 22.04°C			
Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J
Radius cm	85.97	63.81	61.41	36.84	21.27	12.28	12.28	21.27	36.84	61.41	63.81	85.97
Elevation cm												
175						(.1238)	(.1211)					
165						(.3216)	(.3197)					
155						.4950	.5005					
145						.6548	.6563					
135						.7825	.7911					
125						.8994	.9112					
115						1.003	1.015					
105						1.081	1.099					
95	(.6051)	.7955	.8249	1.029	1.123	1.139	1.152	1.127	1.036	.8211	.7832	(.6074)
85	(.6166)	.8126	.8416	1.054	1.145	1.152	1.169	1.140	1.058	.8390	.8004	(.6178)
75	(.6160)	.8130	.8373	1.057	1.147	1.154	1.178	1.134	1.055	.8402	.7977	(.6172)
65						1.126	1.149					
55						1.089	1.101					
45						1.000	1.022					
35						.9043	.9176					
25						.7843	.7982					
15						(.6689)	(.6704)					
5						(.5638)	(.5639)					

25-155 cm	Thimble		Average	Level	$\lambda(m^{-1})$	
	E	F			N & W	S & E
zo(cm)	80.02	79.81	79.92 ±0.11	95 cm	1.826	1.871
$\alpha(m^{-1})$	1.505	1.506	1.506 ±0.003	85	1.816	1.854
				75	1.826	1.860
				Average	1.823	1.862
				Average (N&W, S&E) = 1.843 ±0.009		

Table 11. Buckling Data - Purified ZEEP D₂O Moderator and Coolant

$h_m = 192.05$ cm		Manganese Foils					Jan. 6, 1960		Moderator Temperature 20.67°C				
Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J	
Radius cm	85.97	63.81	61.41	36.84	21.27	12.28	12.28	21.27	36.84	61.41	63.81	85.97	
Elevation cm													
185						(.1681)	(.1685)						
175						(.3273)	(.3281)						
165						(.4713)	(.4681)						
155						.6011	.6034						
145						.7173	.7191						
135						.8155	.8159						
125						.9005	.8965						
115						.9671	.9686						
105						1.015	1.012						
95	(.5308)	.7236	.7386	.9438	1.029	1.052	1.048	1.024	.9461	.7419	.7212	(.5339)	
85	(.5311)	.7299	.7587	.9475	1.027	(1.048)	(1.033)	1.020	.9438	.7456	.7192	(.5387)	
75	(.5269)	.7203	.7258	.9365	1.007	1.027	1.026	1.005	.9272	.7286	.7066	(.5292)	
65						.9944	1.000						
55						.9420	.9540						
45						.8636	.8649						
35						.7640	.7758						
25						.6578	.6697						
15						(.5498)	(.5554)						
5						(.4472)	(.4537)						

25-155 cm	Thimble		Average
	E	F	
z ₀ (cm)	87.59	87.11	87.35 ±0.23
α(m ⁻¹)	1.427	1.412	1.419 ±0.008

Level	λ(m ⁻¹)	
	N & W	S & E
95 cm	1.871	1.863
85	1.831	1.859
75	1.848	1.862
Average	1.850	1.861

Average (N&W, S&E) = 1.856 ±0.006

Table 12. Buckling Data - Purified ZEEP D₂O Moderator and Coolant

$h_m = 192.11$ cm	Copper Foils						Jan. 7, 1960						Moderator Temperature 20.9°C					
Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J						
Radius cm	85.97	63.81	61.41	36.84	21.27	12.28	12.28	21.27	36.84	61.41	63.81	85.97						
Elevation cm																		
185													(.2696)	(.2784)				
175													(.5448)	(.5385)				
165													(.7755)	(.7801)				
155													(1.001)	(1.005)				
145													1.205	1.208				
135													1.366	1.373				
125													1.507	1.511				
115													1.617	1.629				
105													1.704	1.717				
95	(.8831)	1.198	1.231	1.585	1.715	1.754	1.767	1.710	1.585	1.236	1.192	(.8811)						
85	(.8824)	1.198	1.234	1.587	1.718	1.747	1.766	1.711	1.580	1.239	1.192	(.8940)						
75	(.8725)	1.184	1.219	1.572	1.687	1.719	1.740	1.684	1.556	1.228	1.175	(.8796)						
65													1.664	1.680				
55													1.581	1.593				
45													1.454	1.470				
35													1.288	1.299				
25													(1.058)	(1.062)				
15													(.9206)	(.9273)				
5													(.7523)	(.7556)				

35-145 cm	Thimble		Average
	E	F	
z_0 (cm)	87.35	87.12	87.24 ±0.12
α (m ⁻¹)	1.416	1.422	1.419 ±0.005

Level	λ (m ⁻¹)	
	N & W	S & E
95 cm	1.884	1.893
85	1.880	1.887
75	1.870	1.879
Average	1.878	1.886

Average (N&W, S&E) = 1.882 ±0.005

The loading correction ΔB_L^2 was obtained from measurements of pile critical height with and without foils and thimbles by assuming that the radial buckling was independent of loading and critical height, viz.,

$$\Delta B_L^2 = \pi^2 \left[\frac{1}{(h+\Delta h)^2} - \frac{1}{h^2} \right] \quad (3)$$

where Δh is the change in critical height produced by the thimbles and foils. This correction was $\sim 0.4\%$ in α or $\sim 0.3\%$ in B^2 . All values of buckling were corrected to 20°C assuming the temperature coefficient of buckling to be the same as that measured in ZEEP for a lattice of 19-element UO_2 clusters⁽²⁾, i.e. $\frac{dB^2}{dT} = -0.0113 \text{ m}^{-2}/^\circ\text{C}$. The maximum temperature correction ΔB_T^2 was only 0.9% so that the final value of B^2 is not strongly sensitive to the value assumed for $\frac{dB^2}{dT}$.

A summary of the buckling results is given in Table 13. Here the values of α^2 , λ^2 and B^2 obtained from the least squares fitting are listed along with the loading and temperature corrections and final corrected values of B^2 . Also shown in this table are the results for four other flux distributions obtained from the Al-covered Mn-Ni wires irradiated in the Cd ratio measurements. (These distributions are given in Tables 14 - 17.) These fits were done for the lattice with ZED-2 D_2O as coolant and moderator to resolve the unusually large discrepancy between the two values of B^2 obtained from the foil irradiations and for the other three lattices to check the validity of using these data to obtain bucklings. The bucklings obtained for the latter cases agree within experimental error with the foil results, and, since the result for the ZED-2 D_2O case agrees

Table 13. Buckling Values With Corrections for Foil Loading and Moderator Temperature

Date	Moderator Purity (Atom %)	α^2	λ^2	B^2 (m^{-2})	ΔB_T^2	ΔB_L^2	$B^2(20^\circ C)$	Mean $B^2(20^\circ C)$
		(m^{-2})	(m^{-2})	Uncorrected	(m^{-2})	(m^{-2})	(m^{-2})	(m^{-2})
Nov. 4/59	99.526	1.991 [±] .006	3.580 [±] .042	5.571 [±] .043	+0.049	+0.039	5.659 [±] .043	
Nov. 17/59	99.526	1.991 [±] .011	3.519 [±] .045	5.510 [±] .046	+0.027	+0.039	5.576 [±] .046	5.623 [±] 0.034
Nov. 5/59 [*]	99.526	1.994 [±] .014	3.542 [±] .064	5.536 [±] .066	+0.049	+0.049	5.634 [±] .066	
Dec. 10/59 [†]	99.745	2.217 [±] .015	3.283 [±] .033	5.500 [±] .036	+0.020	+0.034	5.554 [±] .036	
Dec. 14/59	99.745	2.253 [±] .009	3.493 [±] .026	5.746 [±] .028	+0.024	+0.035	5.805 [±] .028	5.799 [±] 0.034
Dec. 11/59 [*]	99.745	2.238 [±] .011	3.471 [±] .056	5.709 [±] .057	+0.020	+0.046	5.775 [±] .057	
Dec. 16/59	99.745	2.286 [±] .009	3.448 [±] .033	5.735 [±] .034	+0.022	+0.029	5.786 [±] .034	
Dec. 17/59	99.745 Excluded	2.268 [±] .009	3.397 [±] .033	5.665 [±] .034	+0.023	+0.029	5.717 [±] .034	5.751 [±] 0.024
Dec. 17/59 [*]	99.745 Excluded	2.256 [±] .014	3.426 [±] .030	5.682 [±] .033	+0.023	+0.046	5.751 [±] .033	
Jan. 6/60	99.511	2.014 [±] .022	3.445 [±] .022	5.458 [±] .031	+0.008	+0.039	5.505 [±] .031	
Jan. 7/60	99.511	2.014 [±] .014	3.542 [±] .019	5.555 [±] .024	+0.010	+0.039	5.604 [±] .024	5.565 [±] 0.034
Jan. 12/60 [*]	99.511	2.002 [±] .017	3.474 [±] .074	5.476 [±] .076	+0.018	+0.049	5.543 [±] .076	

^{*}Data obtained from Al-covered Mn wire activities irradiated to obtain the Cd ratio.

[†]Omitted from Mean $B^2(20^\circ C)$

Table 14. Buckling Data - ZEEP D₂O Moderator and Coolant

$h_m = 194.63$ cm		Al covered Mn wires					Nov. 5, 1959		Moderator Temperature 24.3°C			
Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J
Radius cm	85.97	63.81	61.41	36.84	21.27	12.28	12.28	21.27	36.84	61.41	63.81	85.97
Elevation cm												
185								(2.020)				
175						(3.389)						
165								(4.700)				
155						5.939						
145								7.140				
135						7.964						
125								8.877				
115						9.353						
105								9.948				
95		6.787	7.153			10.07		9.858	9.086			(5.124)
85								10.25				
75	(5.031)			9.053	9.628	9.873				7.039	6.723	
65								9.718				
55						9.053						
45								8.434				
35						7.376						
25								6.381				
15						(5.295)						
5								(4.343)				

25-155 cm	Thimble		Average	Level	$\lambda(m^{-1})$
	E	F			All Thimbles
zo(cm)	88.11	88.21	88.16 ± 0.14	95 cm	1.890
$\alpha(m^{-1})$	1.408	1.416	1.412 ± 0.005	75	1.875
				Average	1.882
					± 0.017

Table 15. Buckling Data - ZED-2 D₂O Moderator and Coolant

$h_m = 181.6$ cm	<u>Al covered Mn wires</u>											Dec. 11, 1959	Moderator Temperature 21.8°C
Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J	
Radius cm	85.97	63.81	61.41	36.84	21.27	12.28	12.28	21.27	36.84	61.41	63.81	85.97	
Elevation cm													
175						(1.403)							
165							(2.797)						
155						4.126							
145							5.301						
135						6.256							
125							7.198						
115						7.894							
105							8.495						
95		6.065	6.260			8.799		8.590	7.989			(4.476)	
85							8.995						
75	(4.521)			8.091	8.714	8.824				6.371	6.028		
65							8.734						
55						8.202							
45							7.712						
35						6.759							
25							5.933						
15						(4.852)							
5							(4.022)						

25-155 cm	Thimble		Average	$\lambda(m^{-1})$	
	E	F		Level	All Thimbles
z_0 (cm)	82.39	81.87	82.13 ± 0.26	95 cm	1.858
$\alpha(m^{-1})$	1.503	1.495	1.499 ± 0.004	75	1.868
				Average	1.863
					± 0.015

Table 16. Buckling Data - ZED-2 D₂O Moderator, Coolant Excluded

$h_m = 178.5$ cm		Al covered Mn wires					Dec. 17, 1959		Moderator Temperature 22.0°C			
Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J
Radius cm	85.97	63.81	61.41	36.84	21.27	12.28	12.28	21.27	36.84	61.41	63.81	85.97
Elevation cm												
175												(.7913)
165							(1.940)					
155								2.998				
145							3.921					
135								4.760				
125							5.427					
115								6.059				
105							6.520					
95		4.726	4.915					6.865	6.671	6.185		(3.621)
85							6.925					
75	(3.666)			6.318	6.805			6.990		5.019	4.750	
65							6.760					
55								6.583				
45							6.028					
35								5.472				
25							4.704					
15								(4.018)				
5							(3.329)					

25-155 cm	Thimble		Average	Level	$\lambda(m^{-1})$
	E	F			All Thimbles
z_0 (cm)	80.19	79.88	80.03 ± 0.16	95 cm	1.843
$\alpha(m^{-1})$	1.500	1.505	1.502 ± 0.005	75	1.859
				Average	1.851
					± 0.008

Table 17. Buckling Data - Purified ZEEP D₂O Moderator and Coolant

$h_m = 193.03$ cm	Al covered Mn wires											Jan. 12, 1960	Moderator Temperature 21.6°C
Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J	
Radius cm	85.97	63.81	61.41	36.84	21.27	12.28	12.28	21.27	36.84	61.41	63.81	85.97	
Elevation cm													
185													(.1839)
175													(.3406)
165													(.4879)
155													.6199
145													.7439
135													.8343
125													.9168
115													.9824
105													1.042
95													1.059
85													1.067
75	(.5307)	.7268											1.041
65													.9584
55													.7260
45													(.5416)
35													.7458
25													.9485
15													1.023
5													1.037
													1.016
													.9433
													.8807
													.7711
													.6735
													(.5454)
													(.4534)

25-155 cm	Thimble		Average	Level	$\lambda(m^{-1})$
	E	F			All Thimbles
zo(cm)	88.30	87.83	88.06 ±0.24	95 cm	1.872
$\alpha(m^{-1})$	1.418	1.412	1.415 ±0.006	75	1.833
				Average	1.853
					±0.020

with the December 14 result for this lattice, we have chosen to reject the result of December 10 in the final averaging of the B^2 values. The rather low value of B^2 obtained on December 10 is a bit puzzling and we have no very definite reasons for rejecting it. However, there is a suspicion that during this experiment the coolant was inadvertently excluded from a part of the lattice. This would lead to different neutron spectra in different regions of the pile and hence a distorted flux distribution as seen by the Mn-Ni foils.

The buckling results (with coolant in) given in Table 13 are plotted in Fig. 11 as a function of moderator purity. The dashed line is a "best fit" line drawn through the experimental points. The solid line shown is a calculated curve obtained from a lattice calculation program of Duret and Marriott⁽³⁾ which was modified to allow for changes in D_2O purity. From this graph it can be seen that the calculated bucklings agree with the measured values within $\sim 2\%$ and also that the observed variation of buckling with moderator purity is in excellent agreement with the calculations as evidenced by the fact that the two curves in Fig. 11 have the same slope.

3. Extrapolation Lengths

In addition to bucklings, the flux distributions yield values for the extrapolation lengths if the core size and critical height are known. The radial extrapolation length δ_r is given by

$$\delta_r = R - R_c = \frac{2.405}{\lambda} - R_c \quad (4)$$

where R_c is the core radius, defined for a hexagonal lattice by

$$R_c = 0.525 \sqrt{N} d \quad (5)$$

where N is the number of rods in the pile (55 in this case) and d is the lattice pitch.

The axial extrapolation length δ_z is given by

$$\delta_z = h - h_c = \pi/\alpha - h_c \quad (6)$$

$$= \delta_{zu} + \delta_{zl} \quad (7)$$

where δ_{zu} , δ_{zl} are the upper and lower extrapolation lengths, respectively, and

h_c is the distance from the bottom of the UO_2 to the critical moderator level.

Values of δ_r , δ_{zu} , δ_{zl} were obtained from the flux distributions and these are listed in Table 18.

Table 18. Extrapolation Lengths

Date	R (cm)	h (cm)	h _c (cm)	(a)		(b)		
				z' ₀ (cm)	δ _r (cm)	δ _{zu} (cm)	δ _{z1} (cm)	δ _z (cm)
4/11/59	127.1 [±] 1.7	222.6 [±] 0.5	189.4 [±] 0.2	83.4 [±] 0.1	31.6 [±] 1.7	5.3 [±] 0.3	27.9 [±] 0.3	33.2 [±] 0.5
17/11/59	128.2 [±] 1.8	222.5 [±] 0.8	188.9 [±] 0.2	83.7 [±] 0.2	32.7 [±] 1.8	6.0 [±] 0.4	27.6 [±] 0.4	33.6 [±] 0.8
5/11/59	127.8 [±] 1.6	222.2 [±] 1.2	189.9 [±] 0.2	83.4 [±] 0.2	32.3 [±] 1.6	4.6 [±] 0.6	27.7 [±] 0.6	32.3 [±] 1.2
10/12/59	132.7 [±] 1.5	211.0 [±] 1.0	176.3 [±] 0.2	75.5 [±] 0.2	37.2 [±] 1.5	4.7 [±] 0.5	30.0 [±] 0.5	34.7 [±] 1.0
11/12/59	129.1 [±] 1.5	210.0 [±] 0.9	176.8 [±] 0.2	77.2 [±] 0.2	33.6 [±] 1.5	5.4 [±] 0.5	27.8 [±] 0.5	33.2 [±] 1.0
14/12/59	128.7 [±] 1.1	209.2 [±] 0.6	176.4 [±] 0.2	76.9 [±] 0.1	33.2 [±] 1.1	5.1 [±] 0.3	27.7 [±] 0.3	32.8 [±] 0.6
16/12/59	129.5 [±] 1.4	207.8 [±] 0.6	173.1 [±] 0.2	74.9 [±] 0.1	34.0 [±] 1.4	5.7 [±] 0.3	29.0 [±] 0.3	34.7 [±] 0.6
17/12/59	130.5 [±] 1.5	208.6 [±] 0.6	173.2 [±] 0.2	75.1 [±] 0.1	35.0 [±] 1.5	6.2 [±] 0.3	29.2 [±] 0.3	35.4 [±] 0.6
6/1/60	129.6 [±] 0.9	221.3 [±] 1.7	187.3 [±] 0.2	82.6 [±] 0.2	34.1 [±] 0.9	5.9 [±] 0.9	28.1 [±] 0.9	34.0 [±] 1.7
7/1/60	127.8 [±] 0.9	221.4 [±] 1.1	187.4 [±] 0.2	82.4 [±] 0.2	32.3 [±] 0.9	5.2 [±] 0.6	28.3 [±] 0.6	34.0 [±] 1.1

R_c = 95.5 cm

(a) z'₀ = z₀ - 4.76 cm is the distance from center of pile to bottom of UO₂.

(b) δ_{z1} = $\frac{h}{2}$ - z'₀

CONCLUSIONS

Buckling and Cd ratio measurements have been made in ZEEP in a hexagonal lattice of 7-element UO_2 clusters spaced at 24.56 cm for different moderator purities. The effect of excluding the coolant upon B^2 and the Cd ratio was also measured for one moderator purity. The buckling results obtained were as follows,

$$B^2 = 5.565 \pm 0.034 \text{ m}^{-2} \text{ (99.511 atom \% D}_2\text{O)}$$

$$B^2 = 5.623 \pm 0.034 \text{ m}^{-2} \text{ (99.526 atom \% D}_2\text{O)}$$

$$B^2 = 5.799 \pm 0.034 \text{ m}^{-2} \text{ (99.745 atom \% D}_2\text{O)}$$

and $B^2 = 5.751 \pm 0.024 \text{ m}^{-2} \text{ (99.745 atom \% D}_2\text{O, coolant excluded)}$

These buckling results agree, within $\sim 2\%$, with calculated values obtained from the program of Duret and Marriott⁽³⁾. The measured variation of buckling with D_2O purity is also in excellent agreement with the calculations.

The Cd ratios obtained for 0.051 cm diameter 0.50 cm long Mn-Ni wires placed at interstitial positions in the core were as follows,

$$R_{Cd} = 36.31 \pm 0.11 \text{ (99.511 atom \% D}_2\text{O)}$$

$$R_{Cd} = 36.51 \pm 0.12 \text{ (99.526 atom \% D}_2\text{O)}$$

$$R_{Cd} = 35.69 \pm 0.14 \text{ (99.745 atom \% D}_2\text{O)}$$

$$R_{Cd} = 33.13 \pm 0.12 \text{ (99.745 atom \% D}_2\text{O, coolant excluded)}$$

The differences in these results can be explained on the basis of the different slowing-down powers of the various lattices and also, in the case with the coolant excluded, by the change in thermal neutron lifetime.

ACKNOWLEDGEMENTS

The authors wish to thank all who contributed in any way throughout the course of this work, and in particular W. Dickerson, K.J. Hohban and D.J. Roberts who helped in the preparation and performance of the experiments. They would also like to thank J.T.R. Young who prepared some of the drawings and Miss E. Gehlert who typed the manuscript. They are also grateful to M.F. Duret for modifying his program and also for running it on the computer for the cases which were of interest here. Helpful discussions with E. Critoph, D.W. Hone and A.G. Ward are also acknowledged.

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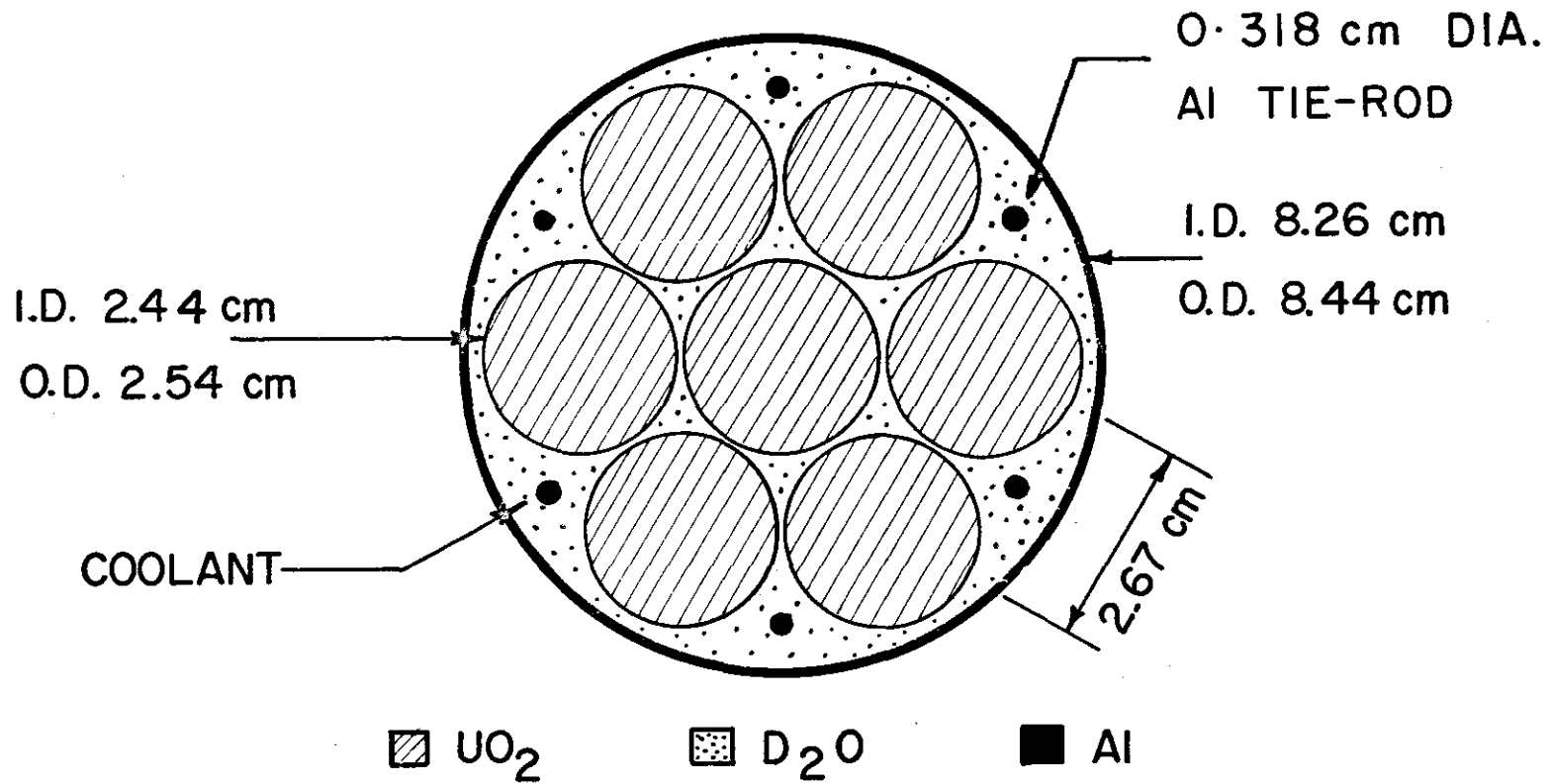


FIG. 1: 7-ELEMENT 2.40 cm UO_2 FUEL CLUSTER

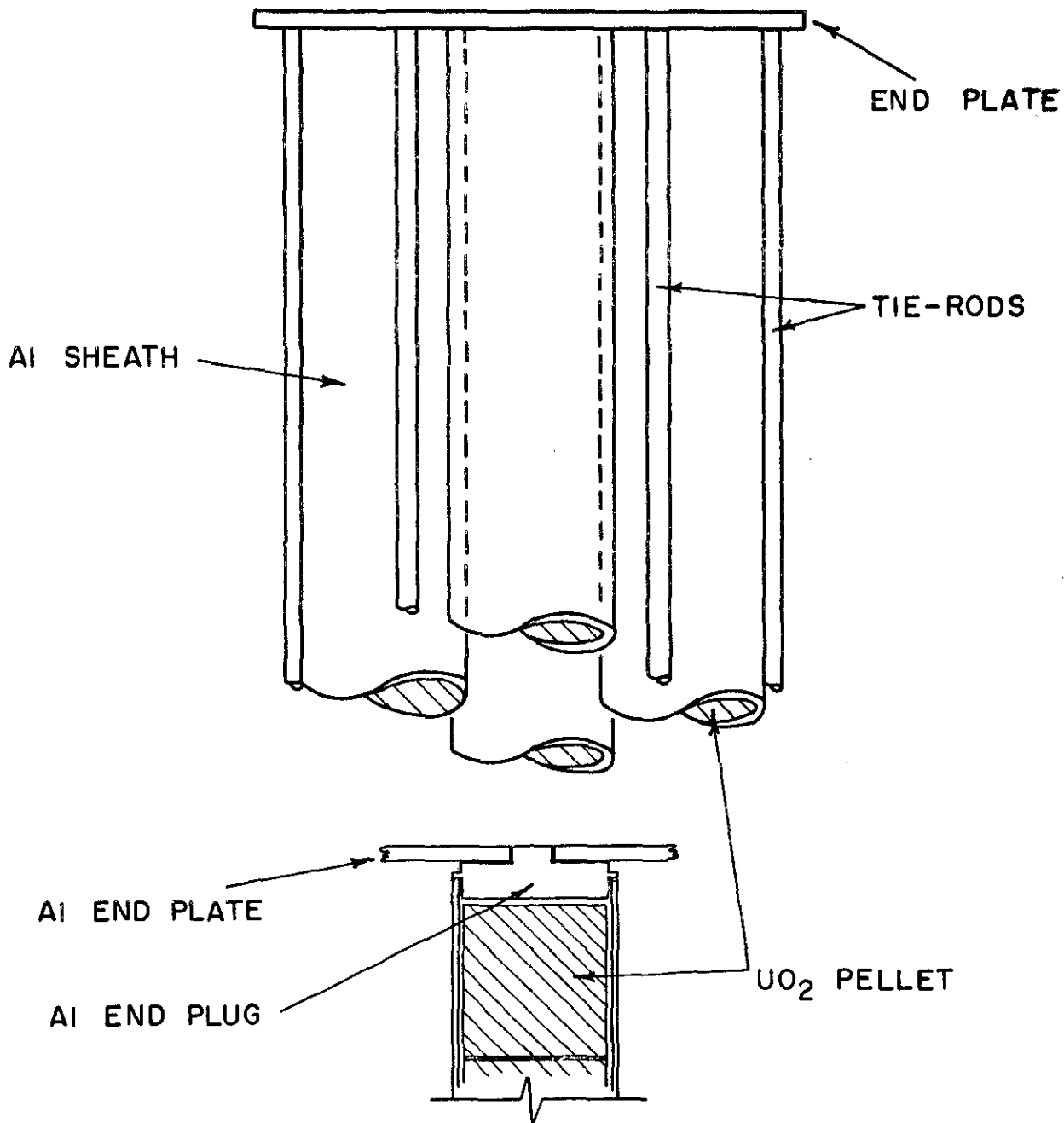
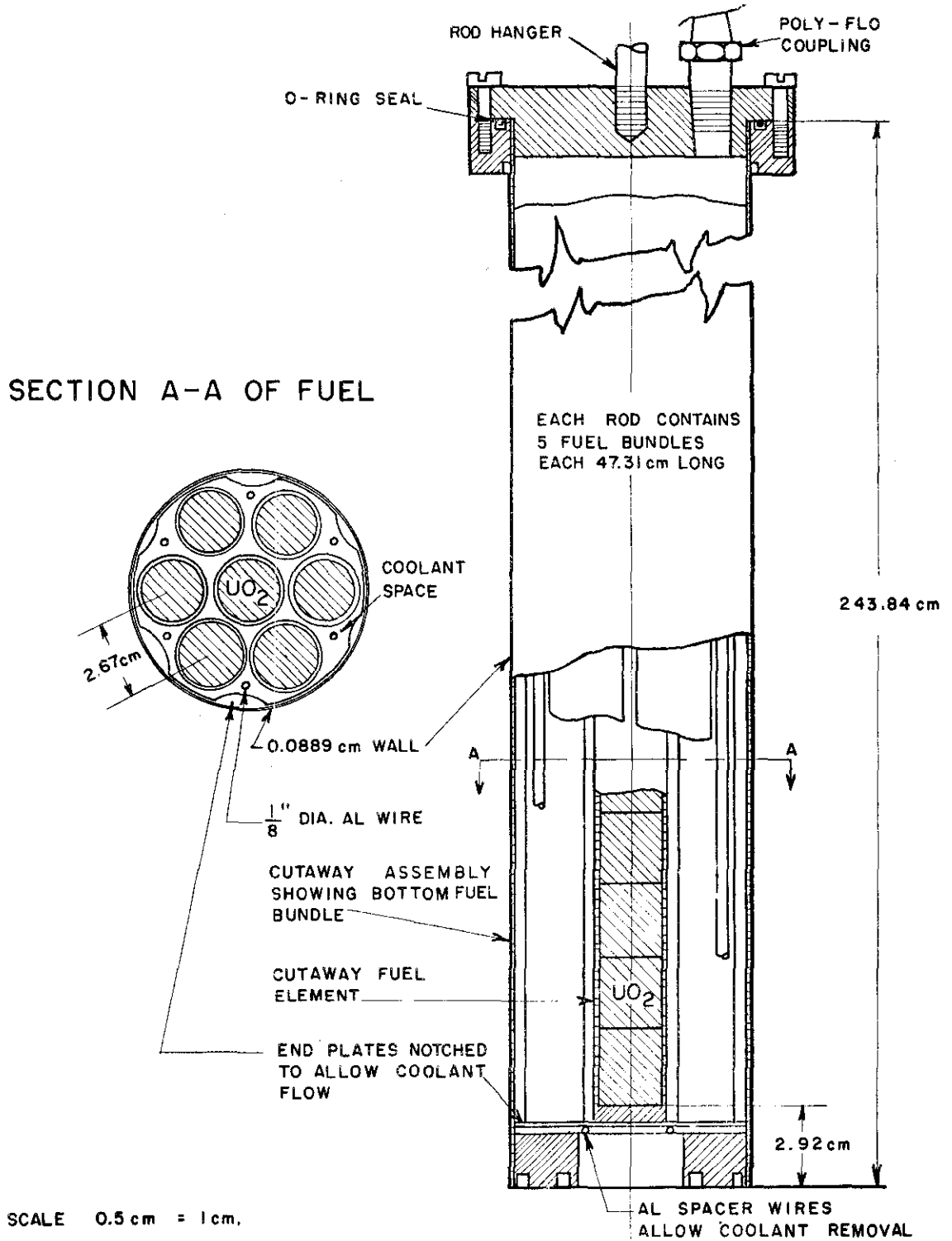
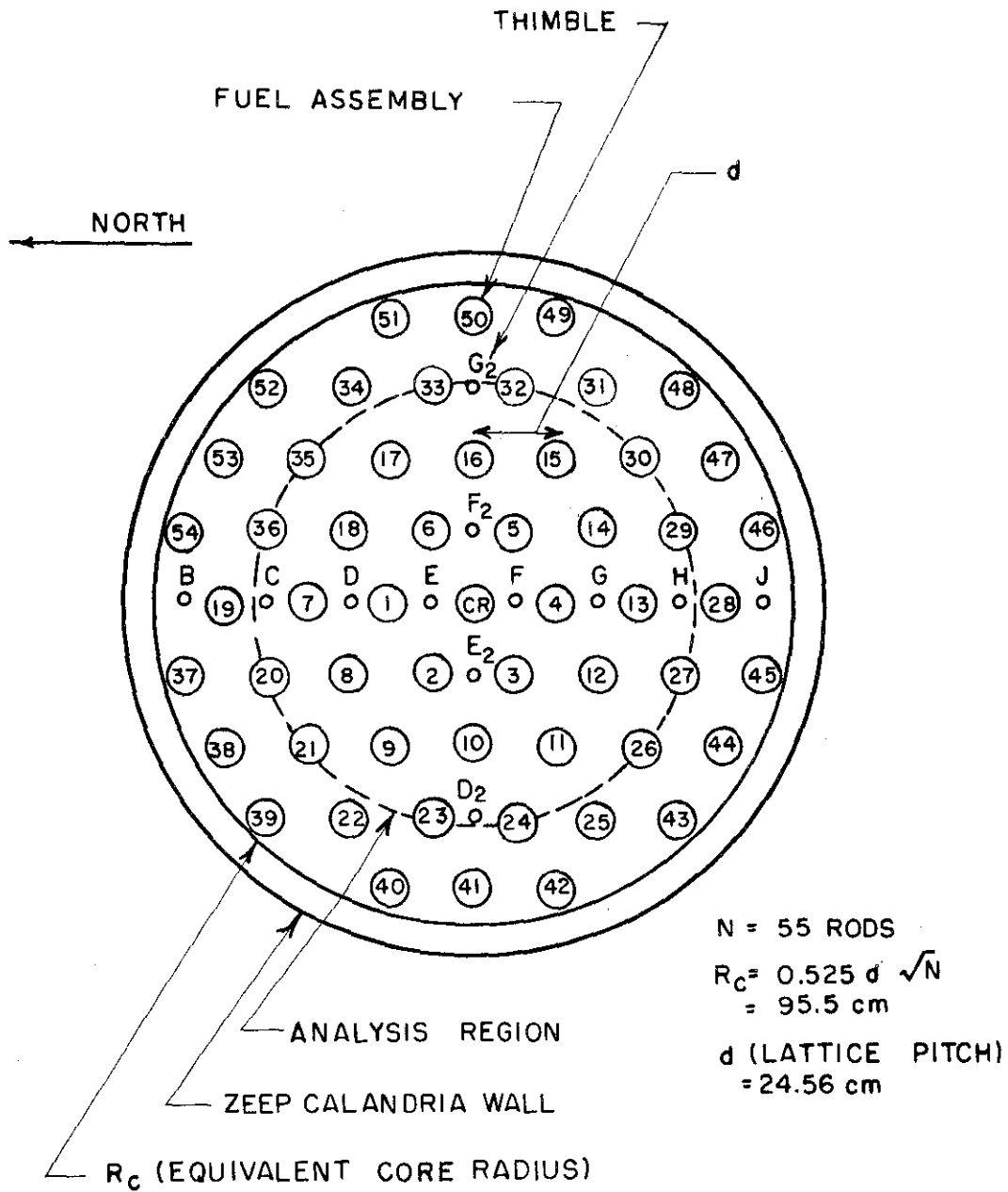


FIG. 2: DETAILS OF FUEL BUNDLE



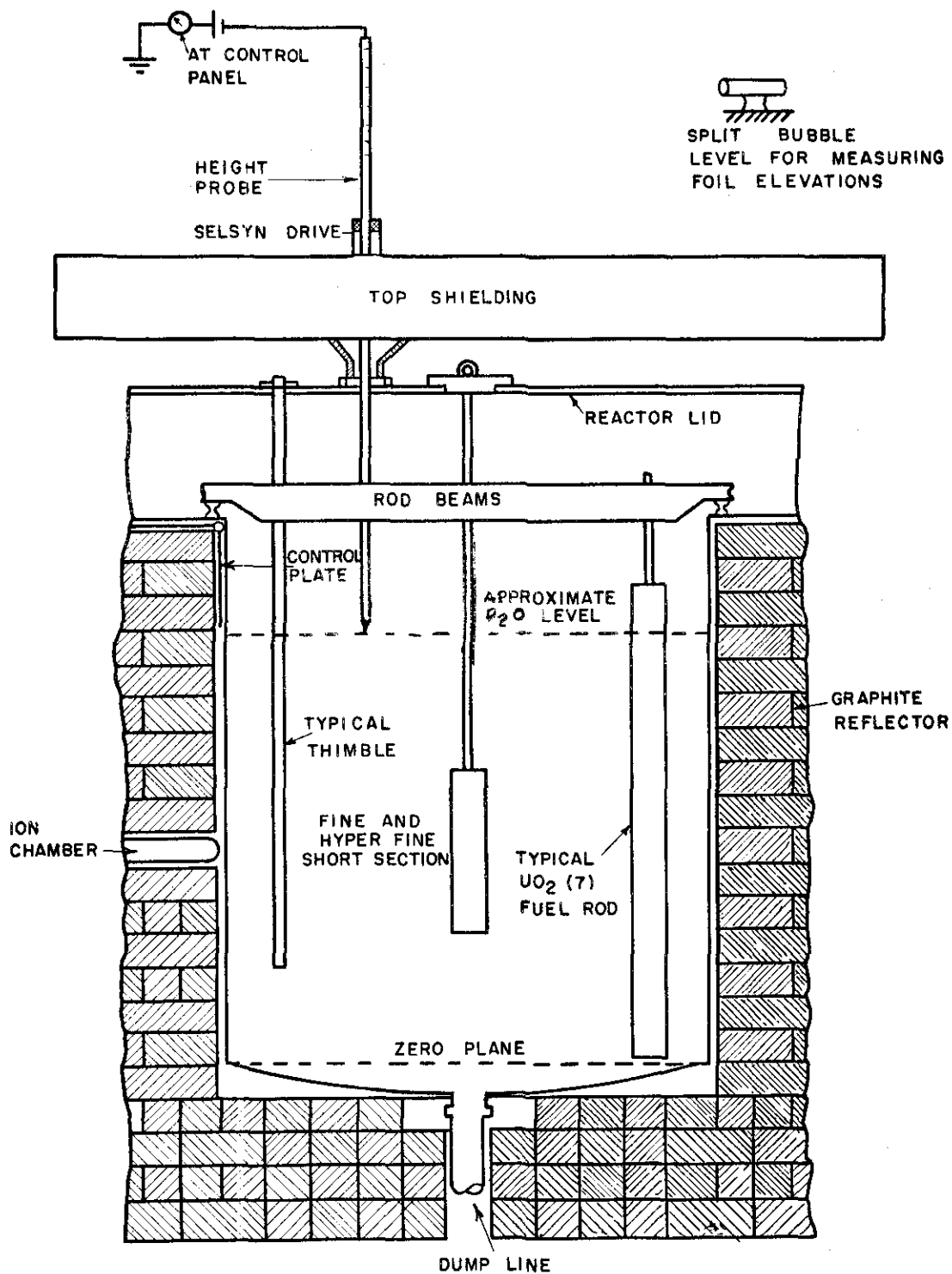
CUTAWAY VIEW OF FUEL ROD
FIGURE 3



CROSS SECTION OF 24.56 cm

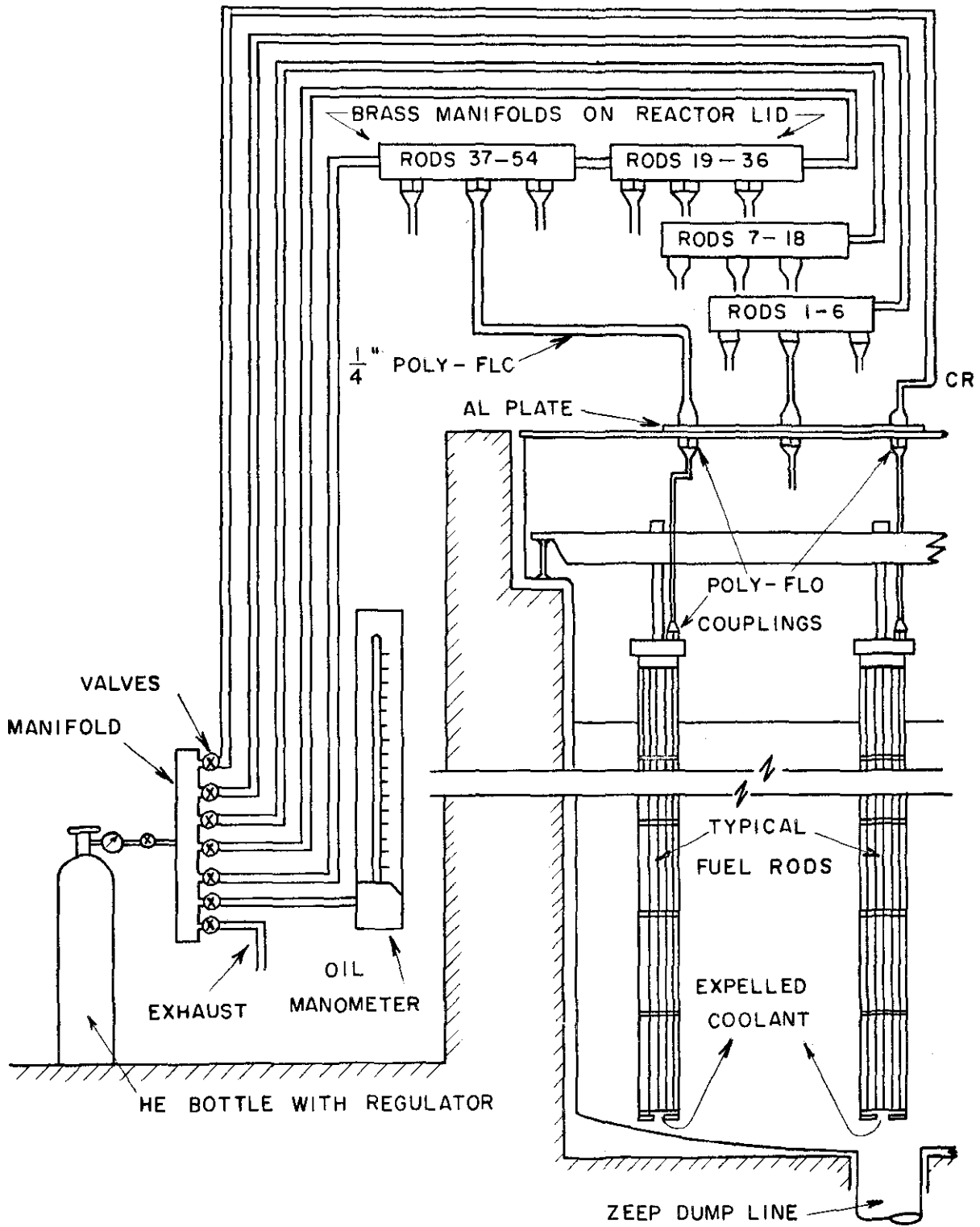
UO₂ (7) LATTICE IN ZEEP

FIGURE 4



CROSS-SECTION OF ZEEP REACTOR

FIGURE 5



COOLANT EXCLUSION CIRCUIT

FIGURE 6

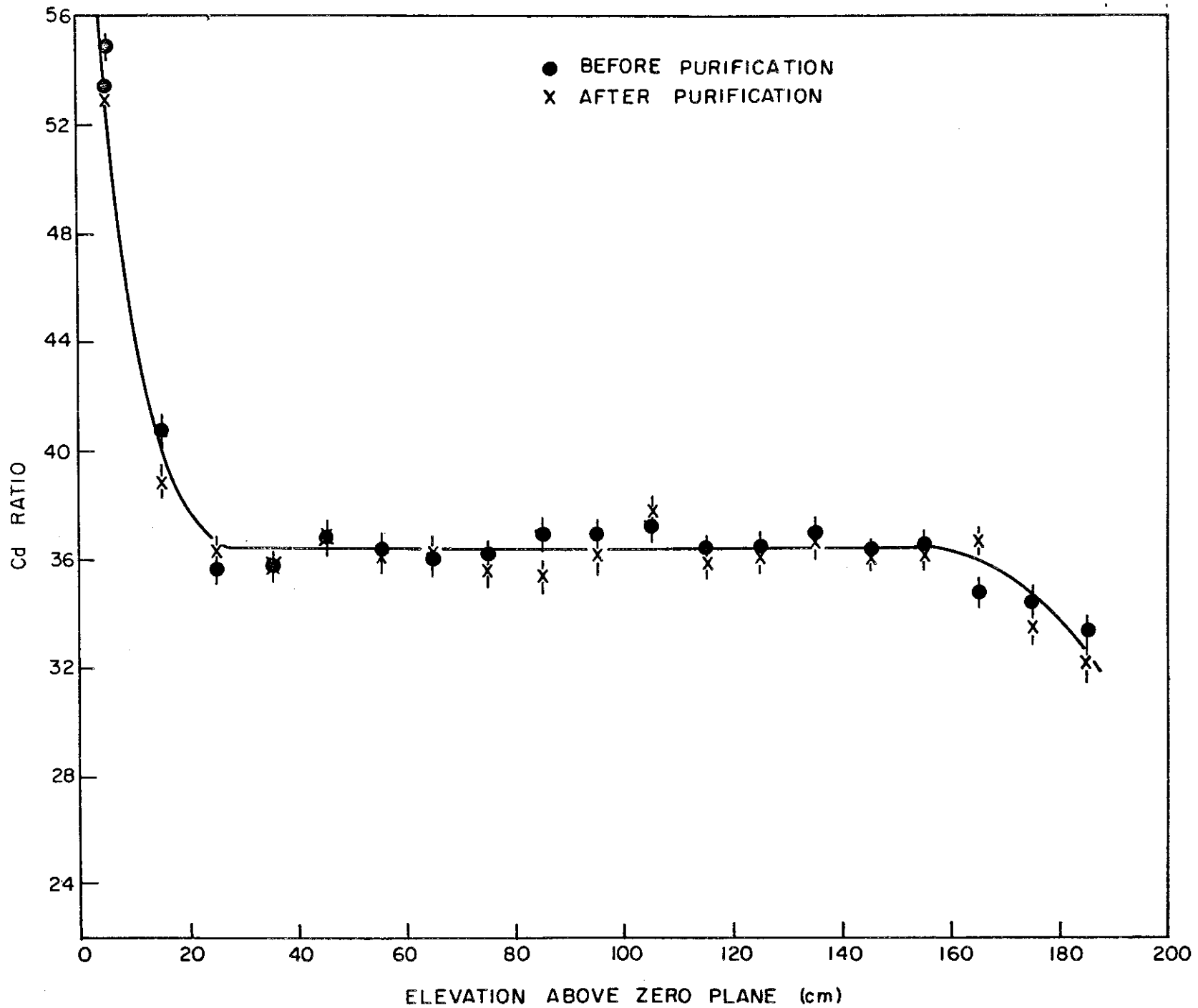


FIG. 7: AXIAL VARIATION OF Cd RATIO-ZEEP D₂O

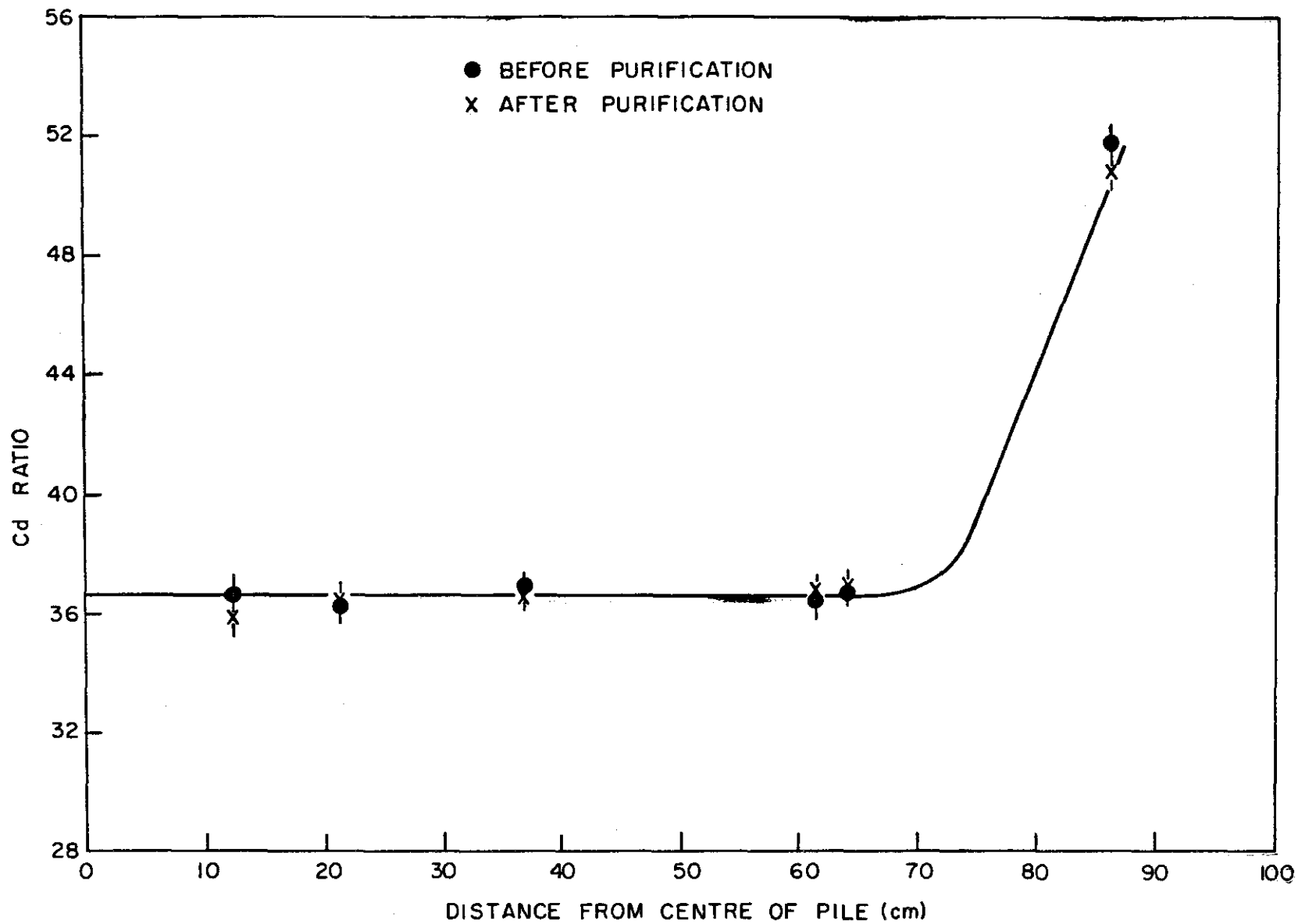


FIG. 8 : RADIAL VARIATION OF Cd RATIO -ZEEP D₂O

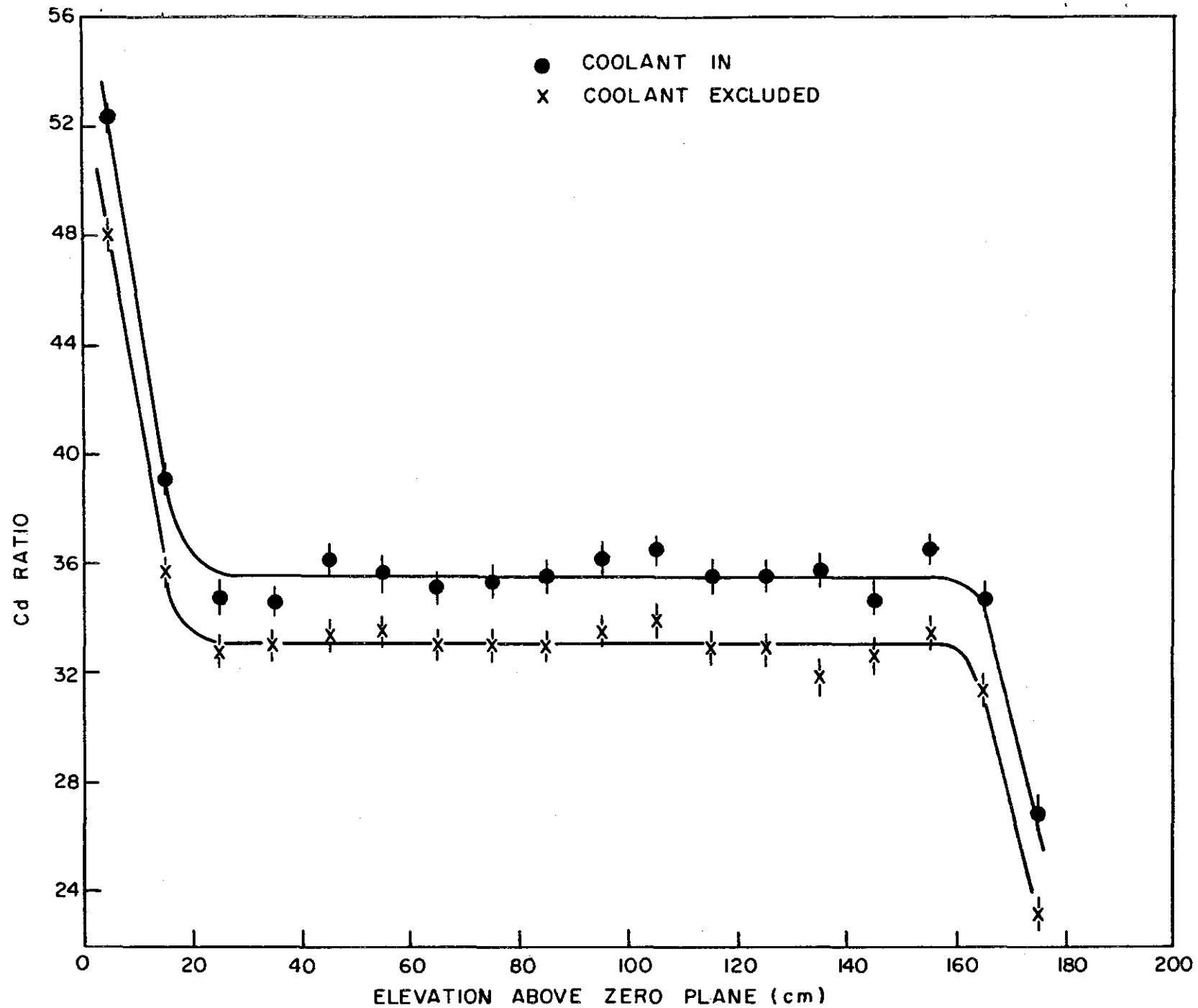


FIG. 9 : AXIAL VARIATION OF Cd RATIO - ZED-2 D₂O

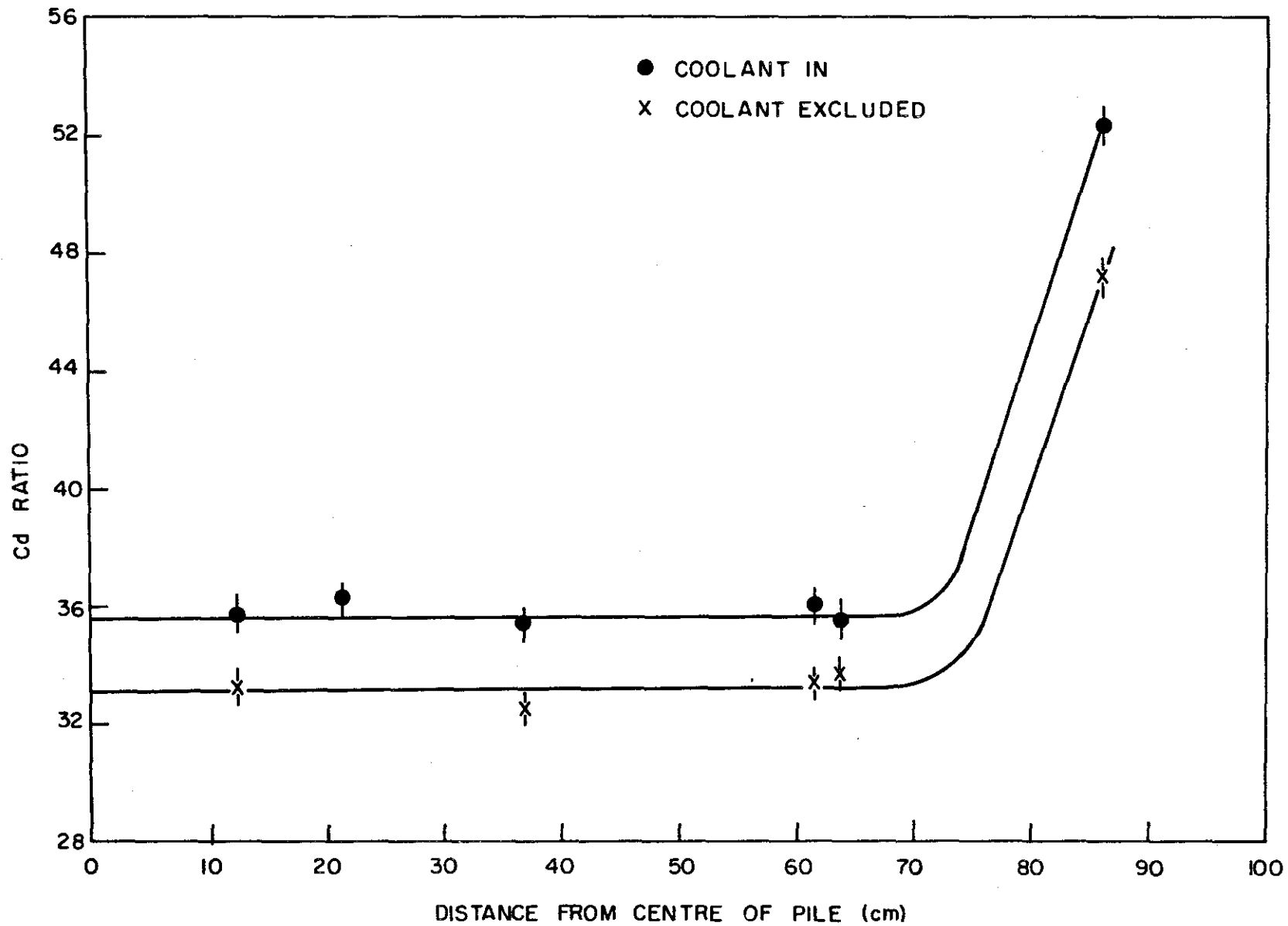


FIG. 10 : RADIAL VARIATION OF Cd RATIO-ZED-2 D₂O

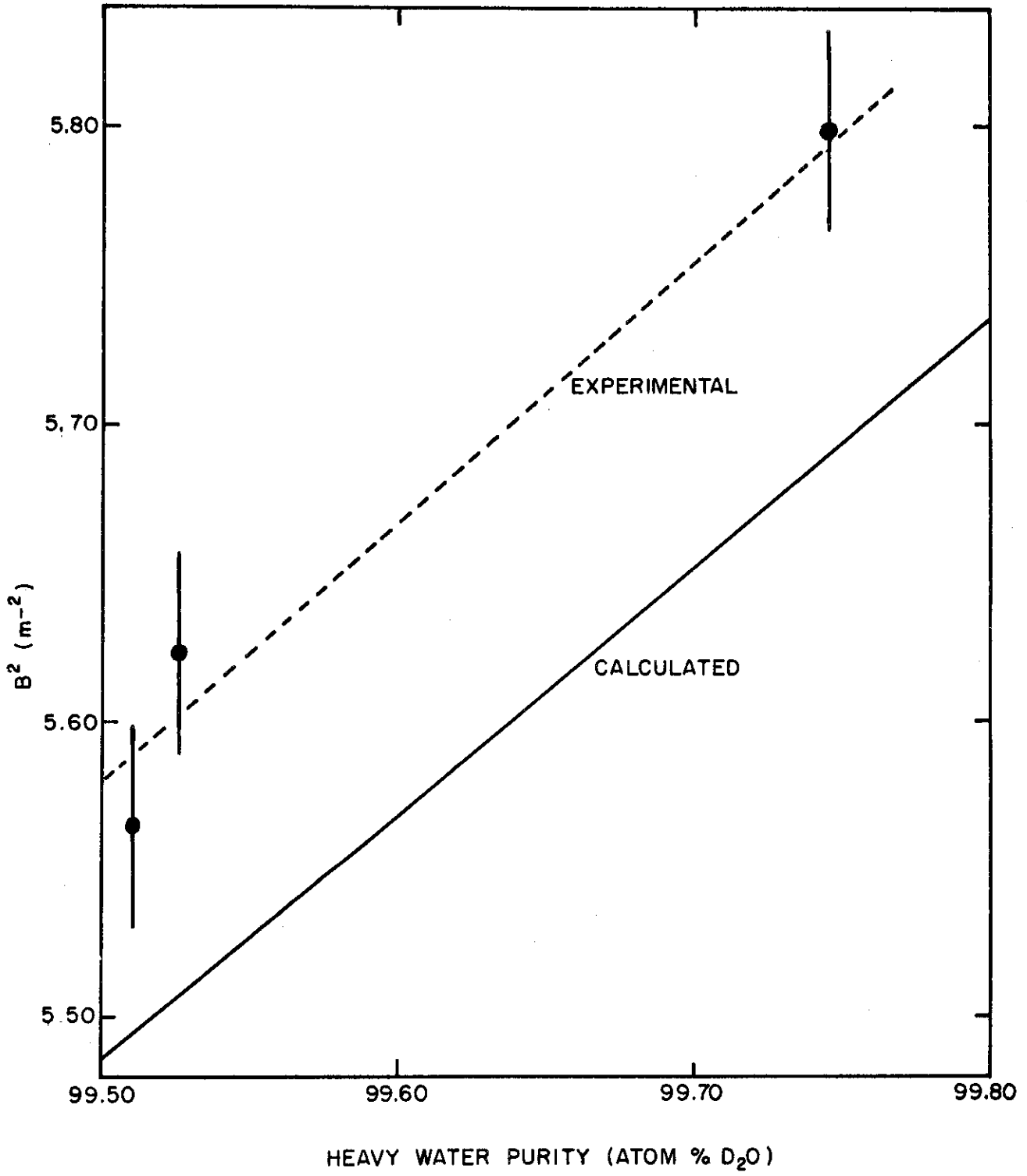


FIG. II BUCKLING vs MODERATOR PURITY