

Atomic Energy of Canada Limited

LATTICE MEASUREMENTS WITH 7-ELEMENT UO_2
CLUSTERS IN ZED-2

Part I: Bucklings over a range of spacings
with three coolants

CRRP-1072

by

G.A. BEER and D.W. HONE

Chalk River, Ontario

January, 1962

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SYNOPSIS

Buckling measurements have been made in ZED-2 in a series of hexagonal lattices of 55 7-element UO_2 clusters with spacings from 18 cm to 36 cm. Three materials in the cluster coolant region were investigated:

- i) D_2O of moderator purity.
- ii) Helium - to simulate a voided condition.
- iii) An organic liquid, HB-40.

The experimental results are compared with values calculated using the latest Chalk River lattice recipes.

Buckling measurements made previously with these 7-element UO_2 clusters in ZEEP are in agreement with the measurements made in ZED-2.

A short description of the ZED-2 reactor has been included.

Chalk River, Ontario

January, 1962

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INTRODUCTORY REMARKS ON 7-ELEMENT CLUSTER MEASUREMENTS

Part of the proposed NPD-2 initial fuel charge will contain 7-element clusters of sintered UO_2 pellets clad in Zircaloy-II. To help determine lattice parameters for these rods, similar 7-element UO_2 fuel clusters, but with aluminum cladding, have been obtained and a series of lattice measurements has been made with this fuel in the D_2O moderated critical assembly ZED-2.

Measurements were made in a lattice of 55 rods at hexagonal spacings within the range 18 cm to 36 cm for three different coolant conditions:

- a) D_2O of the same purity as the moderator,
- b) coolant voided (coolant region filled with helium) and
- c) an organic liquid, HB-40

(for the organic liquid measurements 54 ZEEP rods were placed as drivers around the central core of 55 UO_2 rods to increase the reactivity).

This report is the first of a series which will describe these lattice measurements. It summarizes the buckling measurements, the mid-rod manganese cadmium ratio measurements, and lists the deduced extrapolation lengths. Reports to follow in this series will deal with:

- i) fine structure measurements,
- ii) void coefficient measurements,
- iii) neutron spectrum and temperature measurements, and
- iv) initial conversion coefficient measurements.

It may be noted that a previous report by Beer and Green⁽¹⁾ lists buckling and cadmium ratio measurements made with 55 of the above fuel rods arranged in a 24.56 cm hexagonal lattice in ZEEP. Two moderator purities were used, one of which was very close to that used in ZED-2, 99.74 atom %, and the other 99.526 atom %.

A fairly complete description of the ZED-2 reactor is included in Part I.

INTRODUCTION

This report describes buckling and manganese wire Cd ratio measurements made in ZED-2 in a hexagonal array of 55 7-element UO_2 clusters at spacings within the range 18 cm to 36 cm. Three cases were studied:

- a) Coolant space filled with D_2O of the same purity as the moderator.
- b) Coolant space voided by displacing the D_2O with helium.
- c) Coolant space filled with an organic liquid, HB-40.

The bucklings and Cd ratios for D_2O -cooled and voided rods were measured for each of 7 lattice pitches. The excluded case was not measured at the smallest pitch because the reactivity was insufficient. Bucklings only (i.e. no cadmium ratios) were measured at five spacings for organic-cooled rods immediately after cases (a) and (b) were completed. In resetting the lattice for the organic-cooled rod measurements no attempt was made to return rods filled with organic to the same lattice position they had occupied for cases (a) and (b).

The D_2O purity decreased from 99.745 atom % D_2O to 99.715 atom % during the D_2O -cooled and voided lattice measurements; and from 99.715 atom % to 99.701 atom % during the organic cooled experiments. To facilitate intercomparison, the buckling results have been adjusted to 99.730 atom % D_2O for the D_2O -cooled and voided lattices using the corrections calculated for D_2O -cooled rods by Booth⁽²⁾. The organic-cooled results were corrected to 99.70 atom % using Primeau's correction factors⁽³⁾.

Buckling and Cd ratio values measured in the 24.56 cm lattice in ZED-2 were compared with values measured in ZEEP which have been reported in reference 1. The moderator temperature and purity corrections calculated by Booth⁽²⁾ were used to correct the ZEEP data to equivalent ZED-2 conditions. The comparison showed good agreement.

THE CHALK RIVER D₂O MODERATED CRITICAL ASSEMBLY, ZED-2

To facilitate description of experimental procedures in the recently constructed ZED-2 reactor, a discussion of the major reactor components and their operation has been included in this report. A more detailed description is available⁽⁴⁾.

1. General

ZED-2 is a large D₂O-moderated lattice testing reactor which is essentially an enlarged version of the ZEEP reactor. Its purpose is to allow accurate measurements of lattice parameters for the large fuel assemblies and wide lattice spacings planned for Canadian power reactors.

The reactor vessel (calandria) and its associated graphite reflector and D₂O pump and drain circuits are enclosed within a 7.2 metre square reactor well. The well has 45 cm thick concrete walls which extend from the sub-basement floor to the mezzanine floor level. The lower level walls are light concrete while the upper levels, around the reactor, are heavy concrete. Figure 1 shows a cross-sectional view of the reactor. A 1.05 metre deep 'header room' which contains the remotely operated lattice change mechanism is located within the top of the reactor well. The bottom of the header room is supported by the side graphite reflector and a bracket on the reactor well and is sealed to the open top of the calandria by a flexible rubber ring seal. Access to the room (and consequently to the calandria) can be had either by removal of a 3.3 metre diameter revolving lid located at mezzanine floor level or through aluminum hatches which are clamped to this lid. Two rolling radiation shields provide easy access to the revolving lid. Side access doors to the reactor well are also provided.

A freezer-drier unit located in the sub-basement is used to dry the calandria when required. It is also used to remove water from air which breathes into or out of the reactor vessel (due to atmospheric pressure changes) through a pressure relief pipe during normal operation.

2. Control and Safety Circuits

The heavy water is stored in three large interconnected stainless steel 'dump' tanks in the sub-basement. It can be transferred to the calandria at a rate of up to 35 cu. ft. (11 cm increase in water level) per minute. Various valves and two centrifugal shaft-seal pumps are used to achieve any particular rate. Moderator may be drained from the calandria into one of the dump tanks at a rate which is continuously variable up to about 37 cu. ft. (12 cm) per minute through a 3-inch pipe circuit, or at a fixed slow rate through a 1-inch pipe circuit. Reactor control is achieved by adjustment of the moderator level within the calandria.

To shut down the reactor quickly, moderator is removed rapidly (e.g., 200 cm in about 8 seconds) from the calandria through three 43.8 cm diameter dump lines which connect it to the dump tanks. Fast acting dump valves in these lines open when the reactor is tripped. Three vent return ducts allow for counterflow of air from the tanks to the calandria during a dump.

The reactor may be tripped 'by hand' at several locations in the building or automatically by signals from the safety instrumentation. Three TQU ion chambers are used to measure the reactor power (neutron flux). The main trip signals which these ion chambers ultimately provide are three over-power signals and two rate-of-rise signals.

Additional shutdown capacity may be supplied by up to 12 cadmium absorber rods which are dropped into the reactor core when a reactor irradiation is finished. These units are not part of the primary safety circuit.

Fine adjustment of reactivity (required for some experiments) is provided by an absorbing control ring which surrounds the calandria and moves in the 2.86 cm wide gap between the calandria and the graphite reflector. The absorbing element is a 12.1 cm wide cadmium sheet contained in a stainless steel support. During normal reactor irradiations the control ring is kept in the fully-up position.

3. Calandria

The calandria is a cylindrical tank having an inside diameter of 336 cm and a depth of 334 cm. It is constructed of 57S aluminum which is 0.635 cm thick on the sides and 2.97 cm thick on the bottom. The three 43.8 cm diameter dump lines are welded to the bottom spaced 120° apart just outside a circle of diameter 213 cm. The calandria rests on the graphite bottom reflector.

4. Reflector

The calandria is surrounded by a graphite reflector 60 cm in mean radial thickness on the sides and 90 cm thick on the bottom. The graphite is stacked in block form on a steel pad which in turn is supported by the reactor well. The top of the side reflector is 315 cm above the calandria floor.

The graphite has a density of 1.63 gm/cm³ and an average cross section for thermal neutron capture of 4.18 millibarns.

Provision is made for the removal of a 152.4 cm wide by 152.4 cm high section of the side reflector and a 152.4 cm diameter section of the bottom reflector.

5. Lattice Change Mechanism

The fuel rods are suspended in the calandria from the lattice change mechanism which occupies the main volume of the header room. The mechanism consists of eleven steel beams straddling the top of the calandria from which rods may be hung on offset hangers. Remotely operated mechanical-hydraulic mechanisms are provided either to move the beams across the calandria or to move a row of hangers along the beams, thus permitting a change in lattice spacing for either square or hexagonal lattices. The unit is supported by steel pads bolted to the wall of the reactor well.

6. Measurement of the D₂O Level in the Calandria

The moderator level within the calandria is measured roughly with a pressure transducer which senses D₂O pressure at the bottom of the calandria. A very accurate measurement is obtained with a motor-driven drum-and-cable device which lowers a 10 lb.

probe into the calandria to touch the surface of the water; when electrical contact is made with the D_2O the motor is automatically stopped and the water level is registered at the control console on a mechanical counter. When determining a D_2O level the average of six readings is used. The standard deviation of a typical set of readings is about 0.002 cm. Over the range from 0 to 300 cm an absolute accuracy of ± 0.1 cm is obtained.

The probe travels up or down about 10 cm inside the calandria wall and is protected by a perforated aluminum tube.

7. Measurement of Moderator Temperature

Five recording thermocouples are placed at known elevations about 5 cm inside the calandria wall. The five temperatures will reproduce within $\pm 1/10^\circ F$ during a specific temperature measurement; however the absolute accuracy of these values is the order of $1^\circ F$.

EXPERIMENTAL

1. Description of Fuel Assemblies and Lattices

A cross sectional view of the 7-element UO_2 fuel cluster is given in Fig. 2. The UO_2 is 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 2.438 cm, a wall thickness of 0.051 cm and a length of 46.5 cm to form a cluster 'element'. Seven such elements were fastened to 0.238 cm thick end plates in a hexagonal pattern with a centre-to-centre spacing of 2.667 cm. The overall length of a fuel bundle is 47.30 cm. Five bundles loaded into a 1S aluminum tube with an inside diameter of 8.256 cm and a wall thickness of 0.089 cm formed one fuel assembly. No attempt was made to align the elements in an assembly. The gap between UO_2 in adjacent clusters within these assemblies was 1.63 cm. Fig. 3 shows the details of the bundle construction and Fig. 4 is a sketch of the complete assembly.

When D_2O was the coolant, the heavy water entered the coolant space from the calandria through a hole in the bottom of the containing tube. The end plates of the bundles were notched and short lengths of 0.31 cm diameter aluminum wire were placed below the bottom bundle to allow free movement of the water in the tube. To exclude heavy water from the coolant space, helium under pressure was introduced through the poly-flo coupling as shown in Fig. 4. When the organic liquid was used as the coolant the bottom hole in the assembly was plugged, and the coolant tube was filled with organic liquid to a level which just covered all five fuel bundles. Care was taken to ensure that the liquid was free of bubbles.

The hydrogen impurity in the heavy water was compared periodically to a standard sample and plotted as a function of time. The purity at a particular time was then obtained by interpolation. The purity changed from 99.745 atom % D_2O to 99.715 atom % for the D_2O -cooled and voided experiments and from 99.715 atom % to 99.701 atom % for the organic experiments. An analysis

for other impurities in the D_2O was obtained⁽⁵⁾ and the results are given in Table 1. The effect of the impurities can be expressed in terms of equivalent ppm of boron; the result is that the effect of the sixty-five impurities which could be looked for (hydrogen not included) is equivalent to less than 0.025 ppm boron; 1 ppm boron is equivalent to about 22 mk in the worst case (36 cm lattice), thus these impurities are equivalent to <0.6 mk for the lattices studied. The effect of only the impurities which were detected is equivalent to ~ 0.01 ppm boron.

The organic liquid was analysed for carbon and hydrogen content^(5,6) and for impurities⁽⁵⁾. Six independent measurements from three laboratories showed the amount of carbon was 90.68 weight % and the amount of hydrogen was 9.32 ± 0.08 weight %, leading to a C:H ratio of $C_{18}H_{22.0}$. The impurities looked for (32 elements) are given in Table 2; their absorption effect is equivalent to less than 10^{-4} mk. The density of the liquid was measured to be 1.01 ± 0.01 g per cm^3 at a temperature of $22.6^\circ C$, at Chalk River, and 0.9973 g per cm^3 at $27^\circ C$, at the Canadian General Electric Company⁽⁶⁾. Correcting the measurements to $20^\circ C$, using a measured coefficient of linear expansion of 0.00068 per $^\circ C$, these densities become 1.015 and 1.011, respectively.

The assemblies were hung from beams in the reactor by a gimbal suspension (shown in Fig. 8) which allowed them to swing freely in all directions. There was, however, about a 60 cm length of 6 mm iron rod which was used as a connection between the gimbal and the top of the rod assembly. A check of the overall straightness of the suspended assemblies revealed that the average deviation of the bottoms of the rods from the axis through the centre of the suspension which sits in the rod hanger was 0.16 cm. When the organic coolant was put into the assemblies the top support plates had to be removed but they were marked before removal and were replaced with the same orientation.

TABLE 1
Analysis of D₂O

Element	p.p.m.	p.p.m. boron equiv.	Element	p.p.m.	p.p.m. boron equiv.
Ag	0.006	8.1 x 10 ⁻⁵	Ni	0.05	5.6 x 10 ⁻⁵
Al	0.3	3.6	P	< 0.1	< 0.8
Au	< 0.001	< 1.2	Pr	0.01	0
B	0.008	800.0	Pd	< 0.1	< 10.9
Ba	0.008	0.1	Pt		
Be	< 0.00005	0	Sb	< 0.004	< 0.5
Bi	< 0.001	0	Si	0.01	0
Ca	0.4	6.3	Sm	< 0.002	< 189.2
Cd	0.002	110.7	Sn	< 0.001	0
Co	< 0.002	< 1.8	Ta	< 0.02	< 12.3
Cr	0.004	0.3	Th	< 0.002	< 0.1
Cu	0.02	1.7	Ti	0.0005	0
Dy	< 0.002	< 19.7	U	< 0.05	< 6.5
Eu	< 0.0005	< 19.9	V	< 0.0003	0
Fe	0.1	6.4	W	< 0.002	< 0.5
Ga	< 0.0005	0	Y	< 0.0003	0
Gd	< 0.001	< 343.9	Zn	0.02	0.4
Hf	< 0.001	< 2.0	Zr	0.0005	0
K	0.05	3.8	Rh	< 0.001	< 2.4
Li	< 0.05	< 727.6	Sc	< 0.0002	< 0.1
Mg	0.03	0.1	In	< 0.001	< 4.6
Mn	0.02	6.9	Re	0.001	3.2
Mo	0.001	0	Tl	< 0.002	0
Hg	< 0.02	< 49.9	Sr	0.002	0
Ge	< 0.001	0	Ru	< 0.004	< 0.1
Ir	< 0.002	< 8.1	Tb	< 0.002	< 0.7
Cs	< 0.05	< 16.7	Nd	< 0.002	< 1.4
La	< 0.002	< 0.1	Pr	< 0.002	< 0.2
Yb	< 0.0005	< 1.5	Ce	< 0.002	0
Na	0.05	1.6	Ho	< 0.002	< 1.1
Nb	< 0.002	0	Er	< 0.001	< 1.9

TABLE 2
Organic Coolant Impurities

Element	p.p.m.	p.p.m. boron equiv.	Element	p.p.m.	p.p.m. boron equiv.
Ag	0.003	4.0×10^{-5}	Na		
Al	0.02	0.2	Nb		
B	-	-	Ni	0.0235	5.6×10^{-5}
Ba	0.006	0.1	P		
Be	-	-	Pb	0.006	0
Bi	-	-	Pd	-	-
Ca	0.06	0.9	Pt	-	-
Cd	-	-	Sb	-	-
Co	-	-	Si	0.006	0
Cr	0.002	0.2	Sm		
Cu	0.02	1.7	Sn	0.002	0
Dy			Ta		
Eu			Th		
Fe	0.1	6.4	Ti	0.004	0.7
Ga	-	-	U		
Gd	-	-	V	-	-
Hf	-	-	W	-	-
K			Y	-	-
Li	0.004	0	Zn	0.01	0.2
Mg	-	-	Zr	-	-
Mn	-	-	Sr	0.001	0
Mo					

All of the lattices studied were hexagonal arrays of rods at various spacings. For the D₂O and voided lattices fifty-five fuel assemblies only were used and the spacings between rods were, with D₂O coolant 18, 19, 22, 24, 24.56, 28 and 36 cm and with coolant voided 19, 22, 24.56, 28 and 36 cm, see Figs. 5 and 7. For the organic-cooled experiments some ZEEP rods were used to provide extra reactivity. Six single rods and twenty-four pairs were put around the edge of the core, as shown in Fig. 6. The spacings tested were 19, 20, 22, 24 and 28 cm.

The lattice spacing was set with the remotely operated mechanism. Small adjustments of beams and rod hangers were made by hand, if necessary, to bring the rods to within ± 0.05 cm of their nominal location, except for the organic-cooled rods where the tolerance was relaxed to ± 0.1 cm. In locating the rod hangers a hole in the top, used for anchoring foil hangers, was used as a reference. This hole is coaxial with the rod suspension.

2. Buckling Measurements

The total buckling was determined by measuring neutron flux distributions throughout the core.

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 ; r,z being the cylindrical coordinates. B^2 is the buckling. For a cylindrical reactor with the origin located at distance z_0 below the centre of the flux maximum the fundamental solution of (1) is

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

where $\phi(0,0) \equiv$ the flux at the centre of the pile,

$\alpha = \pi/h$, h being the extrapolated height of the core, and

$\lambda = 2.4048/R$, R being the extrapolated radius.

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

$$\begin{aligned} B^2 &= \alpha^2 + \lambda^2 \\ &= (\pi/h)^2 + (2.4048/R)^2 \end{aligned}$$

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 ZED-2 it has been our experience that the one-group theory is valid in that central region of the core which is greater than about $1\frac{1}{2}$ migration lengths from the core boundaries. The experience has involved cadmium ratio measurements and buckling measurements in cores of different sizes and in different regions of a given core.

For the buckling measurements reported here, the relative neutron flux is measured at positions midway between rods. These are the lettered 'thimble' locations in Figs. 5 and 6. Flux detectors were placed in each of the twelve locations shown, at three levels near the vertical flux maximum. In two of the locations, E and F, detectors were distributed over the full core height. All detectors were spaced vertically at 10 cm intervals.

Copper and manganese foils were used as the neutron detectors. The Mn (10% Ni) foils were 1 cm square, weighed ~ 108 or ~ 120 mgm (there were two batches) and were spot-welded to 25 by 21 by 0.5 mm aluminum rectangular backing plates. The foils had been intercalibrated by irradiating them in large batches in ZEEP and counting the induced β activity with a TQQB electroscope. For the intercalibration irradiation the foils were put, evenly spaced, on an endless belt, about six metres in length. The belt was driven on two pulleys spaced three metres apart and supported within a thin aluminum thimble about 8 cm in diameter. This unit was inserted into the centre rod location of the ZEEP reactor. To ensure uniform irradiation the belt performed more than one thousand cycles (i.e., the attached foils moved up and down through the centre channel more than 1,000 times). The Cu foils were circular, 1.32 cm in diameter, weighed ~ 170 mgm and were glued to the same size of aluminum backing plates as above. These copper foils were weighed to a relative accuracy of $\pm 1/10\%$ and their sensitivities were assumed proportional to these weights.

Both types of foil were placed at marked positions in thin aluminum channels which were then inserted into rectangular

aluminum thimbles as shown in Fig. 9. The thimble bottoms were sealed so that when the units were hung in the moderator the foils and aluminum channels remained dry.

After irradiation the induced Mn^{56} activity ($T_{1/2} = 2.56$ hr.) was measured with a TQQB electroscopes, while the 12.8 hr. Cu^{64} γ activity was counted with NaI(Tl) scintillation counters. The corrected radial and axial distributions of activities were then fitted by the method of least squares to the radial and axial components respectively of Eqn. 2, page 11, to obtain values of λ and α , and hence $B^2 (= \lambda^2 + \alpha^2)$.

3. Cd Ratio Measurements

As an indication of the region of the lattice in which the one-group treatment could be applied, Cd ratio measurements were made for the D_2O -cooled and voided lattices at mid-rod positions using 0.051 cm diameter 0.50 cm long Mn-Ni wires. These wires were contained in aluminum or cadmium capsules 0.794 cm long having 0.076 cm walls. The capsules were mounted on aluminum backing plates which in turn were placed in the aluminum channels (see Fig. 9). The capsules were placed at 10 cm intervals along the vertical axis of the pile in thimbles E and F and at two levels near the mid-plane in the other thimbles. The activated wires were counted with scintillation counters.

4. Critical Height Measurements

In order to obtain the corrections for foil loading and the axial extrapolation lengths, critical moderator heights were determined for the various lattices. These measurements were made with the accurate height indicator, as previously described. Thus the height differences due to 'loading' effects of the foils were known to an accuracy of about ± 0.003 cm. The relation between the heavy water heights and the levels of the foils - required for determination of extrapolation lengths - was known to about ± 0.1 cm.

5. Coolant Exclusion Technique

Buckling and Cd ratio measurements were made at a number of spacings with the D_2O excluded from the coolant region in all 55 rods.

The coolant tubes which contained the fuel bundles were made airtight at the top (see Fig. 4) and each was fitted with 1/4" poly-flo tubing. The 55 poly-flo tubes were taken out through seals in the revolving lid and connected to a manifold maintained at the desired pressure by helium. The helium pressure was measured with an oil manometer connected to the manifold at the helium cylinder, as shown in Fig. 4.

Upon application of helium pressure the D_2O coolant was expelled into the moderator region of the lattice through a hole in the bottom of the coolant tube. By varying the helium pressure, the D_2O level in the coolant tubes could be made to assume any desired level. The relationship between pressure and D_2O level was determined by observing, on the oil manometer, the pressure just required to completely exclude the coolant from the rods for various moderator levels. This point of complete exclusion was determined by observing the onset of bubbling in the moderator. During a foil irradiation a slightly lower pressure (lowered by the equivalent of ~ 1 cm of D_2O) was maintained.

EXPERIMENTAL RESULTS AND DISCUSSION

1. Buckling Results

The results of the flux distribution measurements are given in Tables 6 to 31 along with the moderator critical heights, the average moderator temperatures and the values of α , λ , and z_0 which were obtained from the least squares fits; each table lists relative foil activities at the indicated lattice positions (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 ZED-2 zero plane; i.e. the elevation of the central region of the calandria bottom.

The largest spread in temperature, from the top to the bottom of the moderator, was less than 1°C .

Two values of α and z_0 were obtained from each run by making least squares fits of a cosine function to the data from each of thimbles E and F. Six values of λ were obtained by fitting a J_0 function to the data from the combined West plus South (W+S) and combined East plus North (E+N) axes, or the (W+N) and the (E+S) axes for the three elevations. The error quoted for the α , λ and z_0 values is one of,

- (1) the error calculated from the assumed counting statistics (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 greatest.

The listed errors for organic-cooled bucklings, ($\pm 0.10 \text{ m}^{-2}$) were not based on the experimentally determined errors in α and λ , due partly to the relaxed tolerance on lattice spacing and partly to an unexplained asymmetry in thimbles E and F. None of the errors in B^2 determined as above exceeded $\pm 0.10 \text{ m}^{-2}$, however a number approached or equalled it.

Table 3: Buckling Values with Corrections - D₂O Coolant

Date	Hex. Space (cm)	Moderator Purity (Atom %)	α^2 (m ⁻²)	λ^2 (m ⁻²)	ΔB_L^2 (m ⁻²)	$B^2(T)$ (m ⁻²)	ΔB_T^2 (m ⁻²)	ΔB_W^2 (m ⁻²)	$B^2(20^\circ\text{C})$ (99.730A%) (m ⁻²)
Feb. 14/61	18	99.730	1.186 [±] .005	3.313 [±] .035	+0.040	4.539 [±] .035	+0.037	0	4.576 [±] .035
Feb. 15/61	18	99.731	1.191 [±] .004	3.276 [±] .037	+0.040	4.507 [±] .037	+0.037	0	4.544 [±] .037
Feb. 27/61	19	99.730	1.689 [±] .005	3.480 [±] .044	+0.039	5.208 [±] .045	+0.044	0	5.252 [±] .045
Feb. 28/61	19	99.730	1.684 [±] .006	3.476 [±] .046	+0.039	5.199 [±] .046	+0.044	0	5.244 [±] .046
Mar. 11/61	22	99.728	2.599 [±] .015	3.255 [±] .038	+0.038	5.892 [±] .041	+0.048	+0.002	5.942 [±] .041
Mar. 17/61	22	99.728	2.594 [±] .016	3.321 [±] .032	+0.038	5.953 [±] .038	+0.041	+0.002	5.996 [±] .035
Nov. 10/60	24	99.744	2.834 [±] .013	2.936 [±] .027	+0.032	5.803 [±] .030	+0.048	-.012	5.839 [±] .030
Dec. 8/60	24.56	99.739	2.827 [±] .011	2.914 [±] .017	+0.034	5.775 [±] .020	+0.041	-.008	5.808 [±] .020
Dec. 13/60	24.56	99.737	2.831 [±] .016	2.935 [±] .019	+0.034	5.800 [±] .025	+0.034	-.006	5.828 [±] .025
Jan. 11/61	28	99.730	2.673 [±] .010	2.429 [±] .012	+0.029	5.130 [±] .016	+0.031	0	5.161 [±] .016
Jan. 18/61	28	99.730	2.669 [±] .009	2.449 [±] .012	+0.029	5.147 [±] .016	+0.028	0	5.175 [±] .016
Jan. 30/61	36	99.729	1.668 [±] .009	1.750 [±] .007	+0.021	3.439 [±] .012	+0.015	+0.002	3.456 [±] .012
Jan. 31/61	36	99.729	1.660 [±] .004	1.743 [±] .005	+0.021	3.424 [±] .007	+0.015	+0.002	3.441 [±] .007

Table 4: Buckling Values with Corrections - Coolant Voided

Date	Hex. Space (cm)	Moderator Purity (Atom %)	α^2 (m^{-2})	λ^2 (m^{-2})	ΔB_L^2 (m^{-2})	$B^2(T)$ (m^{-2})	ΔB_T^2 (m^{-2})	ΔB_W^2 (m^{-2})	$B^2(20^\circ C)$ (99.730A%) (m^{-2})
Mar. 2/61	19	99.730	$1.511^{+0.006}$	$3.284^{+0.029}$	$+0.034$	$4.829^{+0.030}$	$+0.042$	0	$4.871^{+0.030}$
Mar. 13/61	22	99.728	$2.516^{+0.027}$	$3.093^{+0.027}$	$+0.036$	$5.645^{+0.038}$	$+0.046$	$+0.002$	$5.692^{+0.038}$
Dec. 16/60	24.56	99.736	$2.832^{+0.013}$	$2.804^{+0.020}$	$+0.034$	$5.670^{+0.024}$	$+0.031$	-0.005	$5.696^{+0.024}$
Dec. 19/60	24.56	99.736	$2.838^{+0.016}$	$2.839^{+0.019}$	$+0.034$	$5.711^{+0.024}$	$+0.028$	-0.005	$5.734^{+0.025}$
Jan. 13/61	28	99.730	$2.775^{+0.012}$	$2.449^{+0.013}$	$+0.030$	$5.254^{+0.018}$	$+0.029$	0	$5.283^{+0.018}$
Feb. 3/61	36	99.729	$1.846^{+0.005}$	$1.732^{+0.005}$	$+0.025$	$3.603^{+0.007}$	$+0.012$	$+0.002$	$3.617^{+0.007}$

Table 5: Buckling Values with Corrections - Organic Coolant

Date	Hex. Space (cm)	Moderator Purity (Atom %)	α^2 (m^{-2})	λ^2 (m^{-2})	ΔB_L^2 (m^{-2})	$B^2(T)$ (m^{-2})	ΔB_T^2 (m^{-2})	ΔB_W^2 (m^{-2})	B^2 (20°C) (99.70 A%) (m^{-2})
May 10/61	19	99.709	1.558 [±] .026	1.658 [±] .097	+0.022	3.238 [±] .10	+0.017	-.006	3.249 [±] 0.1
May 30/61	19	99.702	1.555 [±] .011	1.637 [±] .086	+0.022	3.214 [±] .087	+0.012	-.001	3.225 [±] 0.1
May 9/61	20	99.709	1.707 [±] .030	1.709 [±] .082	+0.016	3.432 [±] .088	+0.012	-.008	3.436 [±] 0.1
May 8/61	22	99.710	1.826 [±] .029	1.639 [±] .058	+0.023	3.488 [±] .065	+0.002	-.010	3.480 [±] 0.1
May 23/61	22	99.704	1.835 [±] .019	-	-	-	-	-	-
May 5/61	24	99.711	1.767 [±] .016	1.484 [±] .034	+0.021	3.272 [±] .038	-.004	-.011	3.257 [±] 0.1
May 11/61	28	99.708	1.337 [±] .010	1.351 [±] .024	+0.020	2.708 [±] .026	-.013	-.011	2.684 [±] 0.1

Table 6: Buckling Data - 18 cm Hex Lattice with D₂O Coolant

$h_m = 273.100$ cm		Manganese Foils				Feb. 14, 1961				Moderator Temperature 23.9°C			
Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J	
Radius cm	63.00	46.77	45.00	27.00	15.59	9.00	9.00	15.59	27.00	45.00	46.77	63.00	
Elevation cm													
260						(.2476)	(.2483)						
250						(.3308)	(.3294)						
240						(.3789)	(.3789)						
230						.4655	.4626						
220						.5611	.5616						
210						.6748	.6693						
200						[.7764]	[.7755]						
190						.8383	.8464						
180						.9126	.9051						
170						.9678	.9621						
160						1.029	1.021						
150						[1.068]	1.067						
140	(.9978)	.8941	.9173	1.024	1.072	1.079	1.078	1.074	1.023	.9055	.9067	(1.021)	
130	(1.003)	.9023	.9241	1.027	1.070	1.082	1.088	1.069	1.024	.9115	.8992	(1.028)	
120	(1.005)	.8996	.9265	1.029	1.069	1.085	1.082	1.072	(1.032)	.9142	.9047	(1.026)	
110						[1.087]	[1.084]						
100						[1.064]	[1.054]						
90						1.005	1.000						
80						.9494	.9525						
70						.8978	.8871						
60						[.8325]	[.8311]						
50						.7449	.7385						
40						.6451	.6373						
30						.5468	.5407						
20						(.4600)	(.4580)						
10						(.4276)	(.4287)						

Fitted Range 30-230 cm	Thimble		Average	λ (m ⁻¹)	
	E	F		S & W	N & E
z_0 (cm)	126.13	126.36	126.25 ^{±.11}	1.8329	1.8271
α (m ⁻¹)	1.0872	1.0911	1.0891 ^{±.0022}	1.7952	1.8483
				1.8014	1.8162
				Average 1.8202 ^{±.0096}	

Table 7: Buckling Data - 18 cm Hex Lattice with D₂O Coolant

$h_m = 272.860$ cm		Manganese Foils						Feb. 15, 1961		Moderator Temperature 23.9°C			
Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J	
Radius cm	63.00	46.77	45.00	27.00	15.59	9.00	9.00	15.59	27.00	45.00	46.77	63.00	
Elevation cm													
260						(.2314)	(.2339)						
250						(.2947)	(.3115)						
240						(.3579)	(.3586)						
230						.4307	.4406						
220						.5340	.5353						
210						.6329	.6332						
200						[.7341]	[.7323]						
190						.7973	.7993						
180						.8606	.8590						
170						.9170	.9169						
160						.9743	.9709						
150						[1.016]	[1.014]						
140	(.9510)	.8506	.8719	.9722	1.012	1.021	1.019	(1.025)	.9630	.8606	.8471	(.9708)	
130	(.9504)	.8525	.8764	.9729	1.014	1.026	1.027	(1.038)	.9684	.8643	.8510	(.9764)	
120	(.9525)	.8598	.8791	.9750	1.012	1.026	1.027	(1.023)	.9696	.8650	.8538	(.9780)	
110						[1.029]	[1.027]						
100						[1.005]	[1.000]						
90						.9531	.9530						
80						.9033	.8993						
70						.8457	.8454						
60						[.7871]	[.7838]						
50						.7038	.6964						
40						.6091	.6023						
30						.5174	.5106						
20						(.4409)	(.4330)						
10						(.4066)	(.4041)						

Fitted Range 30-230 cm	Thimble		Average	Level	λ (m ⁻¹)	
	E	F			S & W	N & E
z_0 (cm)	126.03	126.49	126.26 [±] .23	140 cm	1.8038	1.8225
α (m ⁻¹)	1.0912	1.0917	1.091 ₄ [±] .0002	130	1.8025	1.8376
				120	1.7683	1.8261
					Average 1.810 ₁ [±] .010	

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Table 9: Buckling Data - 19 cm Hex Lattice with D₂O Coolant

$h_m = 220.727$ cm Manganese Foils Feb. 28, 1961 Moderator Temperature 24.7°C

Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J
Radius cm	66.50	49.36	47.50	28.50	16.45	9.50	9.50	16.45	28.50	47.50	49.36	66.50

Elevation
cm

210	(.2182)	(.2134)										
200	(.3662)	(.3589)										
190	.4933	.4861										
180	.6174	.6089										
170	.7336	.7233										
160	.8404	.8315										
150	[.9399]	[.9290]										
140	.9994	.9933										
130	1.046	1.037										
120	1.089	1.084										
110	(.9472)	[.9114]	[.9122]	[1.058]	[1.099]	[1.126]	[1.116]	[1.108]	(1.030)	[.9248]	[.8979]	(.9762)
100	(.9422)	[.9102]	[.9143]	[1.057]	[1.105]	[1.122]	[1.114]	[1.109]	(1.026)	[.9300]	[.8970]	(.9697)
90	(.9251)	.8816	.8867	1.031	1.071	1.093	1.088	1.083	(.9993)	.9042	.8708	(.9435)
80						1.056	1.047					
70						1.008	1.000					
60						[.9492]	[.9398]					
50						.8561	(.8583)					
40						.7455	.7402					
30						.6380	.6296					
20						(.5424)	(.5342)					
10						(.4863)	(.4814)					

Fitted Range 30-190 cm	Thimble		Average	λ (m ⁻¹)		
	E	F		S & W	N & E	
z_0 (cm)	104.24	104.27	104.25 ⁺ .10	1.8626	1.8623	1.8617
α (m ⁻¹)	1.2942	1.3011	1.2977 ⁺ .0035	1.8783	1.8783	1.8722
				Average 1.864 ₄ ⁺ .013		

Table 10: Buckling Data - 22 cm Hex Lattice with D_2O Coolant

$h_m = 174.831$ cm Manganese Foils Mar. 11, 1961 Moderator Temperature 25.3°C

Thimble	B	D_2	C	D	E_2	E	F	F_2	G	H	G_2	J
Radius cm	77.00	57.16	55.00	33.00	19.05	11.00	11.00	19.05	33.00	55.00	57.16	77.00

Elevation
cm

170	(.1330)	(.1394)										
160	(.3040)	(.3068)										
150	.4583	.4562										
140	.5900	.5897										
130	.7151	.7117										
120	.8195	.8173										
110	.9107	.9049	.8445	.8883				.8980	.8307	.7020	.6940	(.6356)
100	.9672	.9631	.8983	.9425				.9526	.8834	.7502	.7354	(.6725)
90	.9943	.9901	.9220	.9705				.9848	.9104	.7679	.7546	(.6922)
80	1.000	.9937										
70	.9906	.9800										
60	.9546	.9425										
50	.8806	.8693										
40	.7847	.7757										
30	.6804	.6725										
20	(.5696)	(.5581)										
10	(.4786)	(.4717)										

Fitted Range	Thimble		Average	λ (m^{-1})		
	E	F		S & W	N & E	Level
20-150 cm						
z_0 (cm)	81.61	81.95	81.78 \pm .18	1.8089	1.8158	90 cm
α (m^{-1})	1.6107	1.6139	1.612 $_3^+$.0046	1.7970	1.7974	100
				1.8050	1.8008	110
				Average 1.804 $_1^+$.011		

Table 11: Buckling Data - 22 cm Hex Lattice with D₂O Coolant

$h_m = 174.723$ cm		Manganese Foils						Mar. 17, 1961		Moderator Temperature 24.5°C			
Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J	
Radius cm	77.00	57.16	55.00	33.00	19.05	11.00	11.00	19.05	33.00	55.00	57.16	77.00	
Elevation cm													
170						(.1532)	(.1592)						
160						(.3575)	(.3497)						
150						.5271	.5234						
140						.6785	.6766						
130						.8130	.8083						
120						.9314	.9251						
110						1.043	1.032						
100	(.7651)	.8262	.8469	(1.030)	1.075	1.106	1.094	1.084	1.016	.8501	.8316	(.7599)	
90	(.7844)	.8503	.8645	(1.049)	1.097	1.133	1.120	1.116	1.039	.8756	(.6664)	(.7858)	
80	(.7887)	.8596	.8780	(1.059)	1.110	1.142	1.137	1.126	1.047	.8810	.8593	(.7861)	
70						1.119	1.130						
60						1.080	1.078						
50						1.000	.9930						
40						.8970	.8824						
30						.7756	.7603						
20						(.6486)	(.6358)						
10						(.5449)	(.5351)						

Fitted Range	Thimble		Average
	E	F	
30-150 cm			
z_0 (cm)	81.77	81.93	$81.85^{+.15}$
α (m ⁻¹)	1.6056	1.6155	$1.610_6^{+.0050}$

Level	λ (m ⁻¹)	
	W & S	E & N
100 cm	1.8386	1.8149
90	1.8314	1.8034
80	1.8204	1.8263
Average $1.822_5^{+.0084}$		

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Table 12: Buckling Data - 24 cm Hex Lattice with D₂O Coolant

$h_m = 167.506$ cm		Copper Foils			Nov. 10, 1960			Moderator Temperature 25.6°C				
Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J
Radius cm	84.00	62.35	60.00	36.00	20.78	12.00	12.00	20.78	36.00	60.00	62.35	84.00
Elevation cm												
160						(4.592)	(4.657)					
150						(8.613)	(8.733)					
140						12.16	12.34					
130						15.54	15.59					
120						18.39	18.41					
110						20.80	20.91					
100						22.55	22.58					
90						23.61	23.56					
80	(15.04)	17.82	18.18	21.66	23.30	23.97	24.00	23.34	21.74	18.07	17.69	(15.19)
70	(14.05)	17.62	17.97	21.52	23.08	23.87	23.66	23.33	21.53	17.91	17.51	(15.09)
60	(14.43)	17.09	17.51	20.85	22.34	23.11	22.88	22.50	20.82	17.29	17.29	(14.52)
50						21.45	21.27					
40						19.22	19.01					
30						16.66	16.40					
20						(13.93)	(13.71)					
10						(11.39)	(11.19)					

Fitted Range 30-140 cm	Thimble		Average	λ (m ⁻¹)		
	E	F		N & W	S & E	Level
z_0 (cm)	78.20	78.82	78.51 ^{±.31}	1.7161	1.7392	1.7142
α (m ⁻¹)	1.6828	1.6845	1.6836 ^{±.0037}	1.6955	1.7078	1.7078
				Average 1.7136 ^{±.0079}		

Table 13: Buckling Data - 24.56 cm Hex Lattice with D₂O Coolant

$h_m = 167.187$ cm Manganese Foils Dec. 8, 1960 Moderator Temperature 24.7°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.

160	(.2332)	(.2351)										
150	(.4486)	(.4499)										
140	.6409	.6425										
130	.8098	.8143										
120	.9540	.9620										
110	1.083	1.088										
100	1.168	1.180										
90	1.230	1.230										
80	(.7736)	.9153	.9437	1.145	1.216	1.247	1.258	1.225	1.132	.9383	.9150	(.7758)
70	(.7675)	.9101	.9332	1.138	1.207	1.243	1.246	1.222	1.131	.9333	.9129	(.7688)
60	(.7414)	.8819	.9023	1.101	1.165	1.200	1.203	1.182	(1.084)	.9049	.8787	(.7399)
50						1.114	1.114					
40						1.000	.9990					
30						.8635	.8636					
20						(.7219)	(.7219)					
10						(.5879)	(.5869)					

Fitted Range 30-140 cm	Thimble		Average	λ (m ⁻¹)			
	E	F		N & W	S & E	Level	
z_0 (cm)	78.30	78.56	78.43 ^{±.13}	1.6950	1.7027	1.7198	80 cm
α (m ⁻¹)	1.6785	1.6843	1.681 ₄ ^{±.0034}	1.6961		1.7154	7C 6C
				Average 1.707 ₁ ^{±.0048}			

Table 14: Buckling Data - 24.56 cm Hex Lattice with D₂O Coolant

$h_m = 167.030$ cm	Copper Foils						Dec. 13, 1960	Moderator Temperature 23.9°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

160	(.1973)	(.1909)										
150	(.3790)	(.3663)										
140	.5355	.5355										
130	.6787	.6779										
120	.8002	.7982										
110	.9067	.9040										
100	.9818	.9842										
90	1.026	1.027										
80	1.039	1.050						1.024	.9527	.7824	.7659	(.6449)
70	1.031	1.044						1.021	.9431	.7769	.7602	(.6313)
60	1.003	1.004						.9899	.9108	.7555	.7346	(.6115)
50	.9253	.9238										
40	.8352	.8403										
30	.7183	.7188										
20	(.5955)	(.5971)										
10	(.4825)	(.4855)										

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Fitted Range 30-140 cm	Thimble		Average	λ (m ⁻¹)	
	E	F		W & S	E & N
z_0 (cm)	78.54	78.45	78.49 ^{±.10}	1.7150	1.7206
α (m ⁻¹)	1.677 ₇	1.687 ₄	1.682 ₆ ^{±.0049}	1.6936	1.7271
				1.7074	1.7157
				Average 1.713 ₂ ^{±.0055}	

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Table 15: Buckling Data - 28 cm Hex Lattice with D₂O Coolant

$h_m = 173.029$ cm Copper Foils Jan. 11, 1961 Moderator Temperature 24.4°C

Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J
Radius cm	98.00	72.75	70.00	42.00	24.25	14.00	14.00	24.25	42.00	70.00	72.75	98.00

Elevation
cm

170	(.2592)	(.2717)										
160	(.7071)	(.7113)										
150	1.106	1.115										
140	1.468	1.475										
130	1.796	1.791										
120	2.065	2.071										
110	2.289	2.295										
100	2.445	(2.502)										
90	(1.381)	1.805	1.848	2.295	2.460	2.527	2.522	2.480	2.290	1.851	1.805	(1.391)
80	(1.390)	1.817	1.865	2.326	2.480	2.549	2.552	2.505	(2.299)	1.861	1.820	(1.399)
70	(1.378)	1.790	1.838	2.286	2.439	2.517	2.512	2.459	2.275	1.831	1.795	(1.377)
60						2.409	2.409					
50						2.232	2.227					
40						1.996	1.979					
30						1.712	1.701					
20						(1.407)	(1.402)					
10						(1.101)	(1.097)					

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Fitted Range 30-150 cm	Thimble		Average	λ (m ⁻¹)		
	E	F		W & S	E & N	E & N
z ₀ (cm)	81.32	81.58	81.45 ^{±.13}	1.5543	1.5518	1.5518
α (m ⁻¹)	1.6334	1.6362	1.634g ^{±.0029}	1.5579	1.5664	1.5618
				1.5581	1.5618	1.5618
				Average 1.558 ₄ ^{±.0039}		

Table 17: Buckling Data - 36 cm Hex Lattice with D₂O Coolant

$h_m = 225.422$ cm Manganese Foils Jan. 30, 1961 Moderator Temperature 23.5°C

Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J
Radius cm	126.00	93.53	90.00	54.00	31.18	18.00	18.00	31.18	54.00	90.00	93.53	126.00

Elevation cm	(.4682) (.4687) (.4577)	.7137 .7125 .6974	.7342 .7349 .7164	.9612 .9610 .9428	1.047 1.047 1.024	1.076 1.078 1.053	1.019 1.012 1.012	1.047 1.043 1.015	.9575 .9544 .9306	.7362 .7324 .7195	.7182 .7141 .7025	(.4680) (.4663) (.4572)
220	(.1107)	(.1157)										
210	(.2521)	(.2515)										
200	(.3871)	(.3876)										
190	.5107	.5131										
180	.6266	.6288										
170	.7356	.7324										
160	.8316	.8301										
150	.9119	.9157										
140	.9740	.9755										
130	1.032	1.024										
120	1.060	1.061										
110	1.076	1.073	.7342	.9612	1.047	1.076	1.019	1.047	.9575	.7362	.7182	(.4680)
100	1.078	1.074	.7349	.9610	1.047	1.078	.9625	1.043	.9544	.7324	.7141	(.4663)
90	1.053	1.024	.7164	.9428	1.024	1.053	.8922	1.015	.9306	.7195	.7025	(.4572)
80							.8016					
70							.8016					
60							.7005					
50							.5919					
40							(.4707)					
30							(.3617)					
20												
10												

Fitted Range 30-190 cm	Thimble		Average	λ (m ⁻¹)	
	E	F		S & W	N & E
z_0 (cm)	106.52	106.59	106.55 [±] .06	1.3261	1.3160
α (m ⁻¹)	1.2935	1.2906	1.2921 [±] .0038	1.3282	1.3223
				1.3295	1.3153
				Average 1.3229 [±] .0028	

Table 18: Buckling Data - 36 cm Hex Lattice with D₂O Coolant
 h_m = 225.392 cm Manganese Foils Jan. 31, 1961 Moderator Temperature 23.3°C

Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J
Radius cm	126.00	93.53	90.00	54.00	31.18	18.00	18.00	31.18	54.00	90.00	93.53	126.00
Elevation cm												
220						(.09246)	(.09348)					
210						(.2114)	(.2119)					
200						(.3236)	(.3272)					
190						.4289	.4321					
180						.5293	.5300					
170						.6204	.6198					
160						.6990	.7002					
150						.7677	.7676					
140						.8252	.8226					
130						.8631	.8610					
120						.8906	.8923					
110	(.3933)	.5995	.6158	.8051	.8779	.9027	.9023	.8810	.8037	.6208	.6007	(.3921)
100	(.3909)	.5969	.6140	.8044	.8751	.8992	.8986	.8768	.7997	.6205	.5992	(.3916)
90	(.3826)	.5850	.6041	(.7452)	.8559	.8799	.8824	.8585	.7869	.6064	.5854	(.3830)
80						.8496	.8476					
70						.8038	.8016					
60						.7469	.7477					
50						.6735	.6718					
40						.5899	.5894					
30						.4976	.4969					
20						(.4028)	(.4006)					
10						(.3016)	(.3008)					

Fitted Range 30-190 cm	Thimble		Average	λ (m ⁻¹)		
	E	F		S & W	N & E	N & E
z ₀ (cm)	106.70	106.78	106.74±.06	1.3246	1.3185	1.3185
α (m ⁻¹)	1.2885	1.2873	1.287 ₉ ±.0020	1.3253	1.3139	1.3202
				1.3188		
				Average 1.320 ₂ ±.0020		

Table 19: Buckling Data - 19 cm Hex Lattice with Coolant Voided
 $h_m = 232.285$ cm Manganese Foils Mar. 2, 1961 Moderator Temperature 24.5°C

Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J
Radius cm	66.50	49.36	47.50	28.50	16.45	9.50	9.50	16.45	28.50	47.50	49.36	66.50
Elevation cm												
220						(.2134)	(.2092)					
210						(.3433)	(.3356)					
200						(.4721)	(.4641)					
190						.5790	.5773					
180						.6890	.6779					
170						.7886	.7743					
160						.8836	.8660					
150						[.9616]	[.9470]					
140						1.004	.9889					
130						1.043	1.027					
120						1.073	1.058					
110	(.9815)	[.8775]	[.8826]	[1.006]	[1.056]	[1.094]	[1.079]	[1.065]	(1.000)	[.8975]	[.8823]	(.9919)
100	(.9773)	[.8769]	[.8816]	[1.001]	[1.050]	[1.089]	[1.078]	[1.058]	(.9909)	[.8900]	[.8720]	(.9853)
90	(.9454)	.8441	.8501	.9674	1.016	1.054	1.037	1.022	(.9594)	.8626	.8423	(.9574)
80						1.016	.9989					
70						.9627	.9503					
60						[.9102]	[.8932]					
50						.8186	.8087					
40						.7201	.7075					
30						.6181	.6063					
20						(.5337)	(.5232)					
10						(.4940)	(.4863)					

Fitted Range	Thimble		Average	λ (m ⁻¹)		
	E	F		W & S	E & N	E & J
30-190 cm				1.8127	1.8029	
z ₀ (cm)	108.50	108.54	108.52 ^{±.10}	1.7942	1.8347	
α (m ⁻¹)	1.2298	1.2286	1.229 ₂ ^{±.0024}	1.8115	1.8177	
				Average 1.812 ₃ ^{±.0080}		

Table 20: Buckling Data - 22 cm Hex Lattice with Coolant Voided

$h_m = 176.066$ cm Copper Foils Mar. 13, 1961 Moderator Temperature 25.0°C

Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J
Radius cm	77.00	57.16	55.00	33.00	19.05	11.00	11.00	19.05	33.00	55.00	57.16	77.00

Elevation
cm

170	(3.320)	(3.463)										
160	(6.954)	(7.114)										
150	10.12	10.24										
140	12.93	13.05										
130	15.45	15.56										
120	17.67	17.61										
110	19.29	19.47			19.06			19.23	18.06	15.37	14.98	(14.37)
100	20.68	20.67		19.20	20.30			20.54	19.16	16.34	15.98	(15.23)
90	21.04	21.10		19.78	20.64			21.05	19.65	16.70	16.40	(15.61)
80	21.47	21.45										
70	21.26	20.95										
60	20.47	(20.46)										
50	18.76	18.64										
40	17.02	16.61										
30	14.79	14.27										
20	(12.66)	(12.43)										
10	(10.89)	(10.84)										

Fitted Range 30-150 cm	Thimble		Average	λ (m ⁻¹)		
	E	F		W & S	E & N	E & J
z ₀ (cm)	81.42	82.63	82.02 ± .61	1.7401	1.7638	1.7610
α (m ⁻¹)	1.5779	1.5946	1.5862 ± .0084	1.7692	1.7570	1.7570
				Average 1.7586 ± .0092		

Table 21: Buckling Data - 24.56 cm Hex Lattice with Coolant Voided

$h_m = 165.173$ cm Manganese Foils Dec. 16, 1960 Moderator Temperature 23.6°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

160	(.1806)	(.1709)										
150	(.3742)	(.3683)										
140	.5455	.5430										
130	.6982	.6947										
120	.8360	.8337										
110	.9456	.9521										
100	1.038	1.032										
90	1.083	1.082										
80	(.7098)	.8160	.8397	1.014	1.073	1.108	1.108	1.088	1.004	.8422	.8204	(.7120)
70	(.7098)	.8154	.8342	1.008	1.072	1.104	1.105	1.082	1.003	.8366	.8227	(.7064)
60	(.6915)	.7932	.8167	.9790	1.042	1.070	1.070	1.056	.9748	.8146	.7996	(.5853)
50						.9984	.9994					
40						.8973	.9053					
30						.7819	.7835					
20						(.6610)	(.6651)					
10						(.5470)	(.5491)					

Fitted Range 30-140 cm	Thimble		Average	λ (m ⁻¹)			
	E	F		S & W	N & E	Level	
z ₀ (cm)	77.16	76.95	77.06 ^{±.11}	1.6787	1.6805	1.6784	80 cm
α (m ⁻¹)	1.6842	1.6816	1.6829 ^{±.0038}	1.6651		1.6704	70 60
				Average 1.6743 ^{±.0061}			

Table 22: Buckling Data - 24.56 cm Hex Lattice with Coolant Voided

$h_m = 165.199$ cm Manganese Foils Dec. 19, 1960 Moderator Temperature 23.3°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

160	(.1799)	(.1691)										
150	(.3741)	(.3682)										
140	.5432	.5377										
130	.6979	.6868										
120	.8350	.8230										
110	.9496	.9361										
100	1.035	1.023										
90	1.077	1.073										
80	1.108	1.097						(1.039)	1.008	.8374	.8158	(.7036)
70	(.7003)	.8070	.8312	1.006	1.066	1.102	1.092	(1.032)	.990	.8367	.8085	(.7000)
60	(.6825)	.7839	.8028	.9777	1.037	1.068	1.067	(.9999)	.9780	.8092	.7885	(.6785)
50						.9979	.9970					
40						.8943	.8943					
30						.7759	.7781					
20						(.6630)	(.6588)					
10						(.5418)	(.5469)					

Fitted Range 30-140 cm	Thimble		Average	λ (m ⁻¹)			
	E	F		S & W	N & E	Level	
z ₀ (cm)	77.28	76.74	77.01 ⁺ .27	1.6970	1.6940	1.6681	80 cm
a (m ⁻¹)	1.6880	1.6815	1.6847 ⁺ .0048	1.6977	1.6857	1.6857	70 60
				Average 1.685 ₀ ⁺ .0057			

Table 23: Buckling Data - 28 cm Hex with Coolant Voided

h_m	Manganese Foils		Jan. 13, 1961		Moderator Temperature 24.1°C							
	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J
Radius cm	98.00	72.75	70.00	42.00	24.25	14.00	14.00	24.25	42.00	70.00	72.75	98.00

Elevation
cm

170	(.0403)	(.0417)										
160	(.2137)	(.2247)										
150	(.3551)	.3995										
140	.5451	.5561										
130	.6918	.6980										
120	.8220	.8204										
110	.9184	.9205										
100	.9909	.9939										
90	(.5783)	.7320	.7602	.9441	1.007	1.039	1.036	1.019	.9428	.7555	.7375	(.5858)
80	(.5898)	.7422	.7721	.9566	1.026	1.053	1.050	1.028	.9581	.7664	.7522	(.5797)
70	(.5833)	.7361	.7657	.9480	1.016	1.042	1.038	1.018	.9430	.7621	(.7516)	(.5797)
60						1.011	1.000					
50						.9407	.9285					
40						.8438	.8348					
30						.7319	.7229					
20						(.6124)	(.6011)					
10						(.4868)	(.4742)					

Fitted Range 30-140 cm	Thimble		Average	λ (m ⁻¹)			
	E	F		W & S	E & N	E & N	
z ₀ (cm)	78.58	79.21	78.90 ⁺ .32	Level 90 cm	1.5667	1.5716	1.5716
α (m ⁻¹)	1.6656	1.6659	1.665g ⁺ .0036	80	1.5684	1.5596	1.5596
				70	1.5646	1.5583	1.5583
				Average 1.564g ⁺ .0042			

Table 24: Buckling Data - 36 cm Hex Lattice with Coolant Voided

$h_m = 212.017$ cm Manganese Foils Feb. 3, 1961 Moderator Temperature 22.8°C

Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J
Radius cm	126.00	93.53	90.00	54.00	31.18	18.00	18.00	31.18	54.00	90.00	93.53	126.00

Elevation
cm

220						(.0262)	(.0261)					
210						(.0635)	(.0652)					
200						(.2108)	(.2130)					
190						.3490	.3502					
180						.4827	.4818					
170						.6014	.6031					
160						.7143	.7103					
150						.8091	.8114					
140						.8856	.8896					
130						.9515	.9540					
120						.9997	.9993					
110	(.4543)	.6853	.7100	.9180	1.001	1.032	1.032	1.003	.9168	.7057	.6860	(.4530)
100	(.4596)	.6911	.7176	.9218	1.009	1.038	1.036	1.011	.9238	.7144	.6913	(.4572)
90	(.4546)	.6827	.7060	.9140	.9983	1.028	1.025	1.001	.9143	.7050	.6859	(.4505)
80						.9999	1.000					
70						.9572	.9520					
60						.8923	.9005					
50						.8089	.8097					
40						.7088	.7115					
30						.6095	.6044					
20						(.4951)	(.4916)					
10						(.3733)	(.3691)					

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Fitted Range 30-190 cm	Thimble		Average	λ (m ⁻¹)			
	E	F		W & S	E & N	E & N	
z ₀ (cm)	99.84	99.88	99.86 ^{±.07}	110 cm	1.3160	1.3209	
α (m ⁻¹)	1.3586	1.3587	1.3586 ^{±.0018}	100	1.3119	1.3145	
				90	1.3183	1.3147	
					Average 1.3160 ^{±.0018}		

Table 25: Buckling Data - 19 cm Hex Lattice with Organic Coolant

$h_m = 233.32$ cm Manganese Foils May 10, 1961 Moderator Temperature 29.0°C

Thimble	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂
Radius cm	49.36	47.50	28.50	16.45	9.50	9.50	16.45	28.50	47.50	49.36

Elevation cm	(.2179) (.3402)	(.4595 .5627 .6624 .7533 .8354 .9098 .9585 .9968)	(1.016 1.031 1.021 .9947 .9510 .8941 .8247 .7337 .6359)	(.5315) (.4358) (.3646)	(.2242) (.3461)	(.4631 .5680 .6643 .7527 .8310 .8947 .9408 .9665)	(.9877 1.000 .9845 .9505 .9132 .8564 .7970 .7168 .6218)	(.5198) (.4261) (.3598)	1.008 1.015 1.006	.9706 .9774 .9675	.9110 .9180 .9098	.8999 .9148 .9059
220												
210												
200												
190												
180												
170												
160												
150												
140												
130												
120	.9096	.9133	.9559	.9840	1.016	.9877	1.008	.9706	.9110	.8999		
110	.9178	.9258	.9647	.9944	1.031	1.000	1.015	.9774	.9180	.9148		
100	.9079	.9162	.9514	.9810	1.021	.9845	1.006	.9675	.9098	.9059		
90					.9947	.9505						
80					.9510	.9132						
70					.8941	.8564						
60					.8247	.7970						
50					.7337	.7168						
40					.6359	.6218						
30					(.5315)	(.5198)						
20					(.4358)	(.4261)						
10					(.3646)	(.3598)						

Fitted Range 40-200 cm	Thimble		Average	λ (m^{-1})				
	E	F		S & W	N & E	Level		
z_0 (cm)	111.24	112.38	111.81 \pm 5.7	1.2782	1.2873	1.2774	1.3154 1.2941	120 cm 110 100
α (m^{-1})	1.2586	1.2380	1.2483 \pm .010	Average			1.2877 \pm .038	

Table 26: Buckling Data - 19 cm Hex Lattice with Organic Coolant

$h_m = 233.65$ cm		Manganese Foils			May 30, 1961			Moderator Temperature 26.5°C		
Thimble	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂
Radius cm	42.36	47.50	28.50	16.45	9.50	9.50	16.45	28.50	47.50	49.36
Elevation cm										
210				(.3435)	(.3355)					
200				.4612	.4535					
190				.5631	.5574					
180				.6622	.6550					
170				.7508	.7435					
160				.8288	.8202					
150				.9038	.8897					
140				.9501	.9385					
130				.9897	.9681					
120	.9075	.9153	.9558	.9776	1.009	.9839	1.007	.9683	.9049	.8967
110	.9158	.9273	.9653	.9883	1.023	1.000	1.011	.9765	.9142	.9109
100	.9075	.9171	.9543	.9761	1.014	.9906	1.004	.9670	.9085	.9031
90				.9852	.9548					
80				.9452	.9161					
70				.8887	.8628					
60				.8199	.8016					
50				.7307	.7206					
40				.6353	.6266					
30				(.5306)	(.5276)					
20				(.4348)	(.4324)					
10				(.3618)	(.3610)					

Fitted Range 40-200 cm	Thimble		Average	λ (m ⁻¹)		
	E	F		S & W	N & E	N & E
z ₀ (cm)	111.22	111.58	111.40 ^{±.18}	Level 120 cm	1.2372	1.3329
α (m ⁻¹)	1.2513	1.2429	1.2471 ^{±.0042}	110	1.2459	1.3125
				100	1.2434	1.3040
			Average	1.2793 ^{±.034}		

Table 27: Buckling Data - 20 cm Hex Lattice with Organic Coolant

$h_m = 221.6$ cm		Manganese Foils			May 9, 1961			Moderator Temperature 28.5°C		
Thimble	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂
Radius cm	51.96	50.00	30.00	17.32	10.00	10.00	17.32	30.00	50.00	51.96
Elevation										
cm										
220				(.07023)	(.0791)					
210				(.2113)	(.2186)					
200				(.3452)	(.3498)					
190				.4652	.4710					
180				.5782	.5816					
170				.6834	.6844					
160				.7785	.7776					
150				.8631	.8543					
140				.9275	.9158					
130				.9791	.9528					
120				1.014	.9873					
110	.9124	.9082	.9740	1.035	1.007		1.023	.9847	.9156	.9048
100	.9085	.9090	.9712	1.034	1.000		1.018	.9779	.9091	.9044
90	.8866	.8923	.9416	1.010	.9709		.9927	.9540	.8900	.8891
80				.9717	.9359					
70				.9212	.8854					
60				.8538	.8306					
50				.7615	.7478					
40				.6668	.6502					
30				(.5600)	(.5432)					
20				(.4573)	(.4473)					
10				(.3770)	(.3705)					

Fitted Range	Thimble		Average	λ (m ⁻¹)		
	E	F		S & W	N & E	
40-190 cm						
z ₀ (cm)	105.86	106.78	106.32 ⁺ .46	1.3372	1.3213	1.3213
α (m ⁻¹)	1.3176	1.2951	1.3064 ⁺ .011	1.3269	1.3054	1.3054
				1.2997	1.2539	1.2539
						1.3074 ⁺ .077

Table 28: Buckling Data - 22 cm Hex Lattice with Organic Coolant

$h_m = 214.16$ cm		Manganese Foils			May 8, 1961			Moderator Temperature 27.5°C		
Thimble	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂
Radius cm	57.16	55.00	33.00	19.05	11.00	11.00	19.05	33.00	55.00	57.16
Elevation cm										
220					(.03637)	(.0367)				
210					(.1180)	(.1192)				
200					(.2716)	(.2721)				
190					.4102	.4113				
180					.5419	.5425				
170					.6640	.6622				
160					.7746	.7738				
150					.8772	.8649				
140					.9516	.9453				
130					1.019	.9973				
120					1.064	1.043				
110	.9491	.9497	1.031	1.058	1.098	1.071	1.081	1.040	.9561	.9461
100	.9464	.9556	1.034	1.061	1.098	1.068	1.078	1.043	.9583	.9509
90	.9338	.9417	1.013	1.042	1.098	1.053	1.061	1.024	.9431	.9361
80					1.046	1.020				
70					.9924	.9672				
60					.9208	.9050				
50					.8260	.8215				
40					.7264	.7174				
30					(.6094)	(.6028)				
20					(.4946)	(.4921)				
10					(.3979)	(.3972)				

Fitted Range 40-190 cm	Thimble		Average	Level	λ (m ⁻¹)	
	E	F			S & W	N & E
z ₀ (cm)	102.39	102.54	102.46 [±] .12	110 cm	1.2948	1.2780
α (m ⁻¹)	1.3620	1.3407	1.3514 [±] .011	100	1.2957	1.2474
				90	1.3177	1.2490
			Average		1.2804 [±] .023	

Table 29: Buckling Data - 22 cm Hex Lattice with Organic Coolant

$h_m = 213.78$ cm Manganese Foils May 23, 1961 Moderator Temperature 27.5°C

	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂
Thimble	57.16	55.00	33.00	19.05	11.00	11.00	19.05	33.00	55.00	57.16
Radius cm	57.16	55.00	33.00	19.05	11.00	11.00	19.05	33.00	55.00	57.16

Elevation
cm

190	.4022	.4172
180	.5377	.5424
170	.6528	.6668
160	.7715	.7815
150	.8715	.8827
140	.9307	.9585
130	.9655	1.024
120	1.060	1.074
110	1.110	1.078
100	1.105	1.095
90	1.085	1.081
80	1.043	1.049
70	.9959	.9912
60	.9311	.9123
50	.8407	.8223
40	.7325	.7196
30	(.6146)	(.6075)

Fitted Range 40-190 cm	Thimble		Average
	E	F	
z_0 (cm)	101.19	102.89	$102.04 \pm .85$
α (m^{-1})	1.3485	1.3604	$1.3544 \pm .0069$

Table 30: Buckling Data - 24 cm Hex Lattice with Organic Coolant

$h_m = 218.5$ cm	Copper Foils					May 5, 1961					Moderator Temperature 28.5°C
Thimble	D_2	C	D	E_2	E	F	F_2	G	H	G_2	
Radius cm	62.35	60.00	36.00	20.78	12.00	12.00	20.78	36.00	60.00	62.35	
Elevation cm											
210					(3.787)	(3.820)					
200					(6.879)	(6.944)					
190					9.800	9.821					
180					12.52	12.54					
170					15.08	15.05					
160					17.28	17.33					
150					19.33	19.29					
140					20.94	20.64					
130					22.19	21.84					
120					22.95	22.73					
110	20.26	20.30	21.97	22.88	23.39	23.12	23.06	22.12	20.32	20.18	
100	20.18	20.30	22.10	22.95	23.69	23.31	23.27	22.20	20.37	20.27	
90	19.81	19.86	21.52	22.42	23.07	22.66	22.59	21.95	19.98	19.79	
80					22.41	21.99					
70					21.20	20.82					
60					19.57	19.28					
50					17.52	17.51					
40					15.39	15.24					
30					(12.92)	(12.81)					
20					(10.43)	(10.31)					

Fitted Range	Thimble			λ (m^{-1})
	E	F	Average	
40-190 cm				Level
z_0 (cm)	104.32	104.54	104.43 \pm .11	110 cm
α (m^{-1})	1.3352	1.3231	1.3292 \pm .0061	100
				90
				Average

Table 31: Buckling Data - 28 cm Hex Lattice with Organic Coolant

$h_m = 255.9$ cm		Manganese Foils			May 11, 1961			Moderator Temperature 29.0°C		
Thimble	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂
Radius cm	72.75	70.00	42.00	24.25	14.00	14.00	24.25	42.00	70.00	72.75
Elevation cm										
220					(.4241)	(.4279)				
210					.5271	.5275				
200					.6256	.6253				
190					.7091	.7132				
180					.7902	.7904				
170					.8566	.8568				
160					.9137	.9123				
150					.9604	.9525				
140					.9925	.9870				
130	.8372	.8497	.9453	.9874	1.013	.9961	1.004	.9542	.8511	.8390
120	.8395	.8553	.9479	.9917	1.015	1.000	1.004	.9563	.8499	.8458
110	.8370	.8480	.9382	.9826	1.011	.9953	.9941	.9471	.8453	.8424
100					.9875	.9722				
90					.9521	.9321				
80					.9039	.8870				
70					.8419	.8226				
60					.7704	.7594				
50					.6842	.6796				
40					.5949	.5897				
30					(.4962)	(.4916)				
20					(.3971)	(.3951)				
10					(.3026)	(.3011)				

Fitted Range 40-210 cm	Thimble		Average	λ (m ⁻¹)			
	E	F		S & W	N & E	N & E	
z ₀ (cm)	121.39	122.10	121.74 ^{±.36}	Level 130 cm	1.1711	1.1651	
α (m ⁻¹)	1.1605	1.1517	1.1561 ^{±.0044}	120	1.1665	1.1595	
				110	1.1619	1.1502	
			Average		1.1624 ^{±.010}		

Table 32: Buckling Values Measured in ZEEP with Corrections - 24.56 cm Spacing

Date	Moderator (Atom %)	α^2 (m^{-2})	λ^2 (m^{-2})	ΔB_L^2 (m^{-2})	$B^2(T)$ (m^{-2})	ΔB_T^2	ΔB_W^2	$B^2(20^\circ C)$ (99.730A%) (m^{-2})	Weighted Average B^2 (m^{-2})
D ₂ O Coolant									
Dec. 14/59	99.745	2.253 ⁺ ₋ .009	3.493 ⁺ ₋ .026	+0.035	5.781 ⁺ ₋ .028	+0.018	-0.013	5.786 ⁺ ₋ .028	5.781 ⁺ ₋ .030
Dec. 11/59	99.745	2.238 ⁺ ₋ .011	3.471 ⁺ ₋ .056	+0.046	5.755 ⁺ ₋ .057	+0.015	-0.013	5.757 ⁺ ₋ .057	
Coolant Voided									
Dec. 16/59	99.745	2.286 ⁺ ₋ .009	3.448 ⁺ ₋ .033	+0.029	5.764 ⁺ ₋ .034	+0.016	-0.013	5.767 ⁺ ₋ .034	5.732 ⁺ ₋ .020
Dec. 17/59	99.745	2.268 ⁺ ₋ .009	3.397 ⁺ ₋ .033	+0.029	5.694 ⁺ ₋ .034	+0.018	-0.013	5.699 ⁺ ₋ .034	
Dec. 17/59	99.745	2.256 ⁺ ₋ .014	3.426 ⁺ ₋ .030	+0.046	5.728 ⁺ ₋ .033	+0.017	-0.013	5.732 ⁺ ₋ .033	

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

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

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

where Δh is the change in critical height produced by the thimbles and foils. A measurement of Δh was made for each spacing for D_2O -cooled rods with the exception of the 18 cm lattice for which the critical D_2O level was above the top of the UO_2 . To obtain ΔB_L^2 for this lattice spacing it was assumed that the quantity $[M^2 \Delta B_L^2 / \phi_{\text{mid-rod}}]^*$ was independent of lattice pitch and the average value of measurements in the 22, 28 and 36 cm lattices was used in conjunction with measured values of L^2 (to yield M^2) and $\phi_{\text{mid-rod}}$ for the 18 cm lattice. The loading correction to B^2 was about 0.75% for all of the D_2O -cooled lattices.

All D_2O -cooled and voided lattice bucklings were corrected to $20^\circ C$ using the temperature coefficients of buckling calculated for D_2O -cooled lattices by Booth⁽²⁾; corrections for the organic-cooled lattices were supplied by Primeau⁽³⁾. The maximum temperature correction ΔB_T^2 was $+0.048 \text{ m}^{-2}$ and the average correction was about 0.02 m^{-2} .

* $\phi_{\text{mid-rod}}$ is the flux at the mid-rod position relative to unit average flux in the UO_2 .

$M^2 = L^2 + L_S^2$ is the migration area of a cell.

The values of L^2 and $\phi_{\text{mid-rod}}$ were obtained from measurements of the neutron distribution throughout the central cell. Further details will be published in another report in this series.

D_2O purity corrections to standard values of 99.730 and 99.70 atom % D_2O were also obtained from references 2 and 3 and are extremely small.

A summary of the buckling results is given in Tables 3 to 5. Here the values of α^2 , λ^2 and B^2 obtained from the least squares fitting are listed along with the loading, temperature and D_2O purity corrections and final corrected values of B^2 .

Buckling values measured with D_2O -cooled and voided rods for the 24.56 cm lattice in ZEEP are shown in Table 32 along with loading corrections and temperature and D_2O purity corrections which are consistent with those used above. From this table and Tables 3 and 4 it can be seen that the ZED-2 results agree with those obtained in ZEEP within experimental error.

A plot of the bucklings as a function of hexagonal spacing is given in Fig. 11. Also shown in this figure are the curves obtained from the latest Chalk River lattice calculation program⁽³⁾ which incorporates measured neutron temperature and r values, a new treatment of the cell fine structure due to McKay⁽⁷⁾ and an improved treatment of p ⁽³⁾.

Although the calculated bucklings for D_2O -cooled and voided lattices lay $\sim 0.4 \text{ m}^{-2}$ below experimental points over the range of spacings investigated, the change in B^2 due to voiding the coolant region was accurately calculated.

2. Cd Ratios

The results of the Cd ratio measurements for D_2O -cooled and voided rods are summarized in Tables 33 to 43. The values shown are the ratios of aluminum-covered to cadmium-covered activities for manganese 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 aluminum-covered wires. Tables 33 to 39 list the results for D_2O -cooled rods and Tables 40 to 43 for voided rods.

Values marked with brackets have been rejected because of their large deviation from the average value and were not used

in further calculations. Many of these rejected values may be explained by the fact that the cadmium cover was found slightly open following the irradiation; such rejected values are marked with an asterisk.

Other values for the 18 cm and 19 cm lattices have been marked with a dagger to indicate that they were at an elevation within 6 cm of one of the bundle-end elevations. In calculating the average and standard deviation of the Cd ratio within the constant (one-group) region these points were omitted.

The above results are also plotted in Figs. 12 to 21. Figs. 12 to 14 show the axial, and Figs. 15 to 17 the radial variations of the Cd ratio for D₂O-cooled rods, and Figs. 18 to 21 the same results for voided rods. 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. The error bars on the points are either:

- i) the standard deviation of all the values within the constant region, σ , for the axial plots, or
- ii) $\frac{\sigma}{\sqrt{2}}$ for the averaged radial plots (i.e., each point is the average of two measurements at a given radius.)

The constant portion of each curve is the average value over the one-group region (dagger-marked points omitted). From these results the region of constant cadmium ratio for D₂O-cooled and voided lattices was taken to be

$0 < r < 2.6d$ where d is the lattice pitch radially, and

$$30 \text{ cm} < z < h_m - 25 \text{ cm}$$

axially for all but the 18 cm lattice for which h_m was above the UO₂ fuel. The constant region for that lattice was taken to be

$$30 \text{ cm} < z < 230 \text{ cm}$$

In fitting the flux distributions of all lattices to obtain the bucklings, the regions used were always equal to or smaller than those given above.

Table 34: Mn Cadmium Ratio - 19 cm Lattice with D₂O Coolant
 Critical Height = 221.30 cm Feb. 28, 1961 Moderator Temperature 24.7°C

Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J
Radius cm	66.50	49.36	47.50	28.50	16.45	9.50	9.50	16.45	28.50	47.50	49.36	66.50
Elevation cm												
210												
200						19.81†						
190							18.26					
180						19.11	18.27					
170								18.78				
160						19.47						
150								19.56†				
140						18.93						
130							18.60					
120						19.36						
110	33.92†			19.60†	19.54†		19.39†			19.63†	19.32†	
100						19.32†						
90		18.84	19.24					18.84	19.26	18.98		33.40
80						18.91						
70							19.08					
60						19.67†						
50							19.19					
40						18.06						
30							18.83					
20						21.81						
10							31.20					

† Bundle end points

Table 35: Mn Cadmium Ratio - 22 cm Lattice with D₂O Coolant

Critical Height = 175.17 cm Mar. 13, 1961 Moderator Temperature 25.0°C

	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J
Radius cm	77.00	57.16	55.00	33.00	19.05	11.00	11.00	19.05	33.00	55.00	57.16	77.00

Elevation
cm

170												
160						22.89	27.47					
150						27.68	28.21					
140						27.26	27.24					
130						27.70	27.67					
120						26.66	25.67					
110						27.89	28.31					
100												
90												
80	45.76	26.90		26.70								
70						27.53	26.47	27.23		27.44		
60						27.66	28.22					
50						26.47	27.22					
40						39.55	30.08					
30												
20												
10												

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Table 37: Mn Cadmium Ratio - 24.56 cm Lattice with D₂O Coolant

Critical Height - 167.48 cm		Dec. 9, 1960										Moderator Temperature 24.6°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														
160							38.25							
150						36.10								
140						36.24								
130						37.21								
120						35.10								
110						36.62								
100						35.11			34.71			35.62	57.49	
90					35.91									
80			36.16											
70				(32.59)*										
60	59.25	36.68				36.07		36.78			36.40			
50						36.25								
40						35.10								
30						40.59								
20						52.10								
10														

*Cd container found partially open following irradiation

Table 38: Mn Cadmium Ratio - 28 cm Lattice with D₂O Coolant
 Critical Height = 173.38 cm Jan. 12, 1961 Moderator Temperature 24.5°C

	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J
Radius cm	98.00	72.75	70.00	42.00	24.25	14.00	14.00	24.25	42.00	70.00	72.75	98.00

Elevation
cm

170						38.74						
160						49.98	50.12					
150						48.72	50.33					
140						50.66	48.91					
130						49.20	50.83					
120						49.63	48.01		49.63		49.12	78.51
110						49.58	50.67		49.62		49.88	
100			49.66			50.11	50.67		50.67			
90	73.81	49.54				(46.46)	49.25					
80						69.66	55.04					
70												
60												
50												
40												
30												
20												
10												

Table 41: Mn Cadmium Ratio - 22 cm Lattice with Coolant Voided

Critical Height = 176.25 cm Mar. 17, 1961 Moderator Temperature 24.6°C

	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J
Radius cm	77.00	57.16	55.00	33.00	19.05	11.00	11.00	19.05	33.00	55.00	57.16	77.00

Elevation
cm

170						21.62						
160						25.62						
150						25.23						
140						24.84						
130						25.33						
120						25.02		25.82				
110						24.53						
100	42.19	-		25.96		24.65		24.98		25.02	42.24	
90					25.54	24.06						
80						25.52						
70			25.78			28.98						
60												
50												
40												
30												
20												

Table 42: Mn Cadmium Ratio - 28 cm Lattice with Coolant Voided
 Critical Height = 168.58 cm Jan. 17, 1961 Moderator Temperature 24.1°C

Thimble	B	D ₂	C	D	E ₂	E	F	F ₂	G	H	G ₂	J
Radius cm	98.00	72.75	70.00	42.00	24.25	14.00	14.00	24.25	42.00	70.00	72.75	98.00
Elevation cm												
170						26.43	42.19					
160						48.13	(49.06)★					
150						46.33	46.16					
140						47.42	48.06					
130						47.14	47.23		47.67		44.53	72.82
120						46.68	47.70			47.90		
110						46.68	47.17					
100			44.96		46.08	47.40	50.68					
90				47.39		46.59						
80	81.85	46.55				66.04						
70												
60												
50												
40												
30												
20												
10												

★ Cd covered wire out of position at end of irradiation

The average values over the region of constant Cd ratio are shown in Table 44 where the errors shown are the standard deviation of the mean.

Table 44: Variation of Mn Cadmium Ratio with Spacing

Lattice Spacing	D ₂ O : UO ₂	Coolant	Mean R _{Cd}
18 cm	7.910	D ₂ O	16.58 ± .13
19	8.957	D ₂ O	19.11 ± .10
22	12.44	D ₂ O	27.34 ± .15
24	15.32	D ₂ O	33.71 ± .18
24.56	15.81	D ₂ O	36.03 ± .15
28	20.92	D ₂ O	49.70 ± .16
36	35.41	D ₂ O	96.44 ± .37
19	8.388	Void	17.61 ± .13
22	11.87	Void	25.30 ± .10
28	20.36	Void	46.87 ± .22
36	34.84	Void	89.11 ± .37

It can be shown that in a homogeneous reactor with $\Sigma_a \ll \Sigma_s$, $R_{Cd}-1$ is proportional to the ratio of slowing down power to absorption. This relation should also apply in a heterogeneous D₂O-moderated core when cell-averaged activities are used in the determination of R_{Cd} . Over a range of lattice spacings where the slowing down density, q , is a constant over the cell, the measured mid-rod activities should be proportional to these cell-averaged activities. The observed behaviour is illustrated in Fig. 22 where the experimental cell boundary R_{Cd} was plotted against:

$$\frac{\text{Slowing Down Power}}{\text{Absorption}} \propto \frac{V_{D_2O}}{V_{UO_2}}$$

where V_{D_2O} is the total volume of D₂O within a lattice cell and V_{UO_2} is the volume of UO₂ within the cell.

The slight deviation from linearity at high $D_2O:UO_2$ ratios (i.e., large cluster spacings) may be explained by a departure from a $1/E$ slowing down distribution at the Mn resonance energy (~ 300 eV). This decrease at the cell boundary from the $1/E$ form of the slowing down distribution at large lattice spacings has been observed⁽⁸⁾ in similar lattices. Because about 40% of the episcadmium activation in Mn is resonance activation, the detectors used were sensitive to this slight decrease in the fast flux at the cell boundary.

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

$$\delta_r = R - R_c = \frac{2.4048}{\lambda} - R_c$$

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

$$R_c = 0.5250 d \sqrt{N}$$

where d is the lattice pitch, and

N is the number of rods in the core (55 here, except for the organic cooled lattices which had driver rods surrounding the core).

The axial extrapolation length δ_z is given by

$$\begin{aligned} \delta_z &= h - (h_m - 10.38) \text{ cm} \\ &= \frac{\pi}{\alpha} - (h_m - 10.38) \text{ cm} = \delta_{zu} + \delta_{zl} \end{aligned}$$

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

$(h_m - 10.38)$ is the distance in cm from the bottom of the UO_2 to the critical moderator level.

Values of δ_r , δ_{zu} and δ_{zl} were obtained from the flux distributions for all lattices and are listed in Tables 45 through 47. The errors quoted were derived from the errors in α , λ , z_0 and h_m . The large radial extrapolation lengths for the organic cooled cores of 55 clusters are caused by the driving rods which surround the core. The large δ_{zu} for the 18 cm D_2O -cooled lattice

resulted from the D_2O level (h_m) being above the elevation of the top of the UO_2 .

The radial and axial extrapolation lengths given in Tables 45 and 46 are plotted as a function of lattice pitch in Figs. 23 through 26.

Table 45: Extrapolation Lengths Measured in ZED-2 - D₂O Coolant

Date	d (cm)	R (cm)	h (cm)	h _c (cm)	z ₀ ^(a) (cm)	δ _r (cm)	δ _{zu} (cm)	δ _{z1} (cm)	δ _z (cm)
14/ 2/61	18	132.1 [±] .7	288.5 [±] .5	273.1 [±] .2	115.9 [±] .1	62.0 [±] .7	25.1 ^{b+} .3	28.4 [±] .6	53.4 [±] .6
15/ 2/61	18	132.9 [±] .8	287.9 [±] .4	272.9 [±] .2	115.9 [±] .2	62.8 [±] .8	24.8 ^{b+} .3	28.1 [±] .4	52.8 [±] .4
27/ 2/61	19	129.1 [±] .7	241.8 [±] .3	220.7 [±] .2	93.8 [±] .1	55.1 [±] .7	4.4 [±] .3	27.1 [±] .4	31.4 [±] .4
28/ 2/61	19	128.9 [±] 1.0	242.1 [±] .6	220.7 [±] .2	93.9 [±] .1	54.9 [±] 1.0	4.6 [±] .4	27.2 [±] .7	31.7 [±] .7
11/ 3/61	22	133.3 [±] .8	194.9 [±] .6	174.8 [±] .2	71.4 [±] .2	47.6 [±] .8	4.4 [±] .4	26.0 [±] .6	30.4 [±] .6
17/ 3/61	22	132.0 [±] .7	195.1 [±] .7	174.7 [±] .2	71.5 [±] .2	46.3 [±] .7	4.7 [±] .4	26.1 [±] .8	30.7 [±] .8
10/11/60	24	140.3 [±] .6	186.6 [±] .3	167.5 [±] .2	68.1 [±] .3	46.9 [±] .6	4.3 [±] .3	25.2 [±] .3	29.5 [±] .3
8/12/60	24.56	140.9 [±] .4	186.8 [±] .3	167.2 [±] .2	68.0 [±] .1	45.3 [±] .4	4.7 [±] .3	25.4 [±] .4	30.1 [±] .4
13/12/60	24.56	140.4 [±] .5	186.8 [±] .5	167.0 [±] .2	68.1 [±] .1	44.8 [±] .5	4.9 [±] .3	25.3 [±] .6	30.2 [±] .6
11/ 1/61	28	154.2 [±] .4	192.2 [±] .4	173.0 [±] .2	71.1 [±] .1	45.2 [±] .2	4.6 [±] .3	25.0 [±] .5	29.6 [±] .5
18/ 1/61	28	153.4 [±] .3	192.3 [±] .4	173.0 [±] .2	70.8 [±] .1	44.4 [±] .3	4.3 [±] .3	25.3 [±] .4	29.7 [±] .4
30/ 1/61	36	181.1 [±] .4	243.2 [±] .3	225.4 [±] .2	96.2 [±] .2	41.6 [±] .4	2.7 [±] .3	25.5 [±] .4	28.1 [±] .4
31/ 1/61	36	182.2 [±] .3	243.9 [±] .3	225.4 [±] .2	96.4 [±] .1	42.0 [±] .3	3.4 [±] .3	25.6 [±] .4	29.0 [±] .4

$R_c = 0.5250 d \sqrt{N}$, $N = 55$ rods. R_c is the core radius.

(a) $z'_0 = z_0 - 10.38$ cm:- The distance from the core centre to the bottom of the UO₂.

(b) $\delta_{zu} = z_0 + \frac{h}{2} - 245.6$:- The distance from the top of the UO₂ to the upper zero of the cosine.

Table 46: Extrapolation Lengths Measured in ZED-2 - Coolant Voided

Date	d (cm)	R (cm)	h (cm)	h_c (cm)	$z_o^i(a)$ (cm)	δ_r (cm)	δ_{zu} (cm)	δ_{z1} (cm)	δ_z (cm)
2/ 3/61	19	132.7 [±] .6	255.6 [±] .6	232.3 [±] .2	98.1 [±] .1	58.7 [±] .6	4.0 [±] .3	29.7 [±] .3	33.7 [±] .6
13/ 3/61	22	136.7 [±] .7	198.1 [±] 1.0	176.1 [±] .2	71.6 [±] .6	51.1 [±] .7	5.0 [±] .8	27.4 [±] .8	32.4 [±] 1.0
16/12/60	24.56	143.6 [±] .5	186.7 [±] .5	165.2 [±] .2	66.7 [±] .1	48.0 [±] .5	5.2 [±] .3	26.7 [±] .3	31.9 [±] .5
19/12/60	24.56	142.9 [±] .5	186.5 [±] .6	165.2 [±] .2	66.6 [±] .3	47.3 [±] .5	5.1 [±] .4	26.6 [±] .4	31.7 [±] .6
13/ 1/61	28	153.7 [±] .4	188.7 [±] .4	168.2 [±] .2	68.5 [±] .3	44.7 [±] .4	5.0 [±] .4	25.8 [±] .4	30.9 [±] .5
3/ 2/61	36	182.7 [±] .3	231.2 [±] .3	212.0 [±] .2	89.5 [±] .1	42.6 [±] .3	3.5 [±] .2	26.1 [±] .2	29.6 [±] .4

$R_c = 0.5250 d \sqrt{N}$, $N = 55$ rods. R_c is the core radius.

(a) $z_o^i = z_o - 10.38$ cm:- The distance from the core centre to the bottom of the UO_2 .

Table 47: Extrapolation Lengths Measured in ZED-2 - Organic Coolant

Date	d (cm)	R (cm)	h (cm)	h_c (cm)	z_o^i (a) (cm)	δ_r (cm)	δ_{zu} (cm)	δ_{z1} (cm)	δ_z (cm)
10/5/61	19	186.8 ^{+5.5}	251.7 ^{+2.1}	233.3 ^{+0.2}	101.4 ^{+0.6}	112.9 ^{+5.5}	4.3 ^{+1.2}	24.4 ^{+1.2}	28.7 ^{+2.1}
30/5/61	19	188.0 ^{+5.0}	251.9 ^{+0.8}	233.6 ^{+0.2}	101.0 ^{+0.2}	114.0 ^{+5.0}	3.7 ^{+0.5}	24.9 ^{+0.5}	28.6 ^{+0.8}
9/5/61	20	184.0 ^{+4.4}	240.5 ^{+2.1}	221.6 ^{+0.2}	95.9 ^{+0.5}	106.1 ^{+4.4}	5.0 ^{+1.2}	24.3 ^{+1.2}	29.3 ^{+2.1}
8/5/61	22	187.9 ^{+3.3}	232.5 ^{+1.8}	214.2 ^{+0.2}	92.1 ^{+0.1}	102.2 ^{+3.3}	4.5 ^{+0.9}	24.2 ^{+0.9}	28.7 ^{+1.8}
23/5/61	22		232.0 ^{+1.2}	213.8 ^{+0.2}	91.7 ^{+0.9}		4.2 ^{+1.1}	24.3 ^{+1.1}	28.6 ^{+1.2}
5/5/61	24	197.4 ^{+2.3}	236.2 ^{+1.1}	218.5 ^{+0.2}	94.0 ^{+0.1}	104.0 ^{+2.3}	4.1 ^{+0.6}	24.1 ^{+0.6}	28.2 ^{+1.1}
11/5/61	28	206.9 ^{+1.8}	271.6 ^{+1.0}	255.9 ^{+0.2}	111.4 ^{+0.4}	97.9 ^{+1.8}	1.7 ^{+0.6}	24.5 ^{+0.6}	26.2 ^{+1.0}

$R_c = 0.525 d \sqrt{N}$, $N = 55$ rods. R_c is the core radius.

(a) $z_o^i = z_o - 10.38$ cm:- The distance from the core centre to the bottom of the UO_2 .

CONCLUSIONS

Bucklings and Mn-Cd ratios were measured over a range of spacings from 18 cm to 36 cm for D₂O-cooled rods, and 19 cm to 36 cm for voided rods. Bucklings were measured over a range from 19 cm to 28 cm for organic-cooled rods.

The measured buckling values for the D₂O-cooled rods agreed within 4% with bucklings calculated using a program similar to that of Duret and Marriott⁽⁹⁾ which had been written specifically for D₂O-cooled rods. The bucklings calculated using this program appropriately modified for a change to organic coolant did not agree at all well with the experiments mainly because of the assumptions concerning flux fine structures in the cell and initial conversion coefficients. Modifications to the program were then made in an attempt to resolve these discrepancies. More recent calculations by Primeau employing a program which incorporates measured r values and neutron temperatures, a new treatment of the cell fine structure due to McKay⁽⁷⁾ and an improved treatment of p give less satisfactory agreement for the D₂O-cooled lattices but much better agreement for the organic-cooled ones (Fig. 11).

The four buckling values obtained in ZED-2 for D₂O-cooled rods and rods with coolant voided agree within the experimental error with the results obtained in ZEEP under the same conditions.

Cadmium ratios obtained for 0.051 cm diameter 0.5 cm long Mn-Ni wires placed at mid-rod positions in the core of D₂O-cooled or voided rods were a linear function of the D₂O:UO₂ ratio at small lattice spacings.

Measures of the radial extrapolation length as a function of core size and measures of the vertical extrapolation length, including a case in which the D₂O was above the fuel top, will be useful for predicting critical sizes in ZED-2.

ACKNOWLEDGEMENTS

The authors are indebted to P. Ferrigan, J. Murphy and E. Pleau for their assistance with reactor operations, to J. Young and E. Engel for similar assistance as well as for help with foil counting and the preparation of a number of the drawings, and to S.E. Frost for numerical work and draughting; also to Mrs. M. Cahill who was in charge of computer data processing. They express their sincere thanks to Miss E. Gehlert for patiently typing both draft and final copies. R.E. Green contributed many thoughts toward the effective layout of the report, read and improved draft copies, and also aided in reactor operation during the experiments. Helpful discussions were held with W.J. Henderson, M.F. Duret, D.B. Primeau and D.L. Booth.

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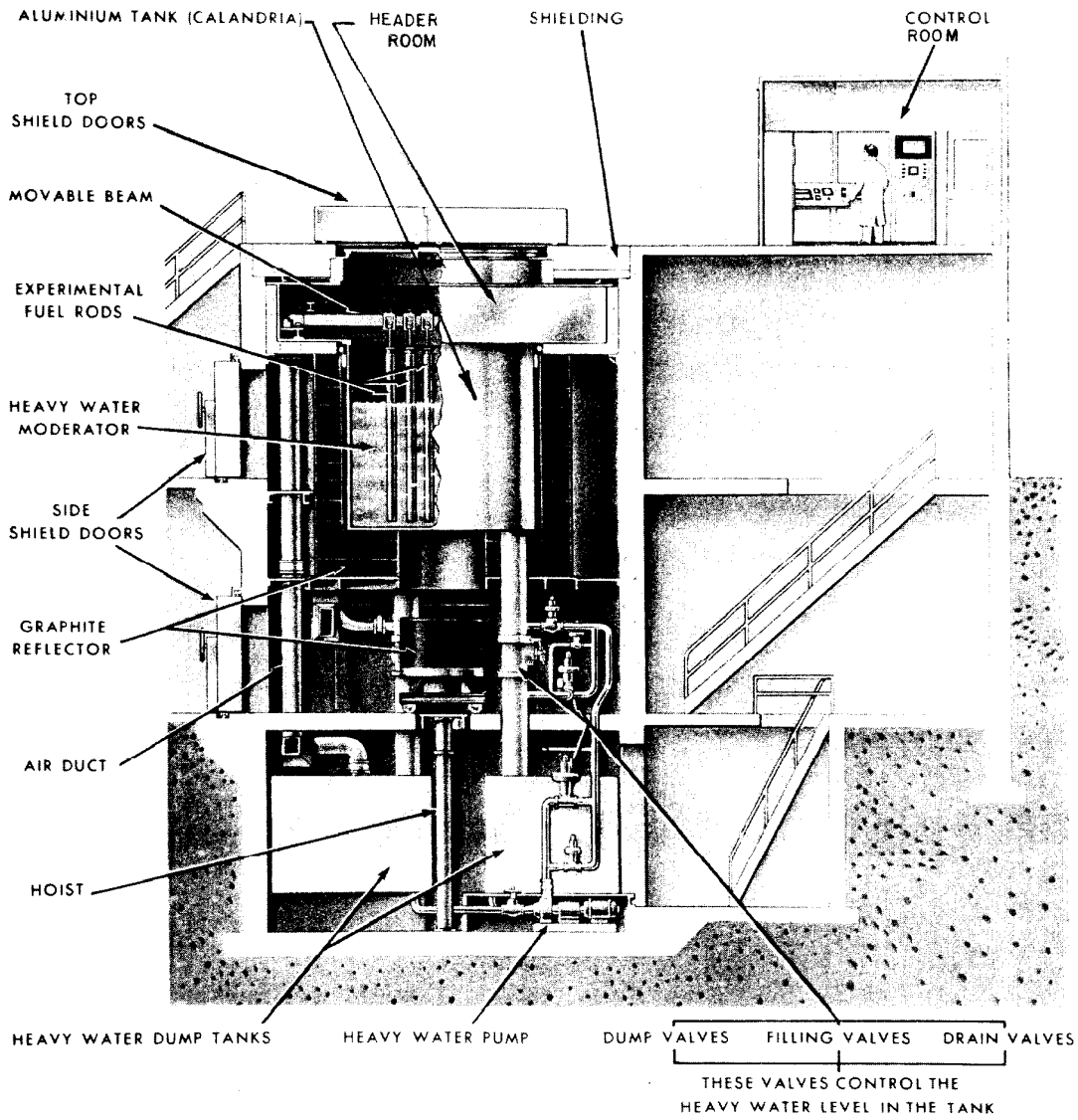


FIG. 1 : ZED-2 REACTOR

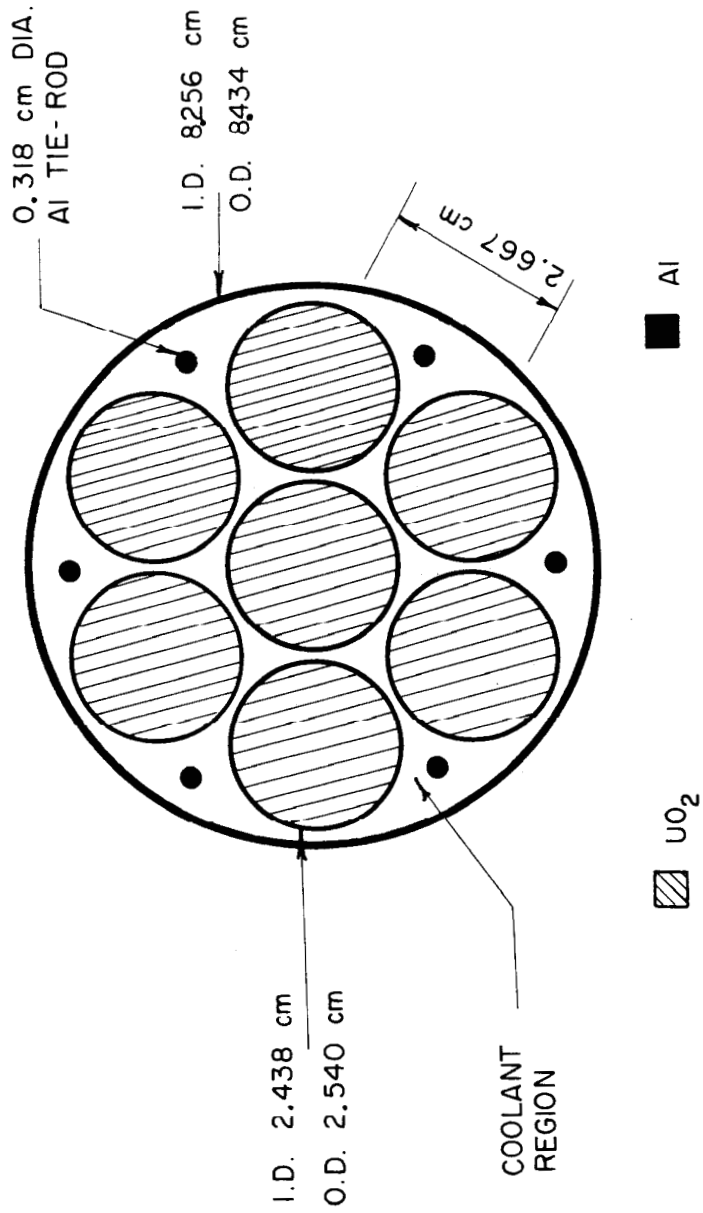


FIG.2 : CROSS SECTION OF 7 - ELEMENT 240 cm UO_2 FUEL

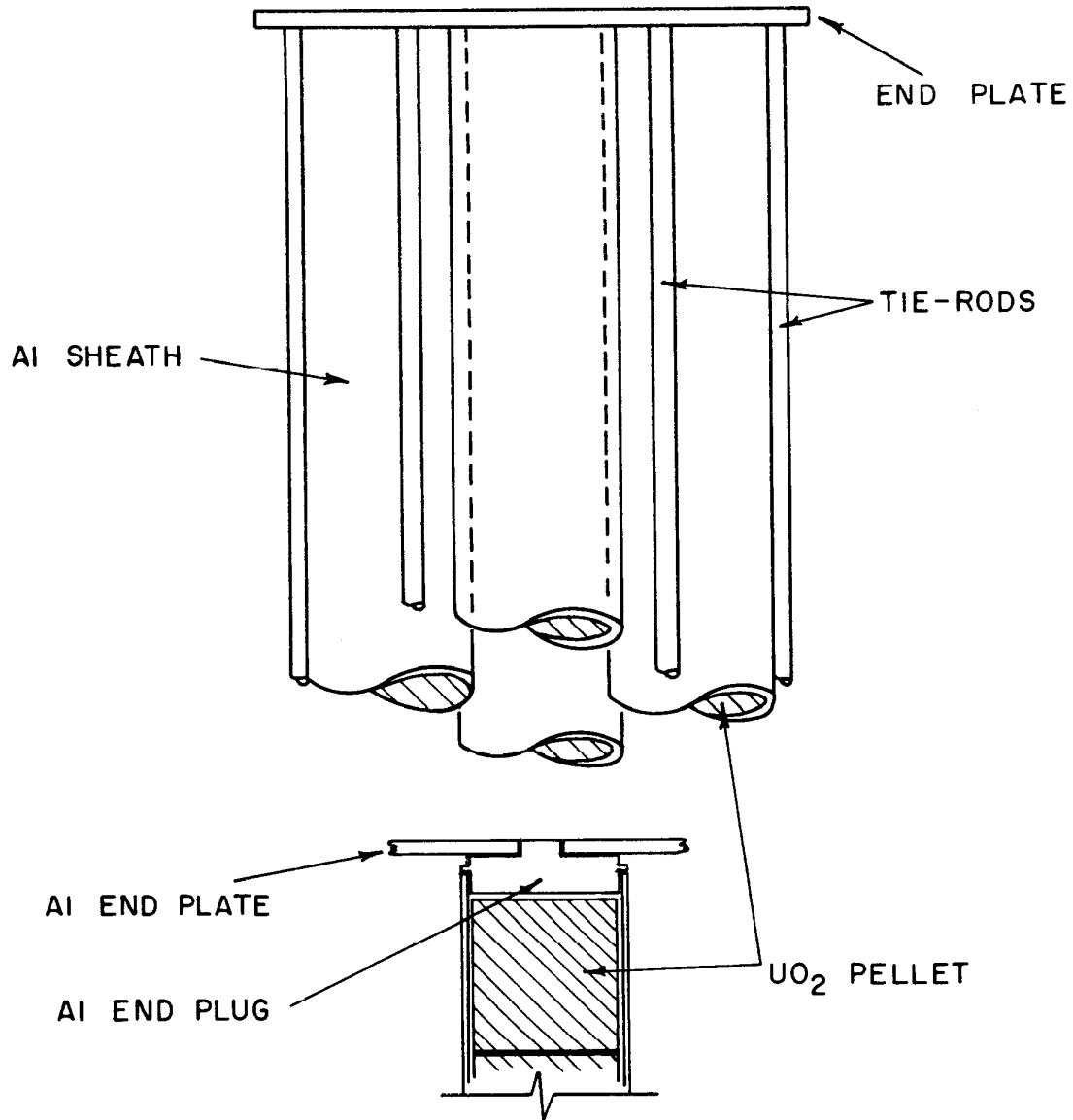
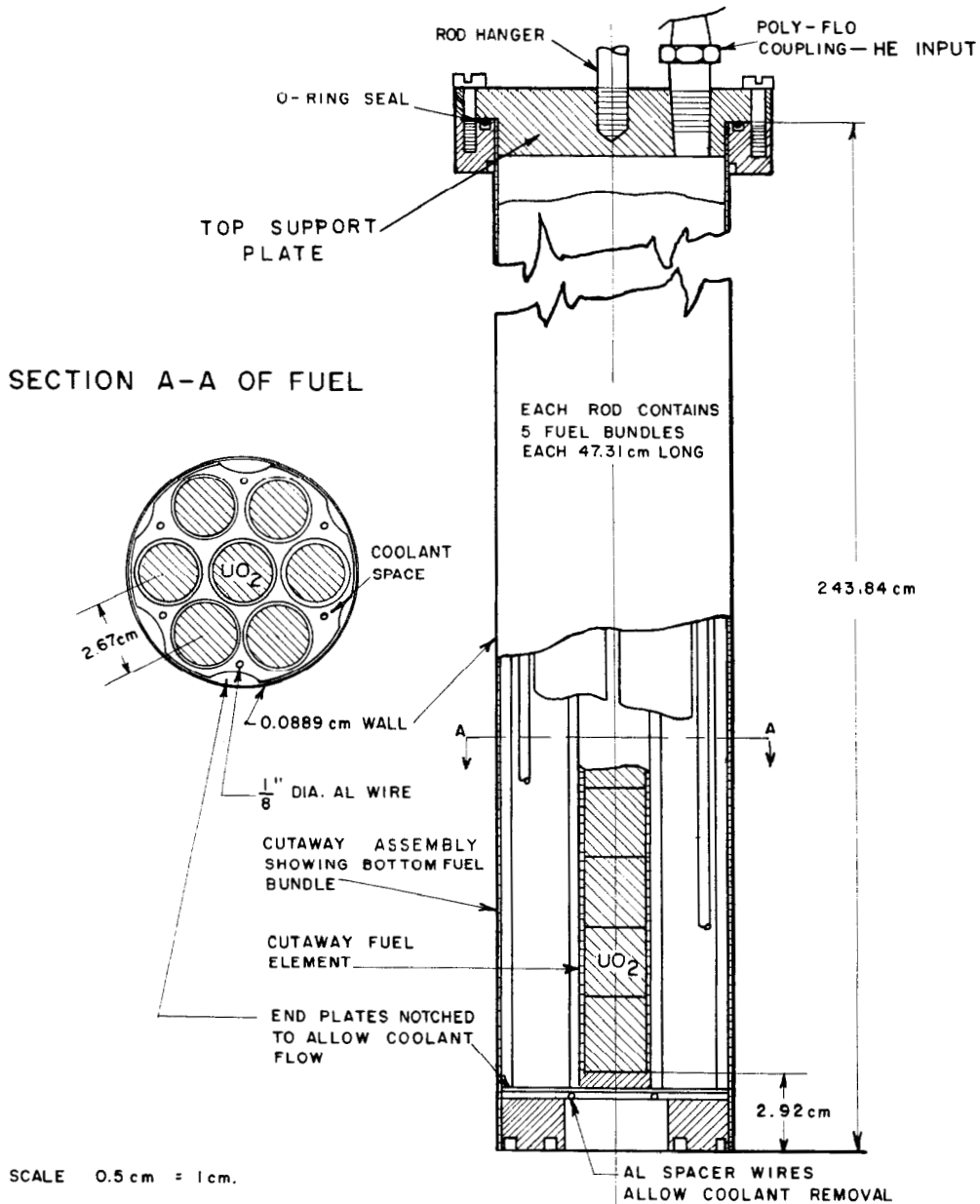


FIG.3 : DETAILS OF FUEL BUNDLE



CUTAWAY VIEW OF FUEL ROD

FIGURE 4

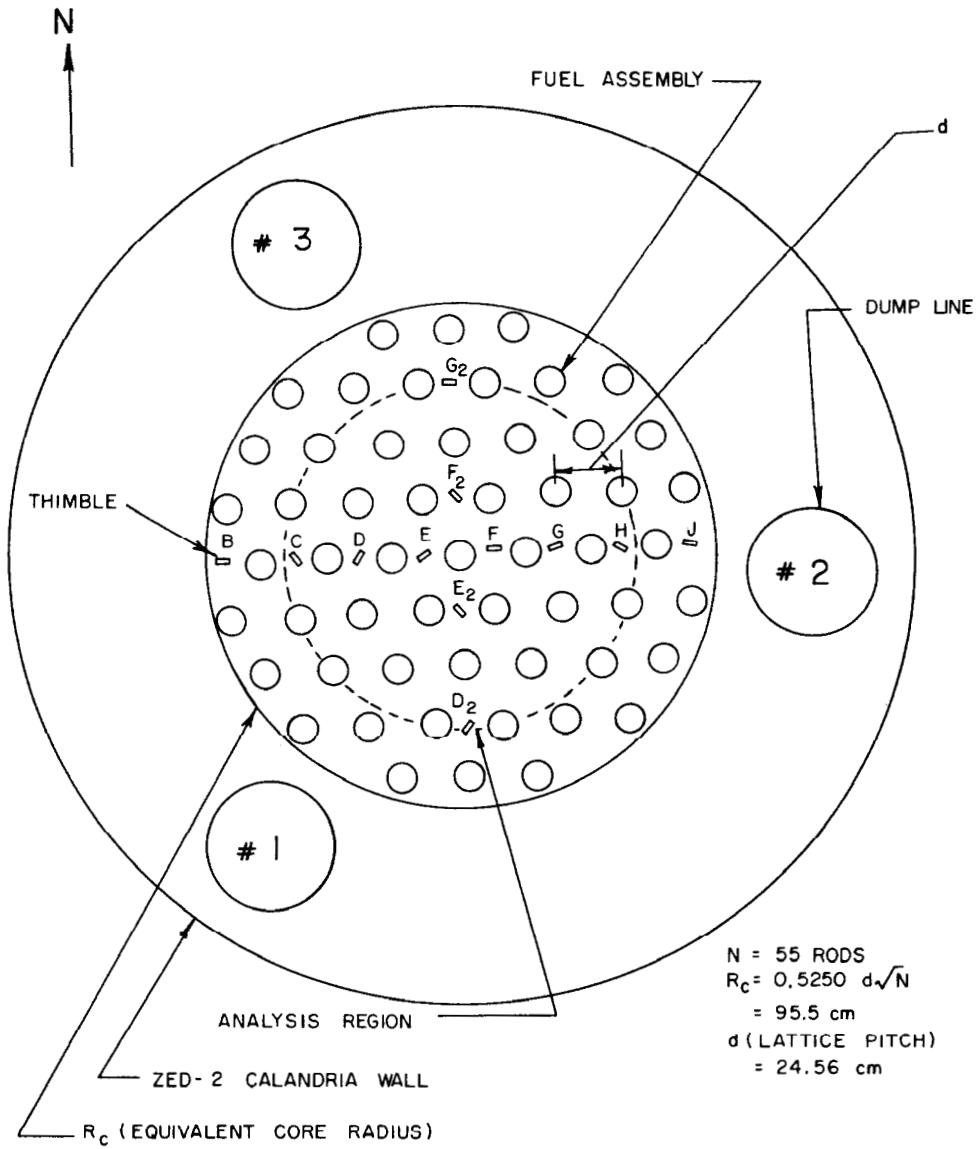


FIG.5 : CROSS SECTION OF 24.56 cm
UO₂ (7) LATTICE IN ZED - 2

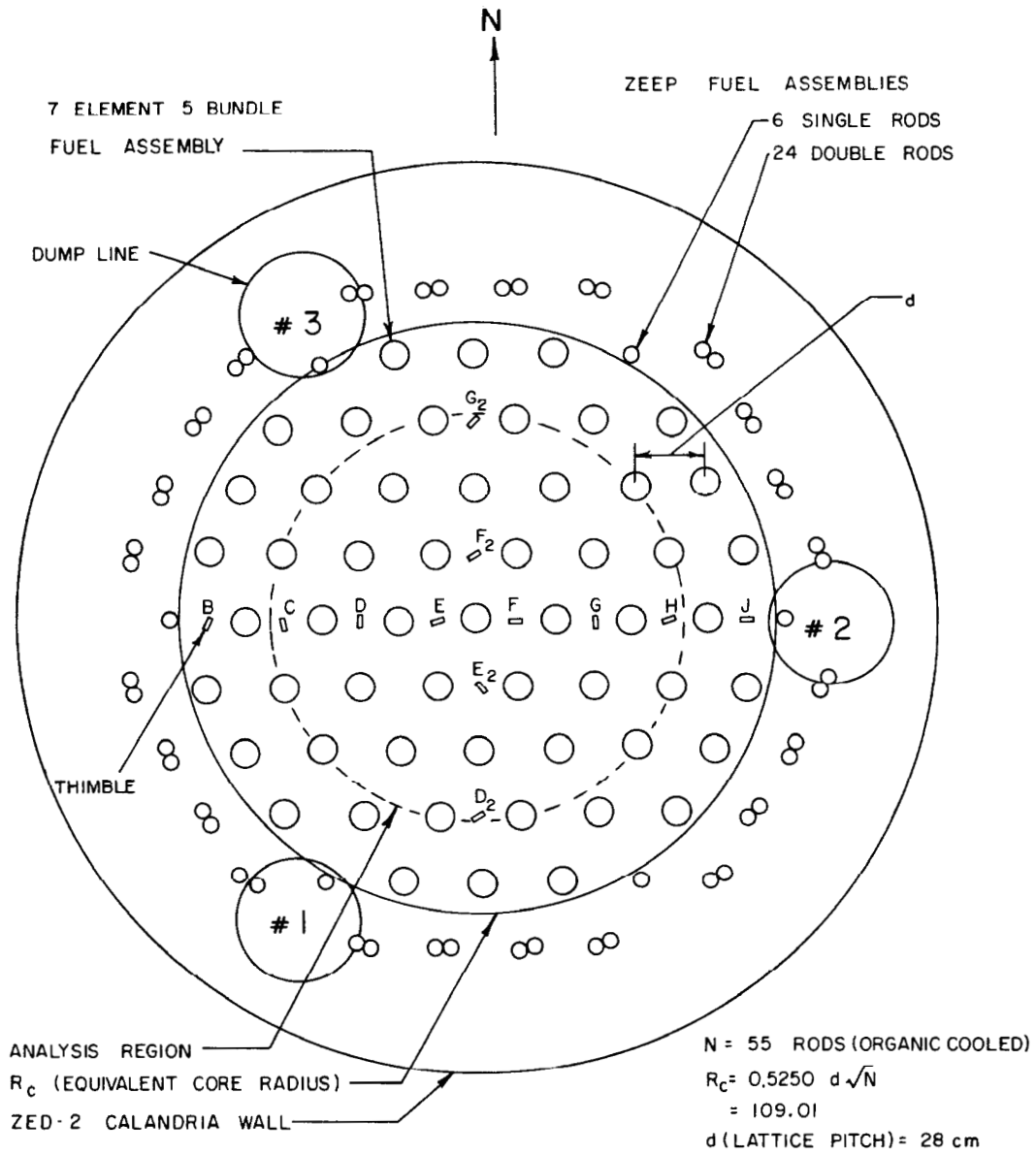


FIG. 6 : CROSS SECTION OF 28 cm ORGANIC COOLED UO_2 (7) LATTICE IN ZED-2

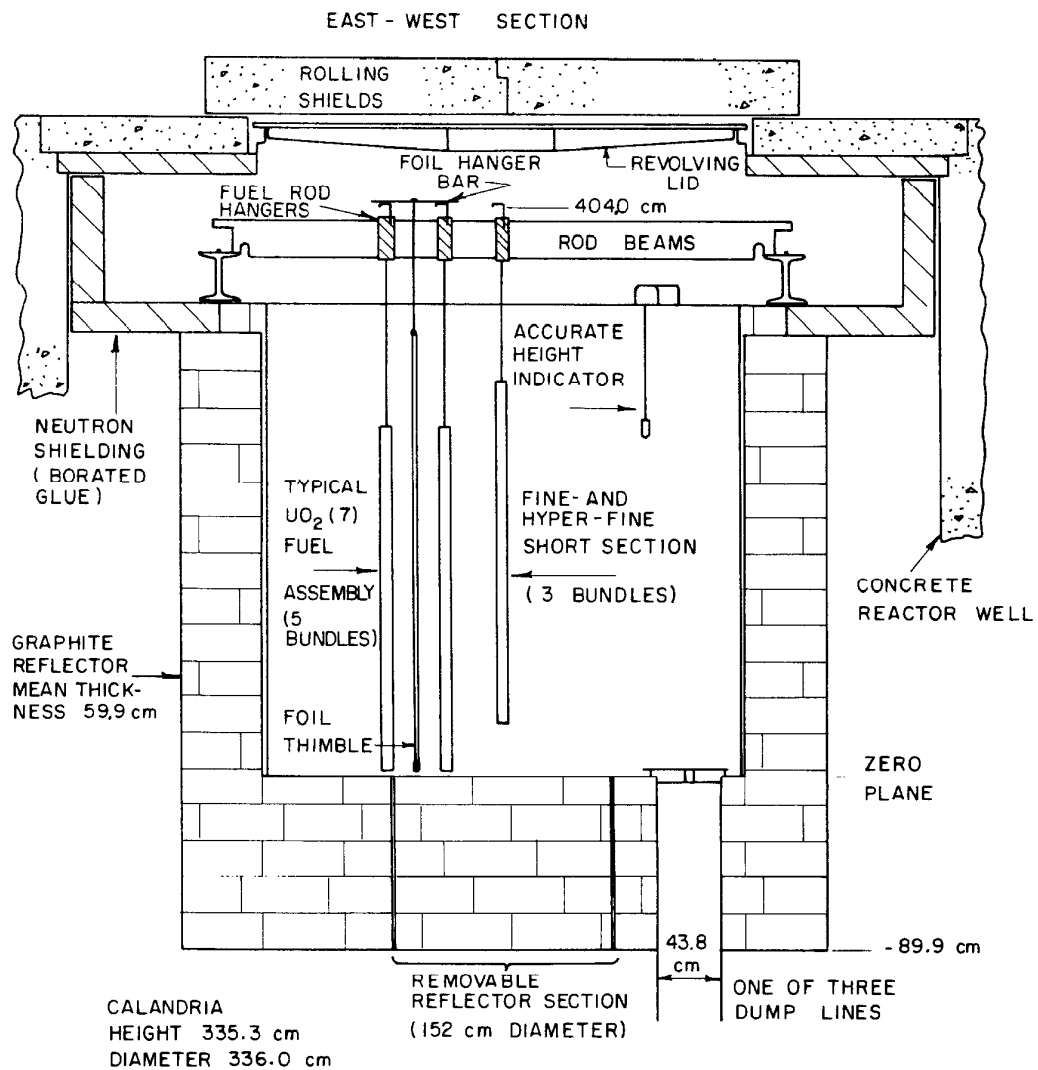


FIG. 7 : CROSS SECTION OF ZED- 2 CALANDRIA & HEADER ROOM

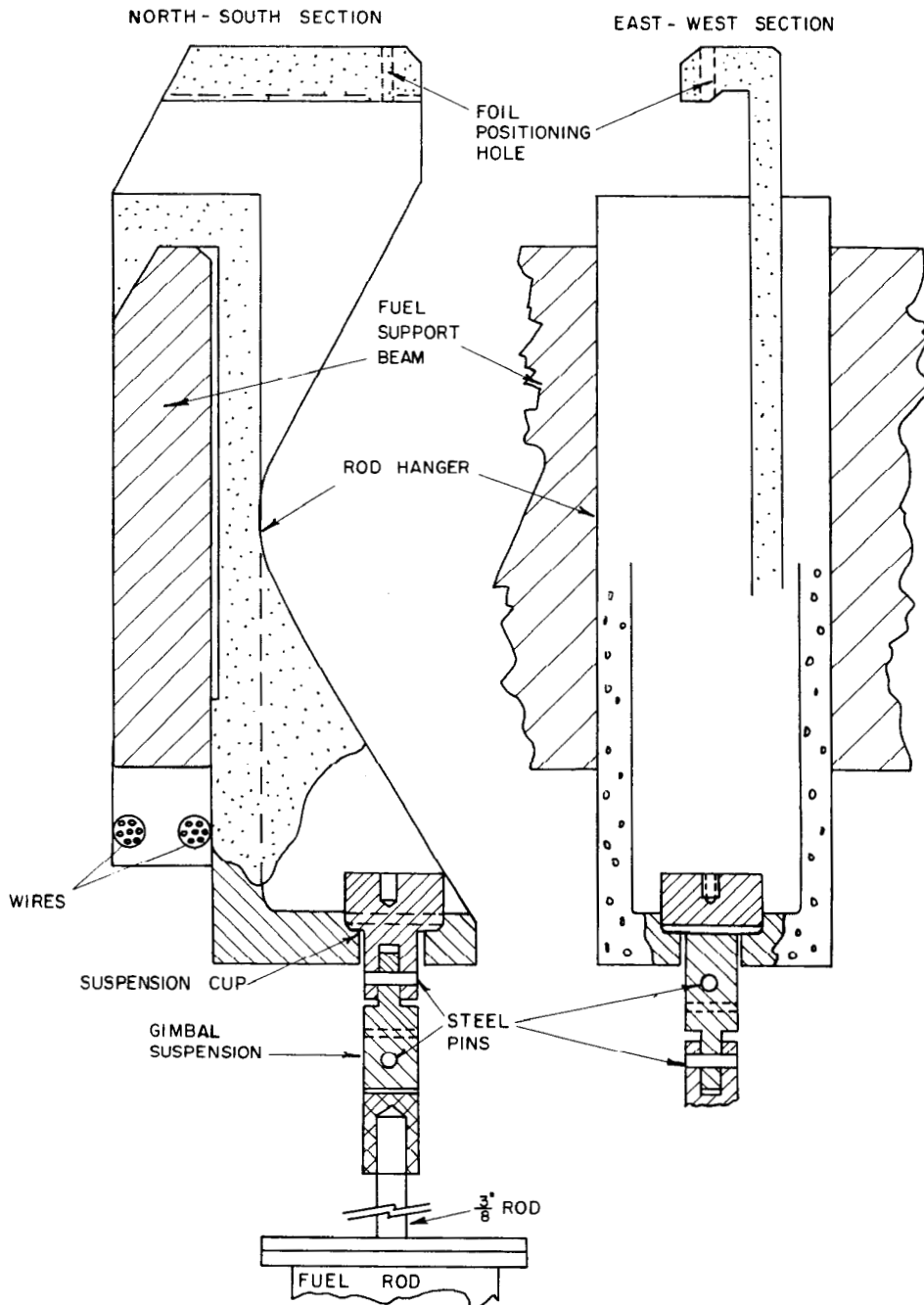


FIG. 8 : ZED-2 ROD HANGER AND ROD SUSPENSION DETAILS

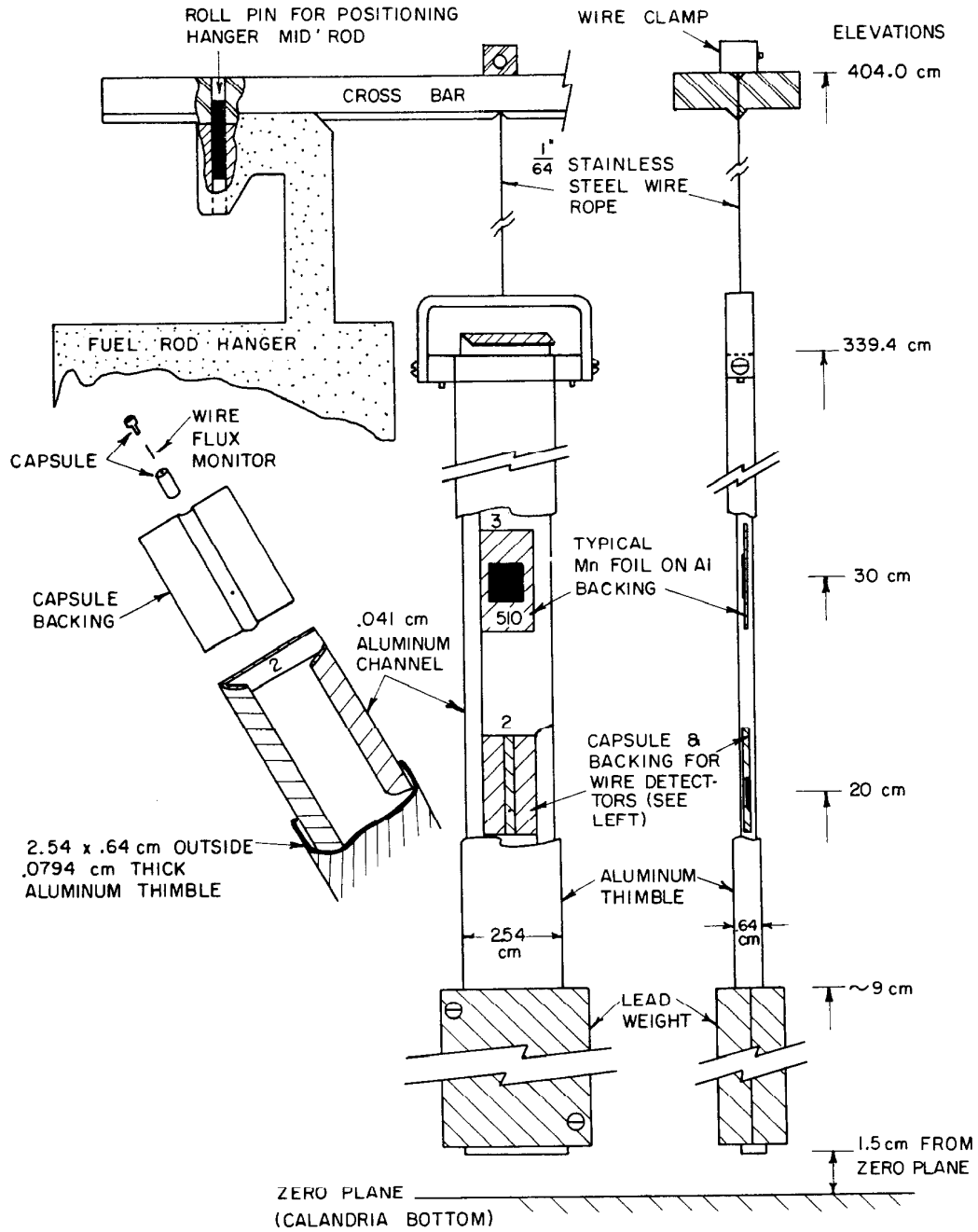


FIG. 9 : ZED-2 FOIL AND WIRE HOLDERS

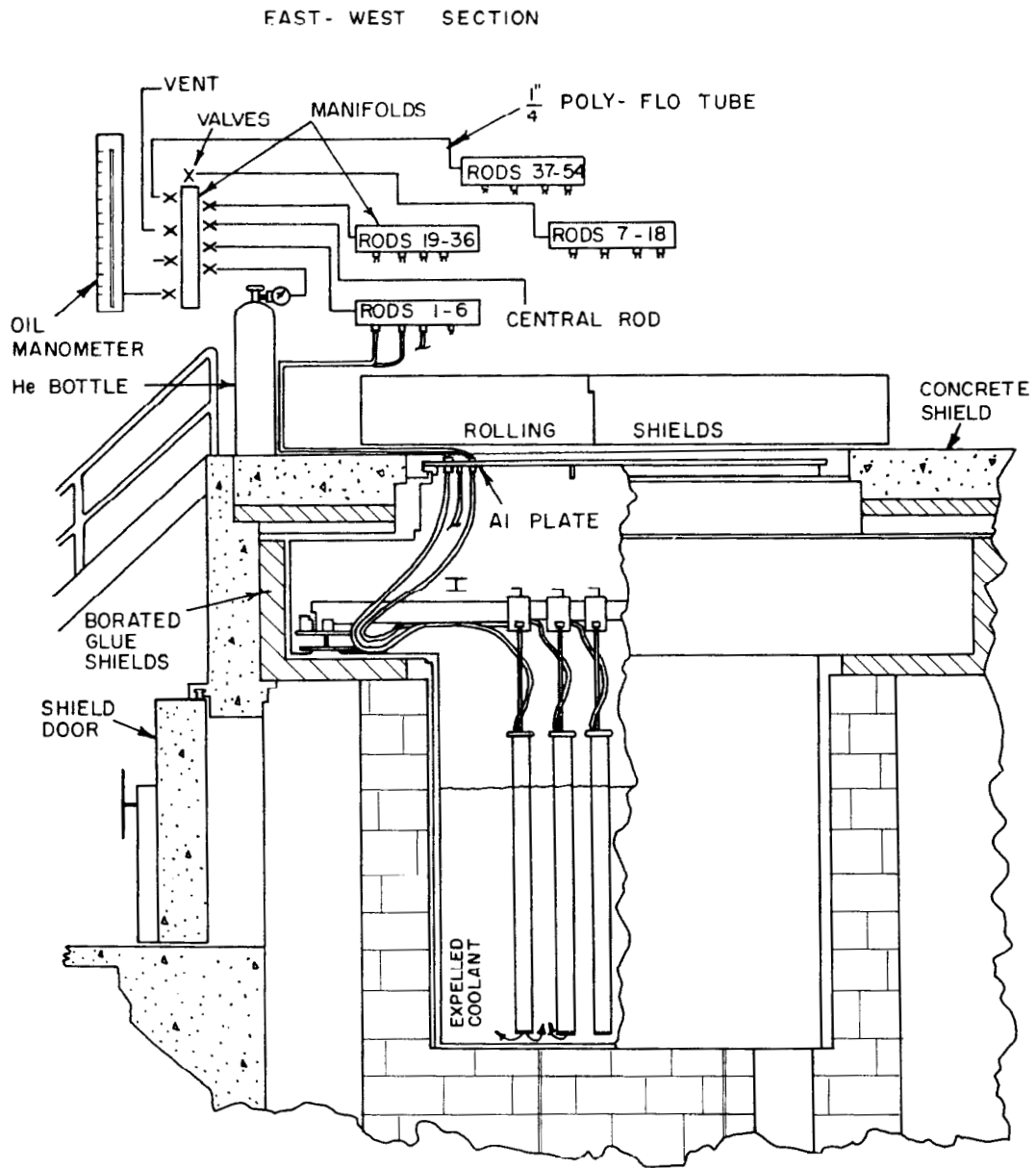


FIG.10 : COOLANT EXCLUSION CIRCUIT IN ZED - 2

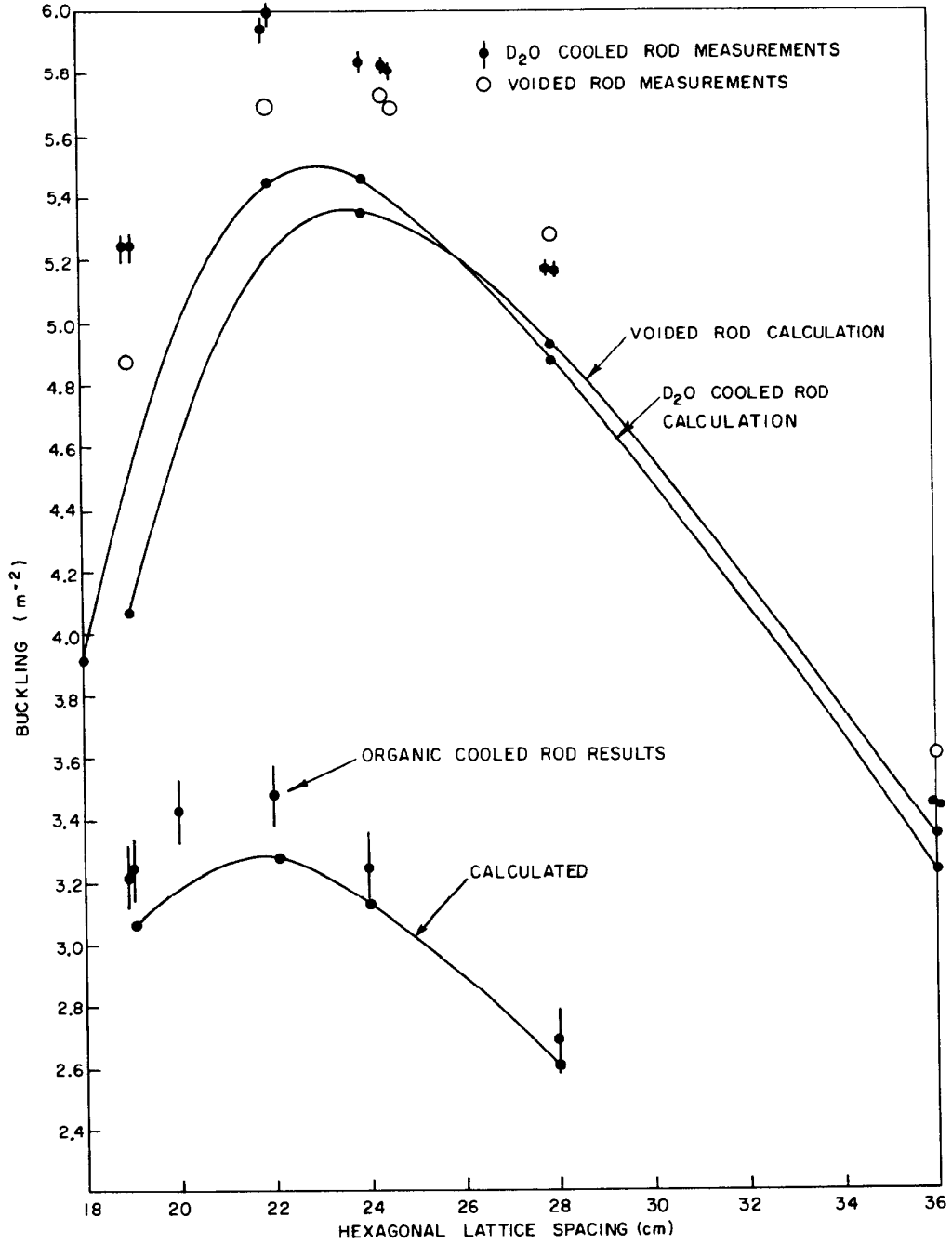


FIG. 11
MEASURED AND CALCULATED BUCKLINGS

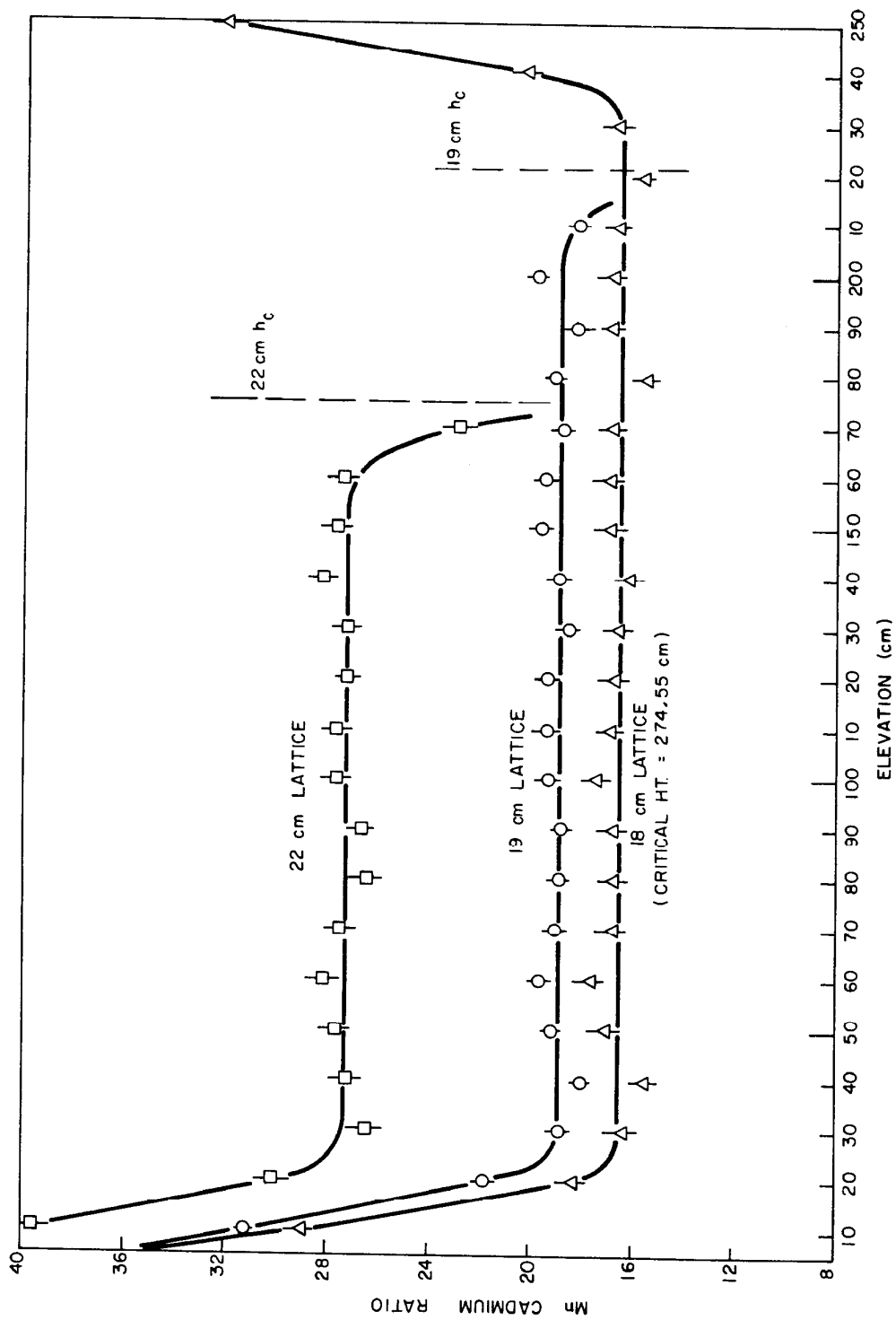


FIG.12 : AXIAL VARIATION OF Mn CADMIUM RATIO—D₂O COOLANT

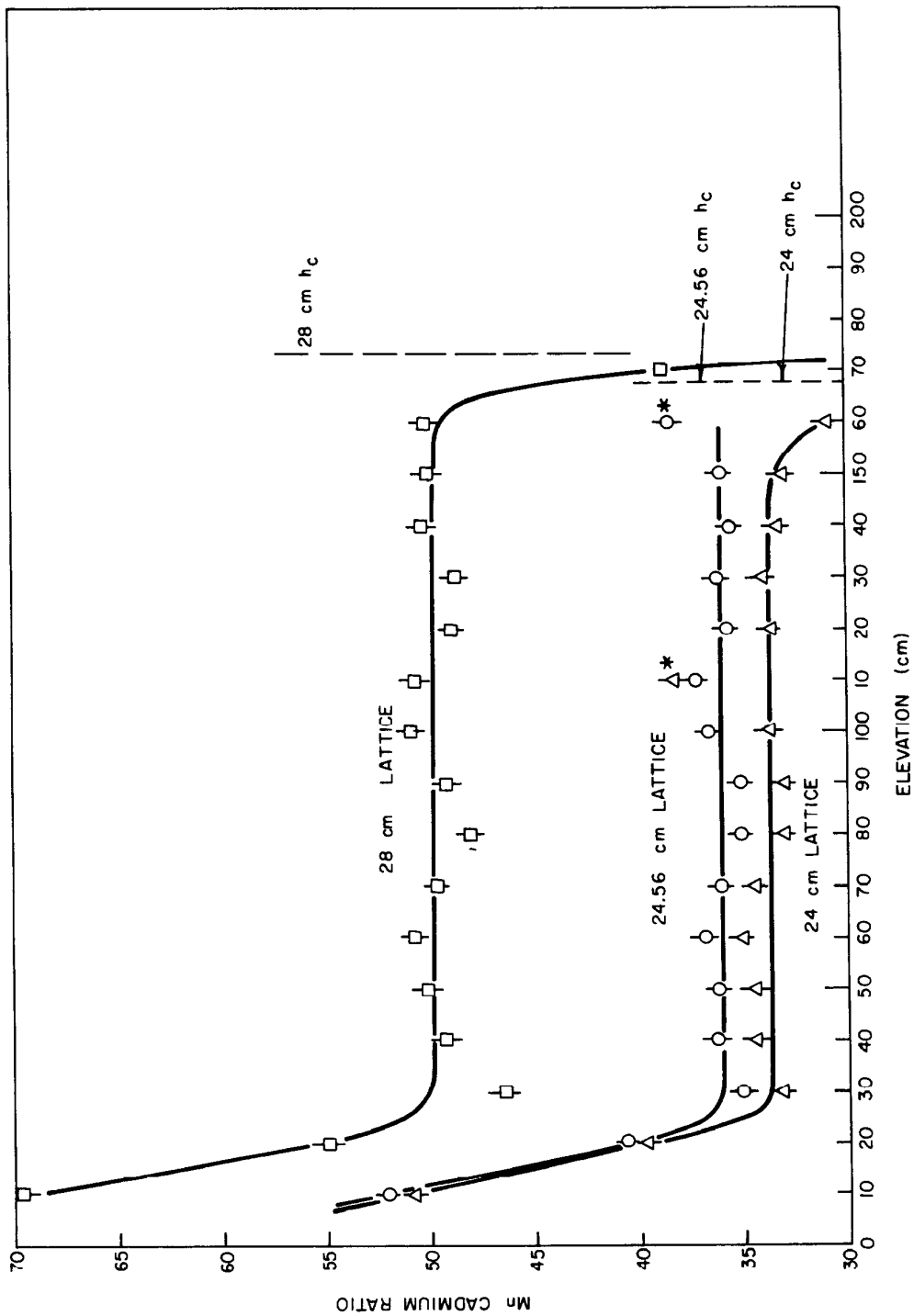


FIG. 13 : AXIAL VARIATION OF Mn CADMIUM RATIO - D₂O COOLANT

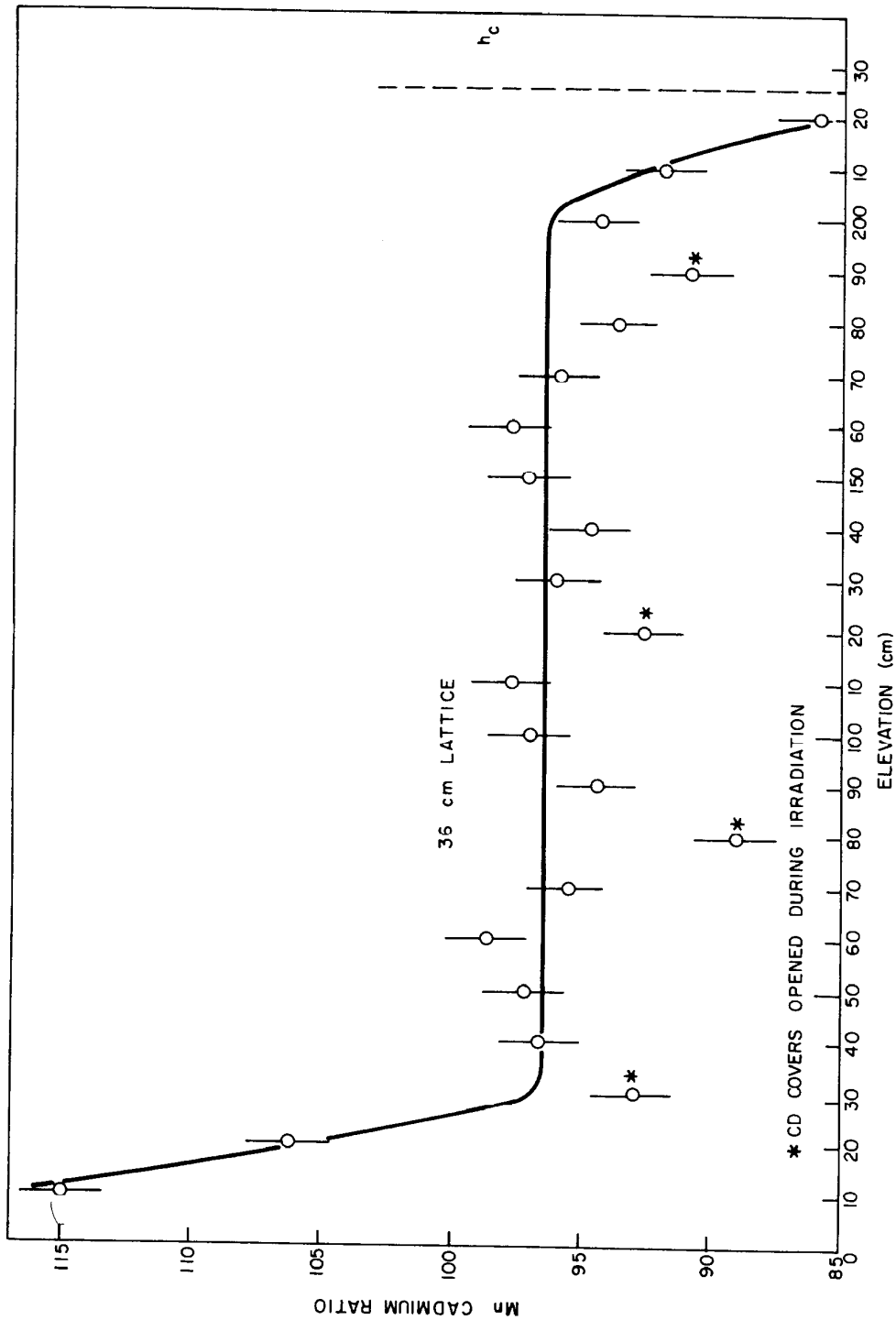


FIG.14 : AXIAL VARIATION OF Mn CADMIUM RATIO — D₂O COOLANT

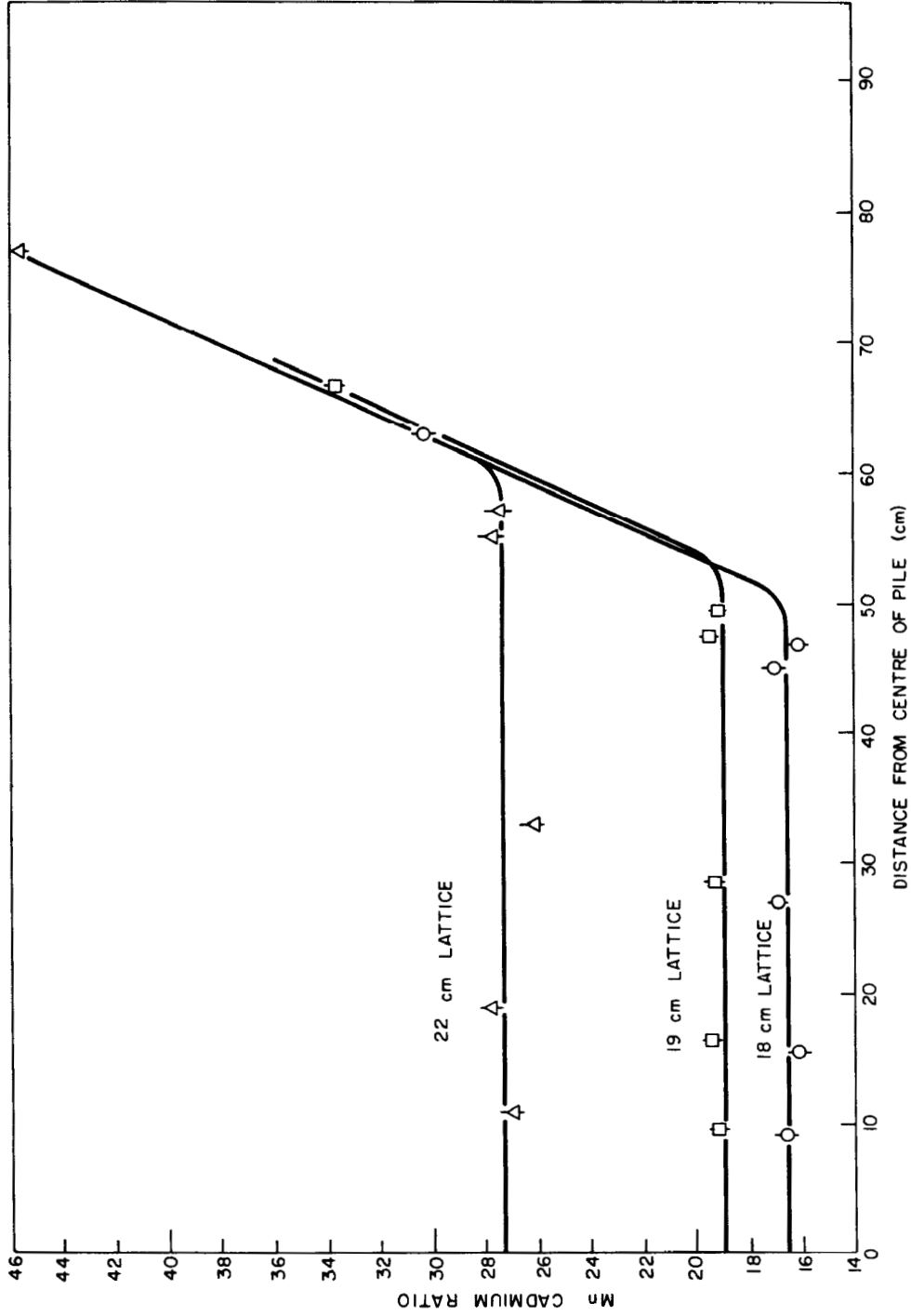


FIG.15 : RADIAL VARIATION OF Mn CADMIUM RATIO—D₂O COOLANT

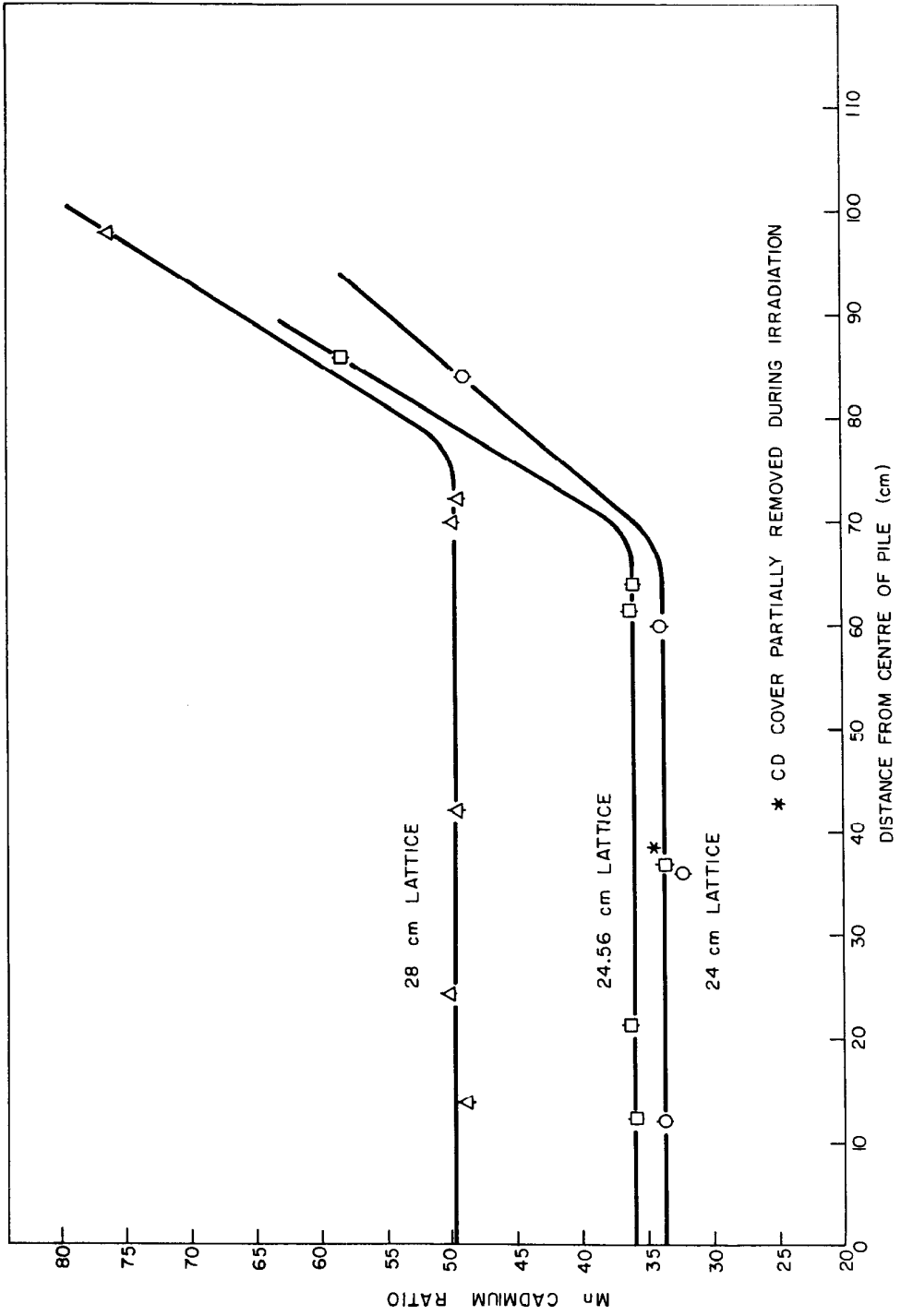


FIG.16 : RADIAL VARIATION OF Mn CADMIUM RATIO — D₂O COOLANT

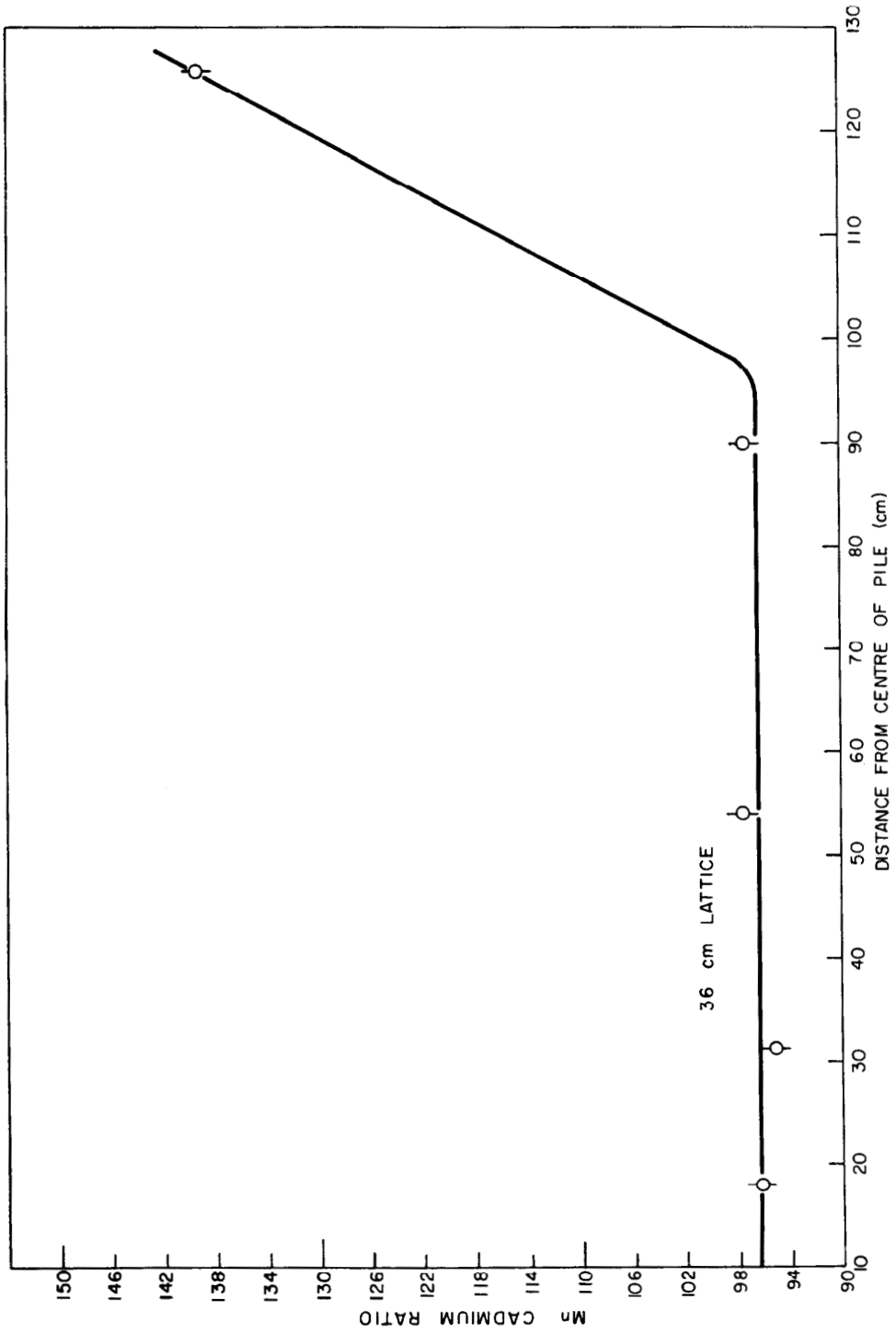


FIG.17 : RADIAL VARIATION OF Mn CADMIUM RATIO—D₂O COOLANT

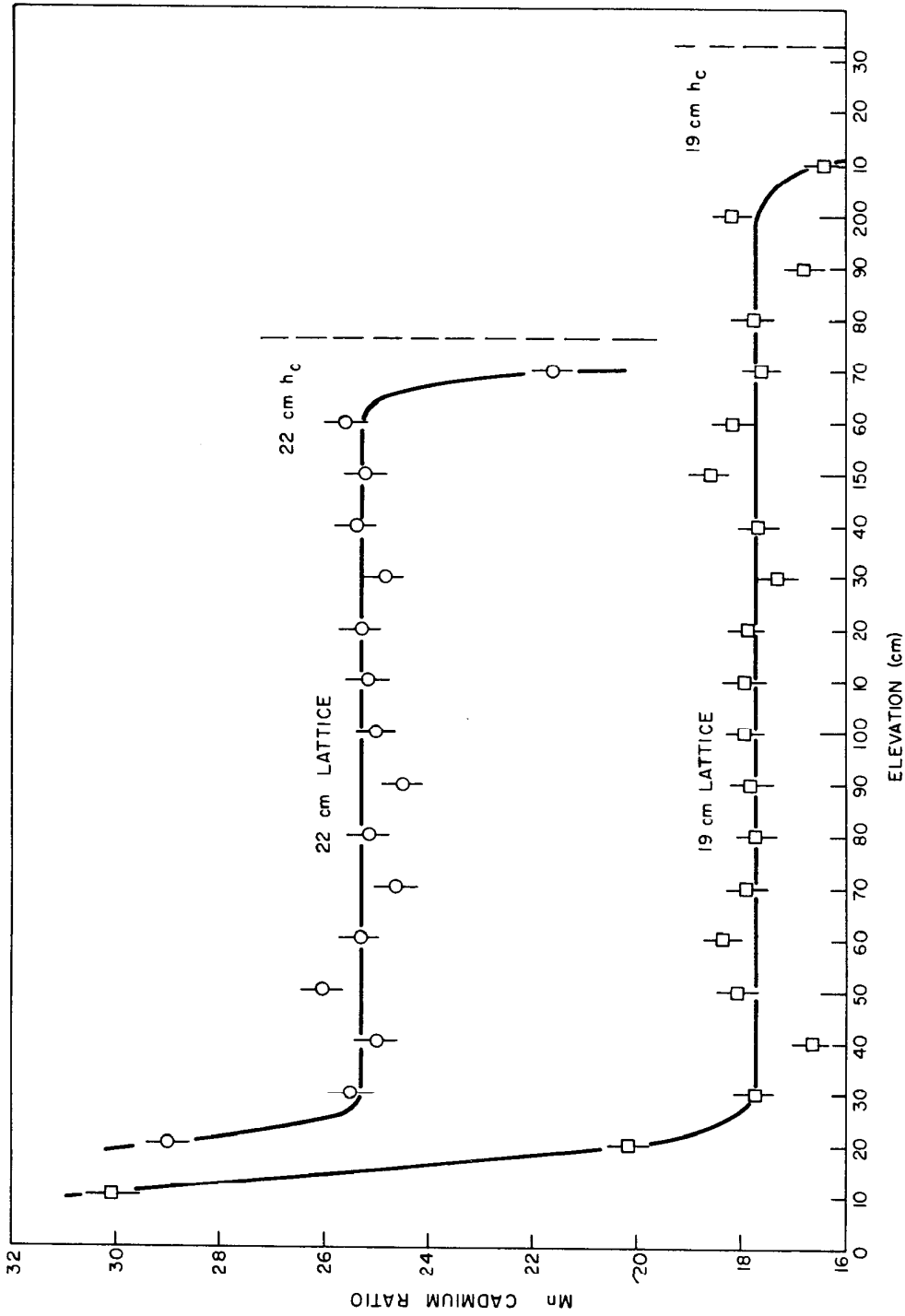


FIG.18 : AXIAL VARIATION OF Mn CADMIUM RATIO—COOLANT VOIDED

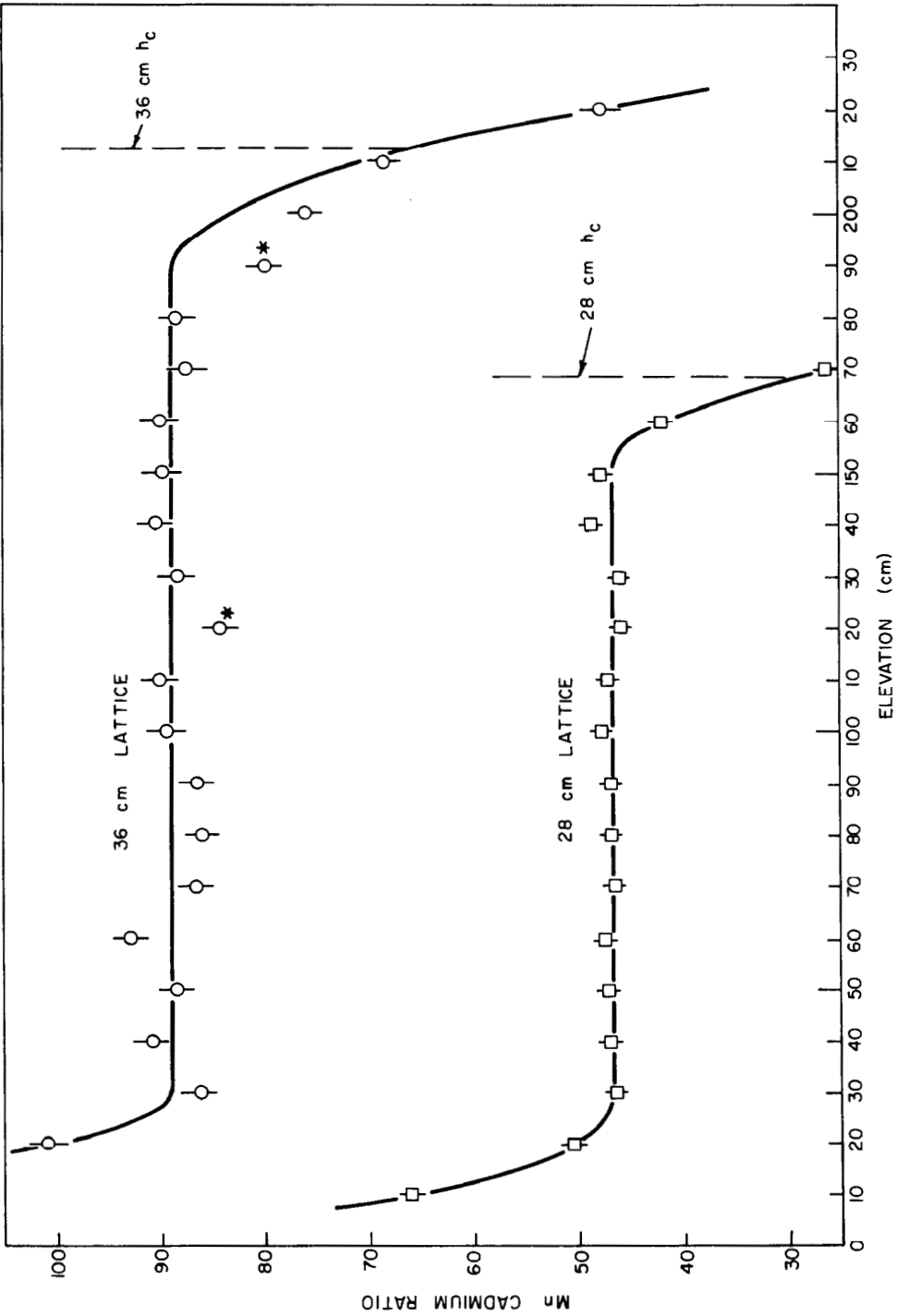


FIG. 19 : AXIAL VARIATION OF Mn CADMIUM RATIO —COOLANT VOIDED

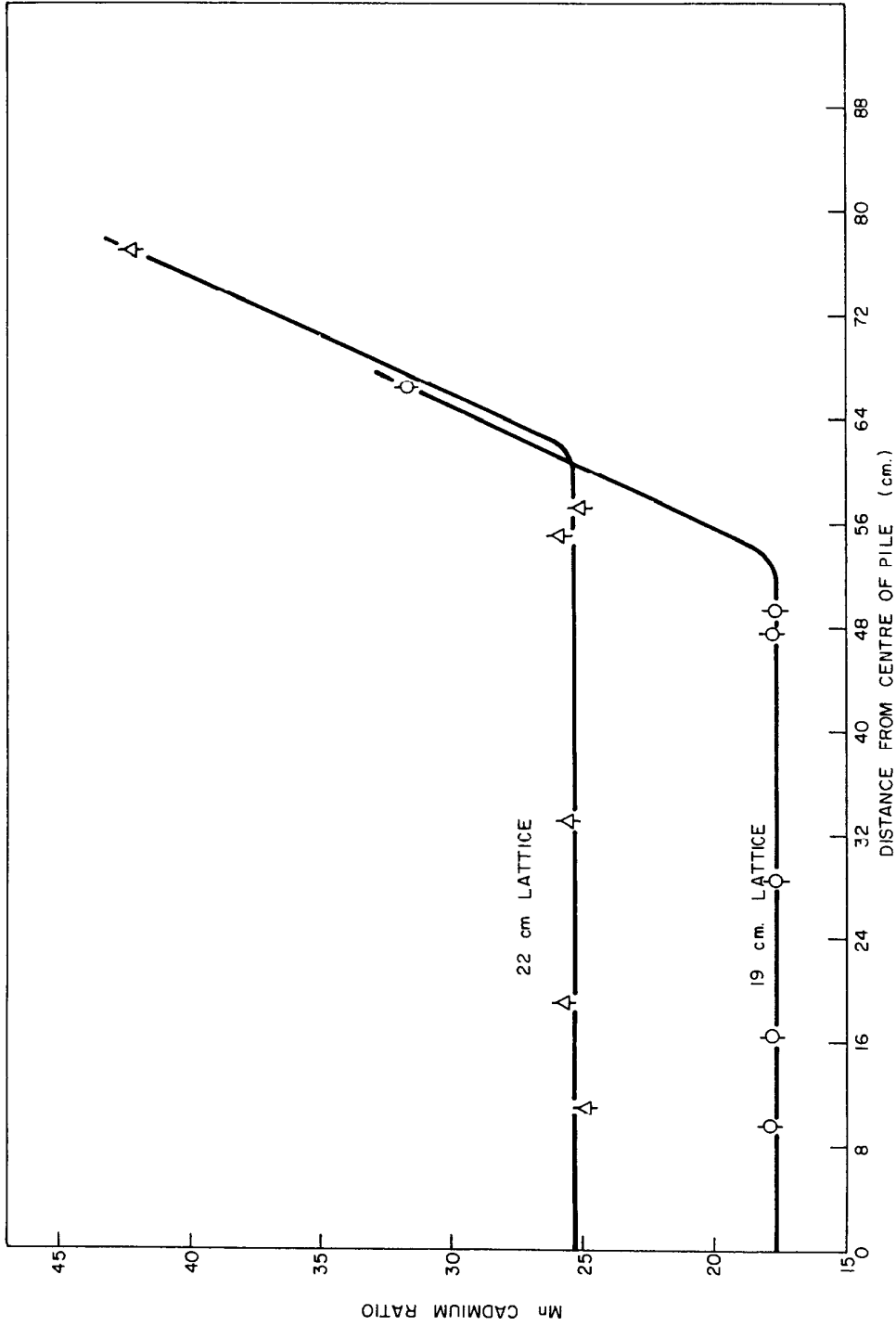


FIG.20 : RADIAL VARIATION OF Mn CADMIUM RATIO-COOLANT VOIDED

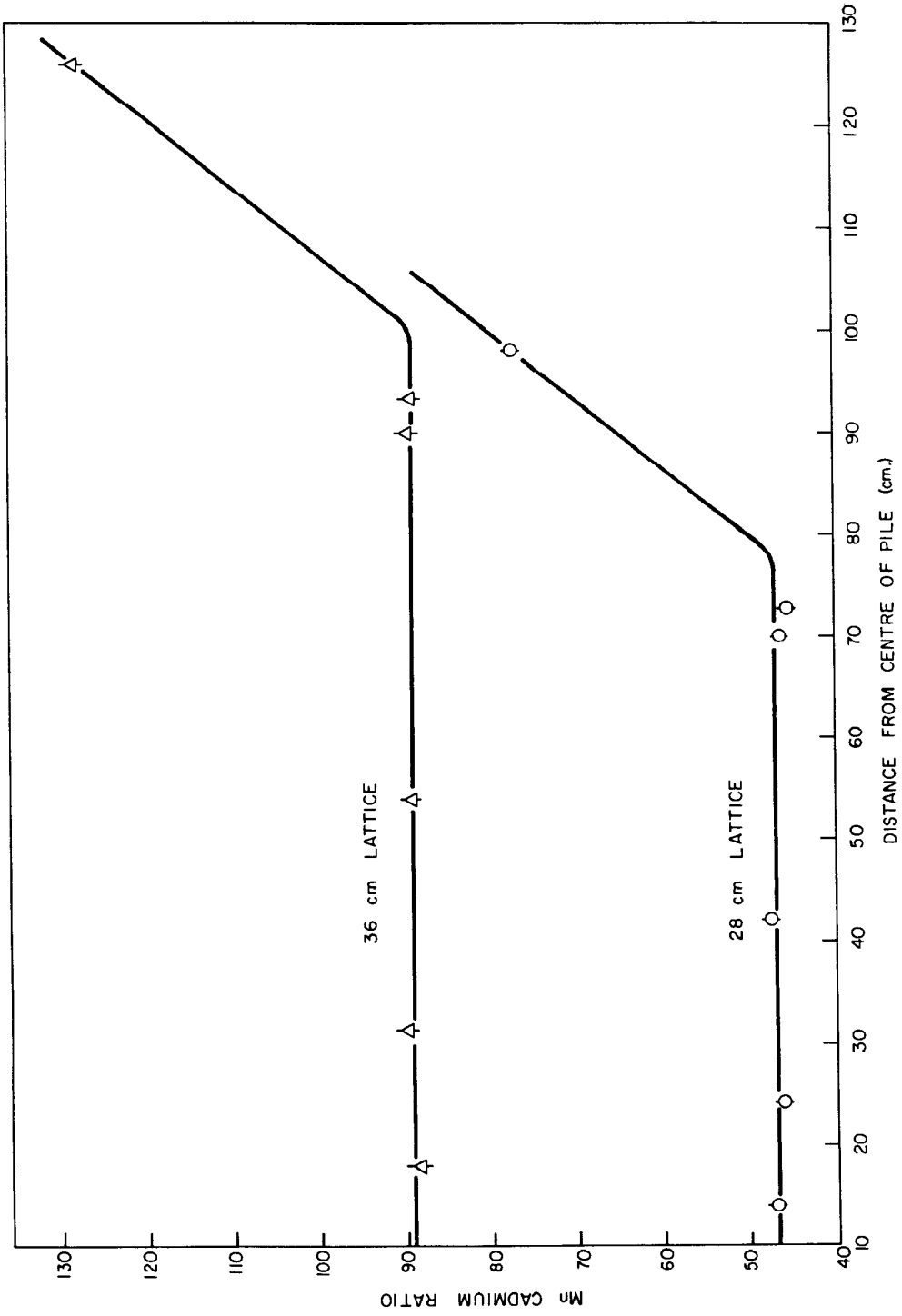


FIG. 2I : RADIAL VARIATION OF Mn CADMIUM RATIO - COOLANT VOIDED

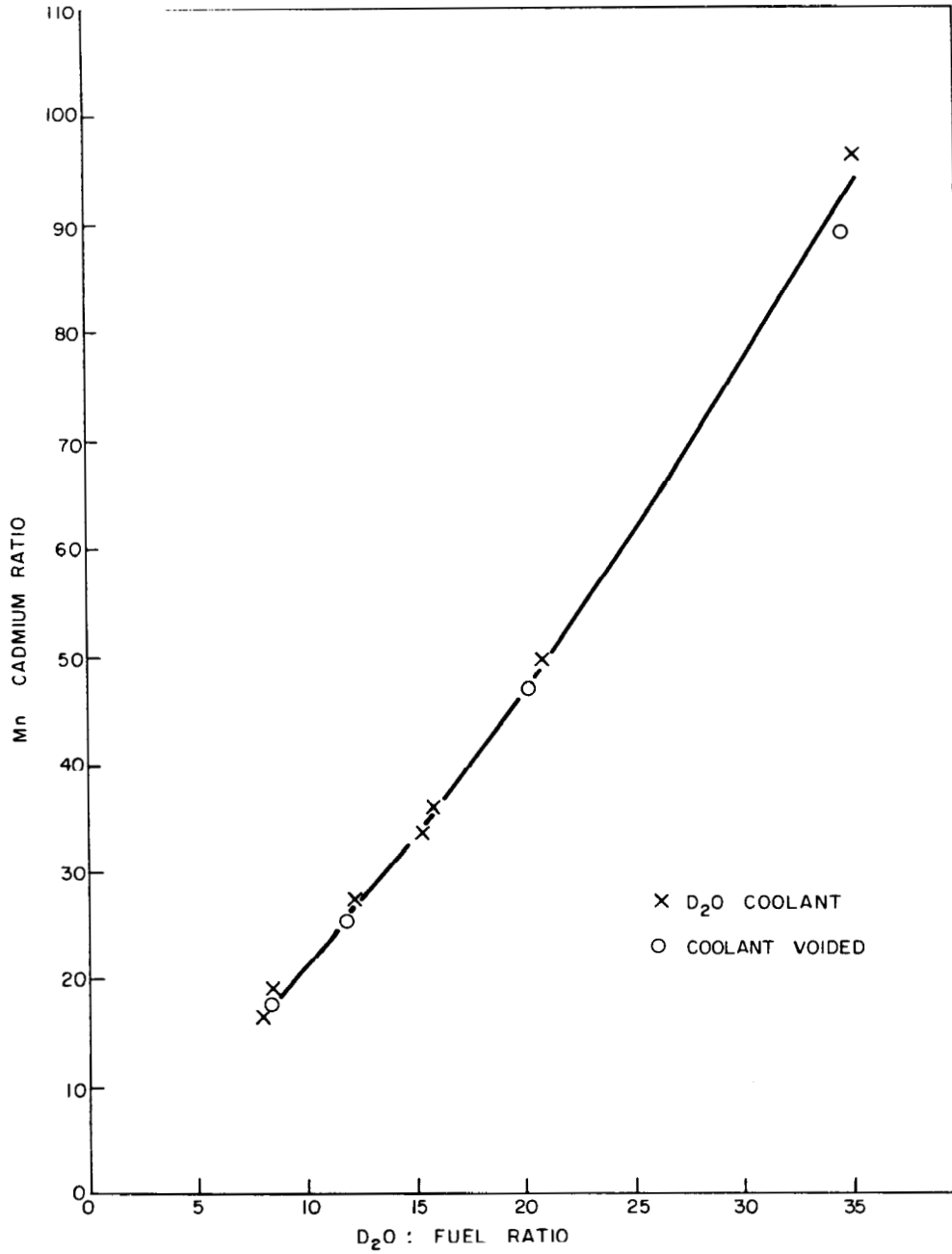


FIG.22: VARIATION OF Mn CADMIUM RATIO WITH D₂O : FUEL RATIO

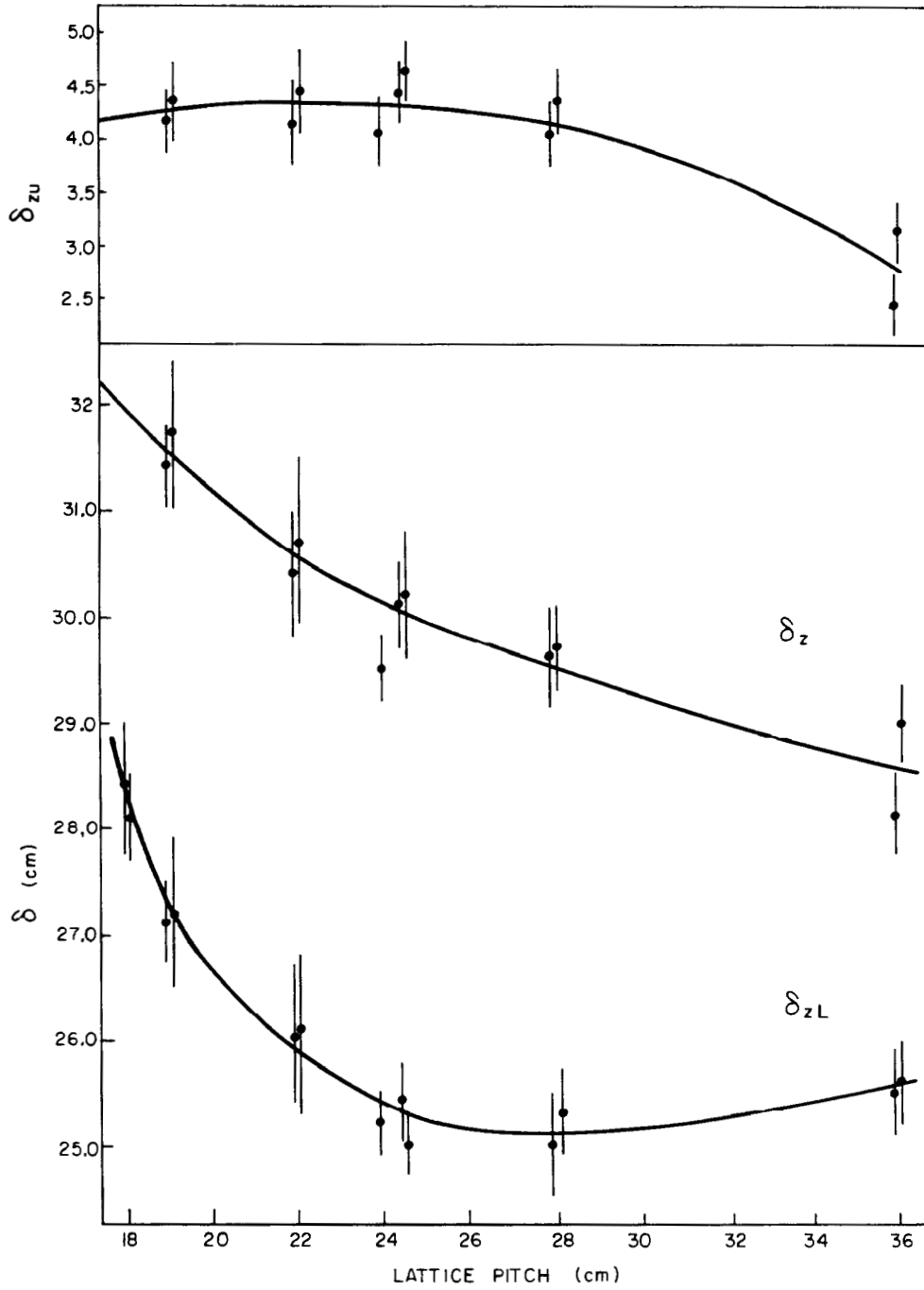


FIG. 23 : AXIAL EXTRAPOLATION LENGTHS - D₂O COOLANT

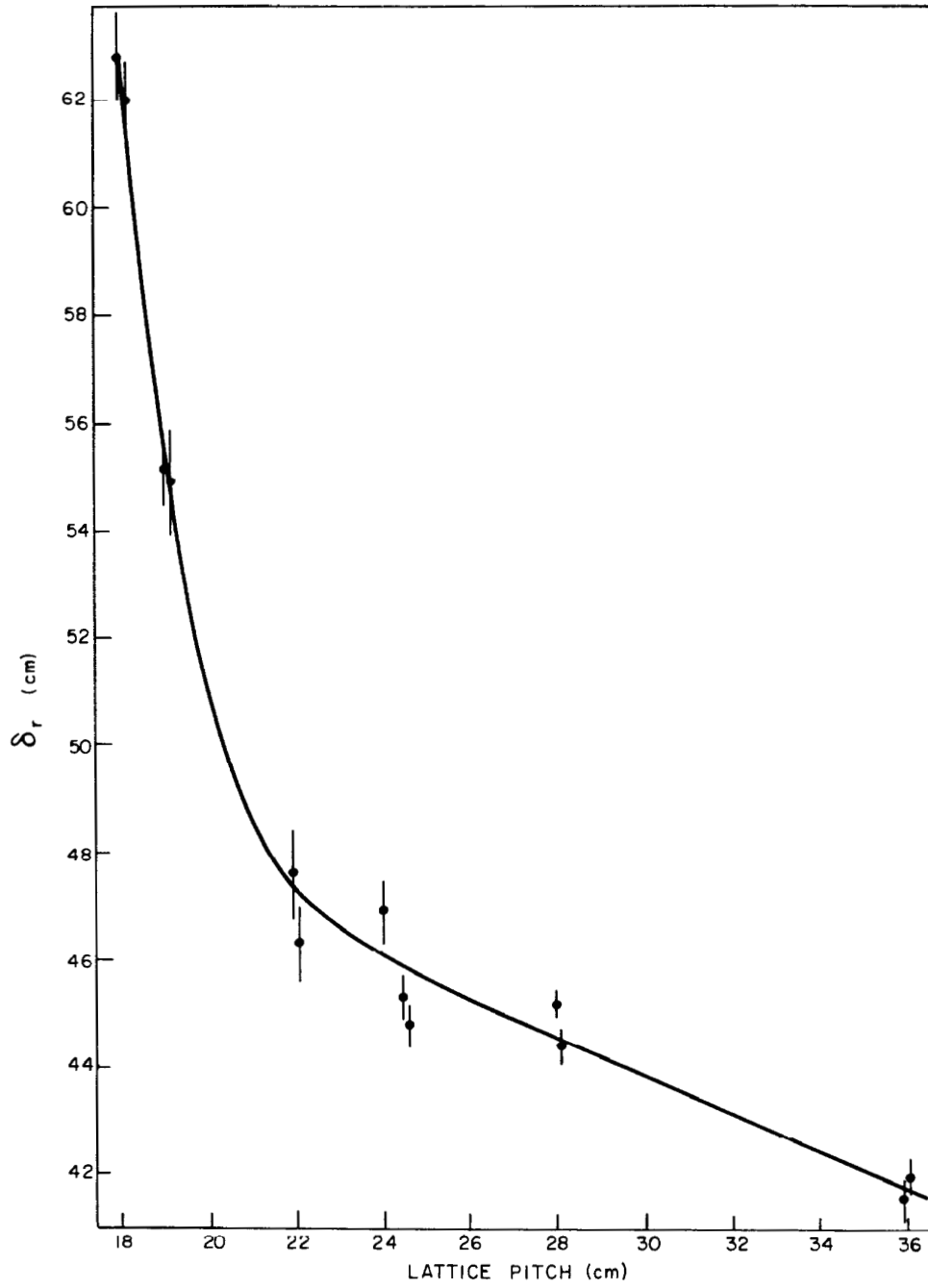


FIG. 24 : RADIAL EXTRAPOLATION LENGTHS - D₂O COOLANT

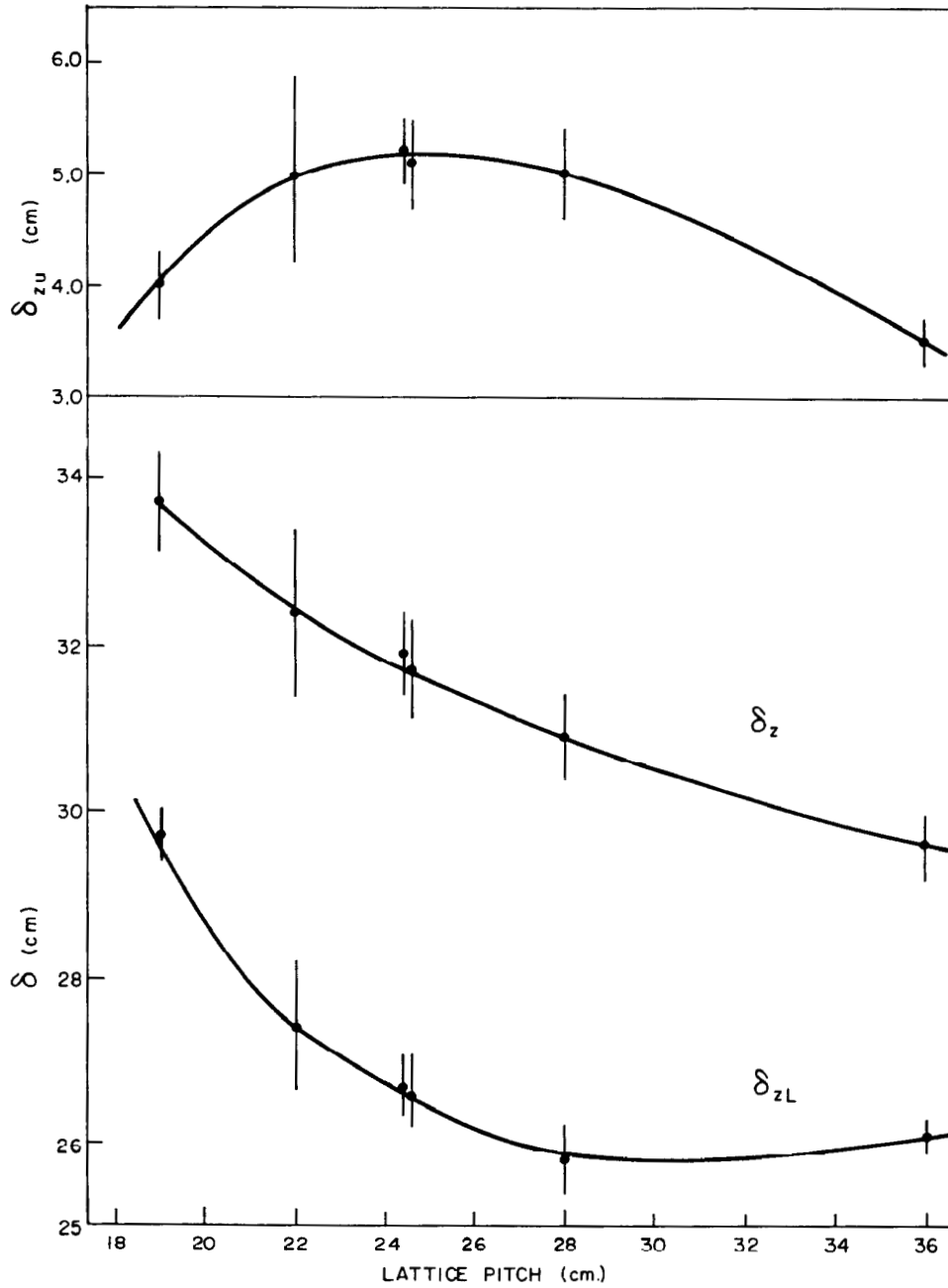


FIG. 25 : AXIAL EXTRAPOLATION LENGTHS - COOLANT VOIDED

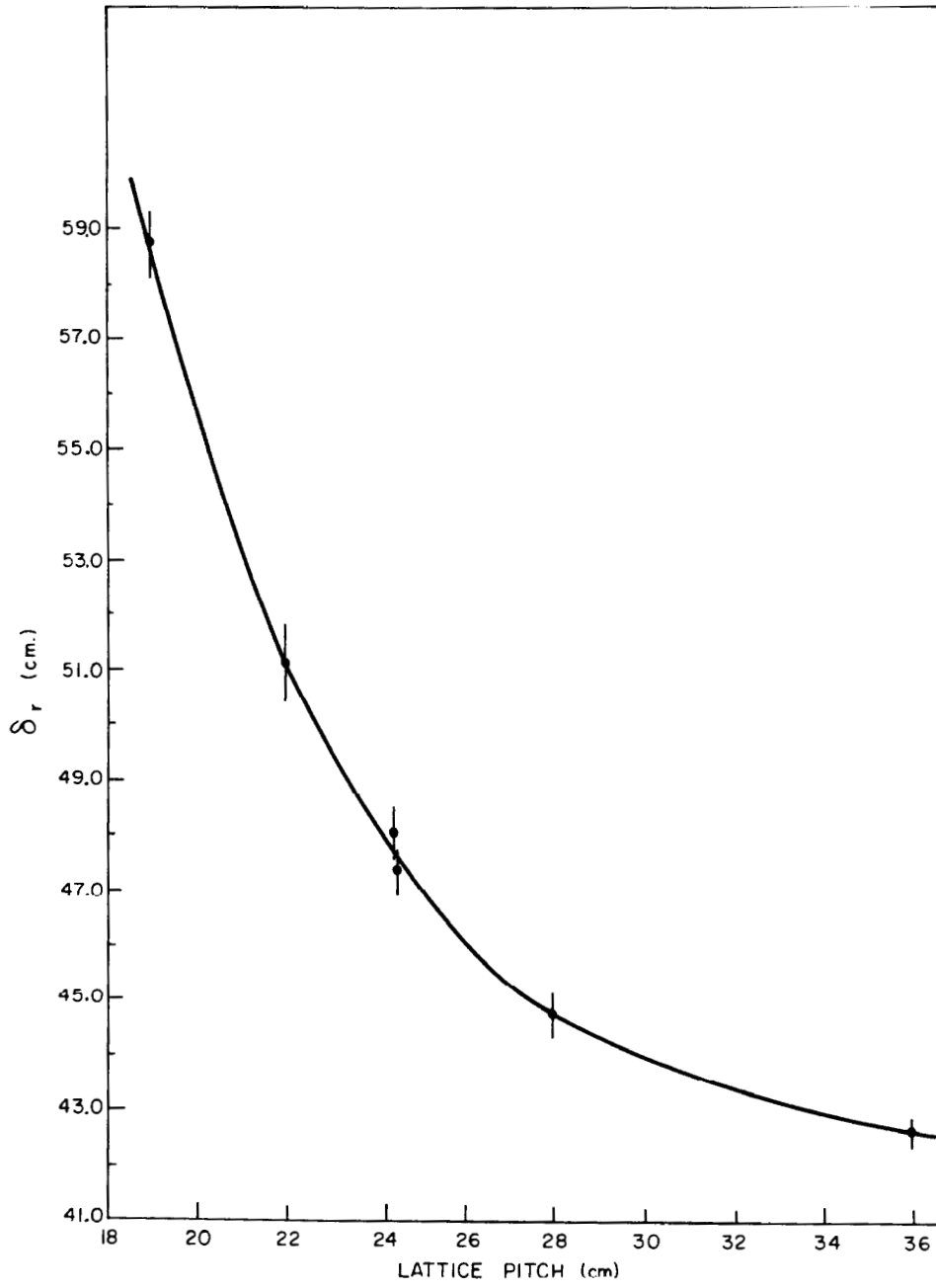


FIG. 26 : RADIAL EXTRAPOLATION LENGTHS-COOLANT VOIDED

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